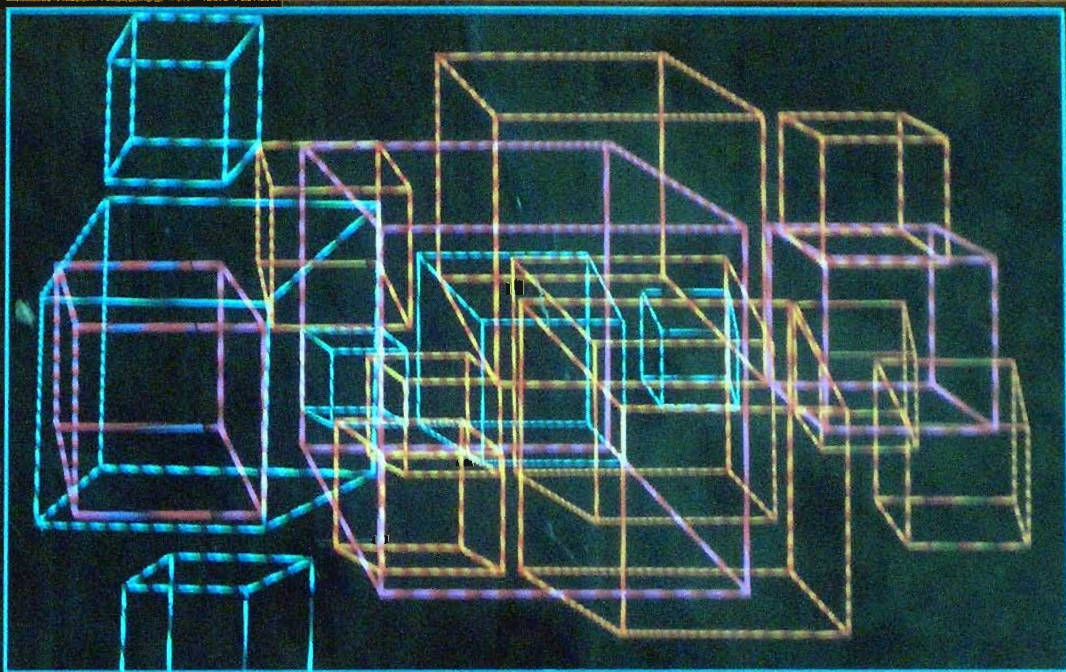
ELECTRICAL SYSTEMS in Buildings



S. David Hughes

Electrical Systems in Buildings

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Preface

This text covers all aspects of the design of electrical power systems as they apply to buildings: industrial and commercial.

The term *commercial building*, as used in this textbook, covers office buildings, schools, stores, institutions, and so forth that are primarily people and public oriented. The term *industrial plant* covers buildings and complexes that are primarily machine and production oriented. The intent of this book is to help the reader understand electrical power systems as they apply to these types of buildings and to appreciate the methods followed by the system designer in selecting the lighting, wiring and devices to be used.

The forms of energy required in a building are thermal (heat), light, and kinetic (mechanical). Why then is energy delivered to a building (or generated within) in the electrical form? The answer is that electrical energy can be transmitted so easily throughout the building to the exact point where the energy is required and then converted to a useful form by the heating unit, light source, or electric motor. This end-use apparatus constitutes the utilization equipment, or system load, of electrical power systems.

The design of an electrical system must begin with a complete listing of the utilization equipment that is to be supplied by the system. Chapters 2–4 of this text deal with two major types of equipment: electric motors and light sources. The material on motors is an overview of the major motor types, including advantages, disadvantages, and principal applications of each type. The material on lighting is an introduction to the major types of light sources, including the application of these sources to illuminate indoor areas to recommended minimum lighting levels.

The design of an electrical system must next focus on two different requirements:

1. The adequacy of the system to deliver sufficient electrical energy of the correct frequency, phase relationships, and voltages

to each piece of utilization equipment. That is, under normal continuous load conditions, the system must operate in a safe and efficient manner.

2. The protection of the system to minimize power outages and damage in the event of prolonged overloading or insulation breakdowns. That is, under abnormal conditions, the potential for damage (both thermal and mechanical) from overcurrents must be minimized.

Chapters 6–10 cover system protection requirements, since the heart of any electrical system consists of those devices that protect and control the flow of power through the feeders and circuits to the utilization points within the system; that is, switches, fuses, circuit breakers, and so on. Also, the very important topic of system and equipment grounding is covered in Chapter 10.

Chapters 11–16 deal with the fundamentals of the design of the electrical system: branch circuits, panelboards, feeders, motor control centers, unit substations, and system protection coordination.

Throughout the text, all related electrical system devices are described and illustrated. In addition, examples show the selection and incorporation of these devices into an overall system. The theory and examples presented are at a level that should be readily understood by students not majoring in electrical technology and yet thorough enough to satisfy those who are.

Chapter 1 covers the basic electrical relationships and standards, which should allow students to understand the balance of the technical material presented in the text. However, the background gained from a basic course in ac circuits, including three-phase wye and delta systems, would be to the student's advantage. For a student on a program of self-study, there are many excellent textbooks that can be used as references in order to gain a better understanding of electrical fundamentals. Some of these books are listed in the bibliography.

Throughout the text, frequent reference is made to the *National Electrical Code*® 1987 (*NEC*®). The titles *National Electrical Code* and *NEC* are registered trademarks of the National Fire Protection Association, Batterymarch Park, Quincy, Massachusetts. In order to better understand the electrical code requirements as they are discussed in this textbook, it is recommended that the reader obtain a copy of the *National Electrical Code* for reference. The *NEC* is the nationally accepted guide in the United States for the safe installation of electrical conductors and equipment. For the Canadian reader, the electrical code requirements are cross-referenced in Appendix A to the *Canadian Electrical Code*, Part 1, which is published by the Canadian Standards Association, Rexdale, Ontario.

Wherever possible throughout this textbook, the International System of Units has been used. This system, given the designation SI, incorporates the metric system of units (meter, kilogram, second). However, for quantities involving physical measurements, the units of feet and inches is also recognized. For example, in lighting, the illuminance level is designated by the number of lumens per unit of area. The unit predominantly used in the United States up to the present time is the lumen per square foot or footcandle. Therefore, the examples involving lighting calculations in Chapter 5 use primarily English units; a few examples using SI units are also included. The tables of recommended illuminance values, prepared by the Illuminating Engineering Society of North America, show the values in both the SI unit (lumens per square meter or Lux) and the English unit (footcandle). Also, the calculations for minimum power demands covered in Chapter 12 are based on unit loadings of volt-amperes per square foot as listed in the *National Electrical Code*.

Another area where English units are used in the United States is the designation of wire and conduit sizes, equipment measurements, and sizes of motors. Wire sizes are based on the unit of the mil (1/1000th of an inch) and conduit sizes are based on inches. Also, table values used for calculating voltage drops and impedances of feeders are based on the distance in feet. Section 90–8, in the introduction to the *National Electrical Code,* states that *values of measurement in the code text will be followed by an approximate equivalent value in SI units. Tables will have a footnote for SI conversion units used in the table.* However, Section 90–8 also states that *conduit size, wire size, horsepower designation for motors, and trade sizes that do not reflect actual measurements; e.g., box sizes, will not be assigned dual designation SI units.* Therefore, all references in this textbook in this regard use the English units.

At the time of writing this textbook, there are many ongoing research projects, which no doubt will have a profound effect on power distribution systems of the future. For example, research work is currently underway on replacing separate wiring systems for electric power, telephones, cable television, security systems, heating controls, and so forth with a single system to service all applications from a common outlet. Article 780, entitled "Closed-Loop and Programmed Power Distribution" has been added to the 1987 edition of the *National Electrical Code* not because there are any working systems of this type available but rather to provide a set of objectives for the guidance of those working to develop this new technology. While applications for this system are directed mainly toward residential installations, there will no doubt be spin-offs that will influence the future installation of systems for office and institutional applications.

The requirements of fire alarm systems, communication systems, public address systems, surveillance systems, and so forth, which may fall within the overall *electrical work* of a building, are beyond the intent of this textbook. These systems are very important but size constraints preclude their being included.

The discussion of code regulations that specifically detail the methods of installing wiring and equipment, which are the concern of the electrical contractor, are generally not within the intent of this textbook. The role of electrical contractors in the successful completion of the electrical system is very important and their expertise is relied upon to properly install the wiring and equipment.

The information and data contained in this textbook is presented solely for the purpose of following the examples, solving the problems at the ends of the chapters, and preparing classroom-related projects. While every attempt has been made to have the data reflect current standards in industry, the manufacturers of the equipment types discussed within this text should be contacted for confirmation of all data and ratings before using any equipment type in actual design specifications. The author and DELMAR Publishers can assume no responsibility for damages that might result from the use of the information presented in this textbook.

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1 Review of Electric Power Fundamentals

OBJECTIVES

After studying this chapter, you will be able to:

- Describe the basic electrical units for current, voltage, resistance, power, and energy.
- Explain the characteristics of series and parallel circuits.
- Describe the additional relationships for alternating currents.
- Recognize the use of phasor diagrams.
- Discuss the effects of inductance and capacitance in alternating current circuits.
- Calculate the impedance and power factor of alternating current circuits.
- Describe the single-phase, three-wire system.
- Describe the relationships of three-phase systems.
- Explain the characteristics of the wye and delta configurations.
- Calculate the line currents and the power of three-phase systems.
- Recognize the problems associated with third harmonics.
- Describe the basic relationships for a transformer and calculate its rated currents.
- Define and properly use the terms nominal voltage, rated voltage, and voltage class.
- Recognize the preferred standard voltages.

INTRODUCTION

The purpose of this chapter is to cover the fundamentals of electricity that will enable the reader to understand the material presented in the balance of this book. Of necessity, the coverage can only be an overview of the basic electrical relationships. For the reader who has had no prior formal training in electrical circuit theory, it is to be hoped that the material presented here will encourage him or her to do further study, using any one of the many textbooks entirely devoted to circuit theory. To this end, a few of the available books are listed in the bibliography. For the reader who has had prior formal training in electrical circuits, it is to be hoped that the material presented here will serve as a good review of the fundamentals of electricity.

As mentioned in the preface, the electrical system is used to transmit energy throughout the building to an exact point, where the energy is then converted to other forms, that is, heat, light, and kinetic. The flow of electrical energy through the feeders and circuits that radiate out from the power source to the utilization points must be understood in order to properly select the components of the system.

1.1 BASIC ELECTRICAL UNITS

The flow of electricity through a circuit is often equated to the flow of liquid through a pipe. For the latter, there is a rate of flow of the liquid, a pressure to force the liquid through the pipe, and a resistance to the flow of the liquid. Similarly, in an electrical circuit there is a rate of flow of electricity (the current), a pressure to force the current through the circuit (the voltage), and a resistance to the flow of current. The basic electric circuit is shown in Figure 1.1. Let us examine these basic relationships in more detail.

1.1.1 Current

All matter is made up of atoms. Each atom has a nucleus around which electrons orbit in a manner similar to the planets revolving around the sun. Depending on the structure of the atom, some electrons are able to move freely from one atom to an adjacent atom. Normally, the movement of electrons within the matter is random; that is, there is no net movement in a specific direction. However, when a force is applied to the ends of the matter, there is a net drift

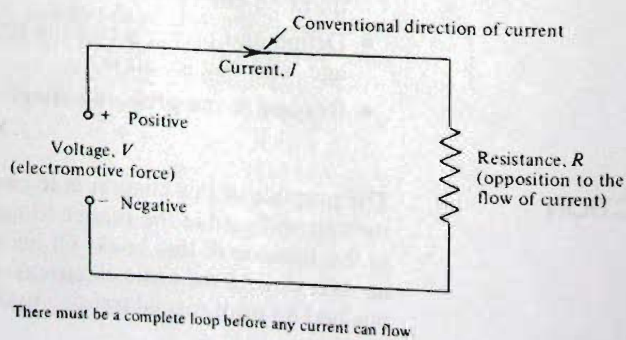


FIGURE 1.1

Basic electric circuit

of electrons in one direction. This net drift of electrons constitutes an electrical current.

The atomic structure of metals is such that there are electrons in the outer orbit that are relatively free to move from one atom to another. Metals are therefore classified as conductors, with silver having the highest conductivity, copper 95% relative conductivity, and aluminum about 60% relative conductivity. On the other hand, the atomic structure of insulators is such that relatively few free electrons are available; therefore, for all practical purposes, insulators are unable to carry any current.

Before any current can flow, an electric circuit must form a complete loop, as shown in Figure 1.1. Current is a quantity since it is a measure of the net drift of electrons through a conductor, that is, the rate of flow of the electric medium per unit of time. The symbol for current is I (from intensity of electron flow) and the unit of measure is the ampere (A). It has been calculated that 1 ampere is equal to 1 coulomb (6.25×10^{18} electrons) passing a given point in 1 second. If you are wondering why such an awkward number, it must be remembered that the electrical units were established before the electron theory for matter was formulated. Since the precise measurement of the rate of flow of electrons is difficult, the SI definition of the *ampere is the constant current that, if maintained in two straight parallel conductors of infinite length of negligible circular cross section and placed 1 meter apart in vacuum, would produce between these conductors a force equal to* 2×10^{-7} *newton per meter of length.*

1.1.2 Voltage

As we have already mentioned, for current to flow in a conductor, a force must be applied to the ends of the conductor. This force is called the *electromotive force* (electron moving force). The electromotive force (emf) can be produced by chemical means (for example, a battery) or by electromechanical means (a generator). The voltage is then a measure of the electromotive force produced by the source. The general symbol for voltage is V, and the unit of measurement is the volt, also symbol V. *One volt is the potential difference between two points in an electrical circuit when the energy involved in moving 1 coulomb of electrons from the one point to the other is 1 joule*. Thus, the volt is equated to the SI unit of energy, the joule, which is defined in Section 1.1.4. Note that the term voltage may also be applied to the potential difference across an element within a circuit, as is explained in the next section.

The direction of current flow within a circuit is determined by the polarity of the source voltage. The polarity in turn is designated by positive and negative terminals. The conventional current direction is such that current flows through the circuit from the positive terminal to the negative terminal of the source, as shown in Figure 1.1. Unfortunately, this is opposite to the direction of flow of the electrons through the circuit. Again, the discrepancy arises from the fact that the laws governing electricity were established long before the electron theory was formulated. Readers who refer to other books for additional reading on electrical circuits should always check whether the author is using the conventional current direction or is in fact using the direction of electron flow. If the latter, then relationships such as the right-hand rule are referred to as the left-hand rule.

1.1.3 Resistance and Ohm's Law

The resistance of a circuit is a measure of the opposition to the flow of the current through the circuit. For a circuit with a constant resistance, there is a direct relationship between the current that flows and the voltage that is applied. If the voltage is doubled, then the current will double; if the voltage is tripled, then the current will triple. In other words, for a given circuit, the ratio of the applied voltage to the current is a constant. This relationship can be expressed in equation form thus:

$$R = \frac{V}{I} \tag{1.1}$$

where V = voltage
I = current
R = resistance

This basic relationship is known as Ohm's law. Note that the resistance is a measure of the voltage required per ampere of current that flows and, as such, a unit of volts per ampere could have been adopted. However, the ohm was selected as the unit of electrical resistance with the symbol Ω (capital Greek letter omega). *One ohm is the electrical resistance that allows exactly 1 ampere to flow when exactly 1 volt is applied.*

Note that resistance is a quality of the conducting material. The term *resistor* then applies to a device designed to have a specific resistance. Ohm's law can be used in many ways to solve electrical circuit problems, as shown in the following examples.

EXAMPLE 1.1

If 120 V is applied to a circuit and the current is measured at 10 A, calculate the resistance of the circuit.

Solution

From Ohm's law,

$$R = \frac{V}{I} = \frac{120}{10} = 12\ \Omega$$

■ EXAMPLE 1.2

If 120 V is applied to a circuit that has 15 Ω of resistance, calculate the current that will flow.

Solution

Rearranging Ohm's law,

$$I = \frac{V}{R} = \frac{120}{15} = 8 \text{ A}$$

■ EXAMPLE 1.3

The current flowing through a 5 Ω resistor is 20 A. Calculate the potential difference across the resistor.

Solution

Rearranging Ohm's law again,

$$V = IR = 20 \times 5 = 100 \text{ V}$$

Note the use of the term potential difference in Example 1.3. Previously, voltage was described as a measure of the electromotive force applied to a circuit. However, voltage can also represent a difference in potential across a circuit element. This potential difference is more commonly referred to as *voltage drop*.

Refer to Figure 1.2. Voltmeter V_1 measures the voltage of the source and voltmeter V_2 measures the voltage across the resistance R. When the switch is closed, both voltmeters read the same since the voltage drop across the resistance must match the emf of the source. Next, the switch is opened. V_1 will still show a reading as the emf of the source is still present. However, voltmeter V_2 now reads zero, as there can be no voltage drop across the resistance when there is no current flowing through it. In fact, the voltage drop across a circuit element is often called the *IR drop*.

In a circuit where it is important to differentiate between the source voltage and the voltage drops, the symbol E is used to designate the source voltage and the symbol V is used to designate the voltage drop. When the switch is closed and current is flowing, the circuit is referred to as a *closed* or *energized* circuit, and when the switch is opened, the circuit is referred to as an *open* or *de-energized* circuit.

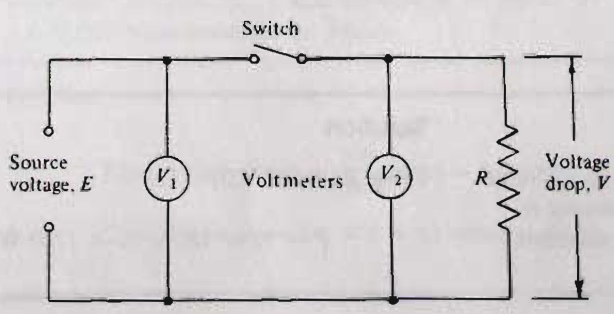


FIGURE 1.2

Difference between source voltage and voltage drop

1.1.4 Power and Energy

We return again to the basic function of an electric circuit and that is to transmit energy. Thus, there must be a point where energy is put into the circuit (the source) and a point where energy is taken out of the circuit (the load). Energy can most easily be defined as the ability to do work. Work, in turn, can be thought of as the process of transforming energy from one form into another. An electric motor converts electrical energy into kinetic (mechanical) energy, an electric heater converts electrical energy into thermal energy (heat), and a light bulb converts electric energy into light. Energy and work are numerically equal, and the same unit of measurement is used for both. The SI unit for energy is the joule (J). *One joule is the energy required to move an object 1 meter against a force of 1 newton.* Note that the joule is defined in mechanical terms. It is desirable that the same unit of energy be used for both mechanical and electrical systems so that calculations can be readily related from one system to the other. Therefore, the equivalent amount of electrical energy is also called a joule.

Power is the rate at which energy is converted or in other words the rate of doing work. The symbol for power is P, and the SI unit of measurement is the watt (W). *One watt is the rate of doing work when 1 joule of energy is expended in 1 second.* For large units of power, the kilowatt (kW), which equals 1000 watts, is used.

By combining the definitions for the volt and the ampere and rationalizing their units, the following relationship is derived:

$$P = VI \tag{1.2}$$

where P is the power in watts. This is one of the most useful equations in electrical technology; that is, the power in watts is the product of the volts times the amperes. Substituting $V = IR$ from Ohm's law into Equation 1.2 gives the following:

$$P = I^2R \tag{1.3}$$

The following examples illustrate the use of these power relationships.

EXAMPLE 1.4

If 120 V is applied to a circuit and the resulting current is measured at 10 A, calculate the power.

Solution

From Equation 1.2,

$$P = VI = 120 \times 10 = 1200\ \text{W}$$

■ EXAMPLE 1.5

The current flowing through a 15 Ω resistor is 20 A. Calculate the power.

Solution

From Equation 1.3,

$$P = I^2R = (20)^2 \times 15 = 6000 \text{ W}$$
$$= 6.0 \text{ kW}$$

■ EXAMPLE 1.6

Calculate the current drawn by a 120 V, 100 W light bulb when it is energized.

Solution

Rearranging Equation 1.2,

$$I = \frac{P}{V} = \frac{100}{120} = 0.833 \text{ A}$$

It is important that the reader not only follow the mathematical calculations in the previous examples but also realize the information being provided. In Example 1.4, the values given apply to a circuit and therefore the watts calculated not only indicate the power being supplied but also represent the total power being dissipated throughout the circuit (that is, turned into another form). In Example 1.5, the values given apply to a resistor (an element in the circuit), and therefore the watts calculated indicate the power being dissipated by the resistor (that is, turned into heat). This resistor could be just one of several elements connected into the circuit. Note that the power dissipated through a resistance is directly proportional to the square of the current. If the current is doubled, the heat generated is increased four times. This is important to remember with regard to feeders and circuits supplying utilization equipment. The heat given off due to the resistance of the conductors is power that for all practical purposes is a loss to the system. This loss is often referred to as the *I^2R loss*. In Example 1.6, the values given also apply to a single device (the light bulb), and Equation 1.2 is used to determine the current requirements of the device.

Remembering again that a watt is 1 joule per second, then 1 joule of electrical energy is equal to 1 watt-second. However, the unit of watt-second is very small, so a more practical unit is the kilowatt-hour (kWh). The kilowatt is 1000 watts and 1 hour is 3600 seconds. Therefore, 1 kilowatt-hour is equal to 1000 × 3600 or 3,600,000 watt-seconds or joules.

■ EXAMPLE 1.7

A 100 W light bulb burns for 24 h. The rate for electrical energy is 5 cents/kWh. Calculate the cost of operating the light bulb.

Solution

$$\text{Energy consumed} = \frac{100}{1000} \times 24 = 2.4 \text{ kWh}$$

$$\text{Cost of energy} = 2.4 \times 5 = 12 \text{ cents} = \$0.12$$

All the foregoing has been based on the SI system of units. Fortunately, both the English and the SI units for electrical measurements are the same. However, the units of mechanical power are different. The English system is based on the unit of the horsepower (hp), which is equal to doing work at the rate of 550 foot-pounds per second. The conversion factor between the horsepower and the watt is then:

$$1 \text{ hp} = 746 \text{ W} = 0.746 \text{ kW} \tag{1.4}$$

EXAMPLE 1.8

Determine the rating in kilowatts of a 10 hp motor.

Solution

$$10 \text{ hp} = 10 \times 0.746 = 7.46 \text{ kW}$$

1.2 CIRCUIT ARRANGEMENTS

Section 1.1 dealt with the basic electrical relationships of a simple circuit. Practical circuits can consist of more than one circuit element. The configuration in which these elements are connected into the circuit determines whether it is a series circuit, a parallel circuit, or a combination of the two.

1.2.1 Series Circuit

A *series circuit* is one in which all the elements are connected end to end so that there is only one complete path for the current. Figure 1.3 shows a circuit with three elements connected in series. The

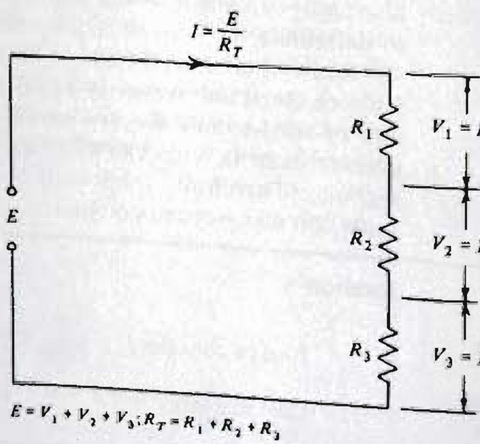


FIGURE 1.3

Series circuit with three elements

characteristics of a series circuit are that the current through each element is the same, but the voltage across each element can be different. The voltage across each element (V_1, V_2, and V_3), from Ohm's law, is the product of the current times the specific resistance of the element. The applied voltage E must equal the sum of the individual voltage drops across the circuit elements. The following example illustrates the relationships for a series circuit.

EXAMPLE 1.9

The values of the circuit elements in Figure 1.3 are $R_1 = 10\ \Omega$, $R_2 = 20\ \Omega$, and $R_3 = 30\ \Omega$. The source voltage E is 120 V. Calculate (a) the current flowing in the circuit and (b) the voltage drop across each element.

Solution

(a) Total resistance $R_T = 10 + 20 + 30 = 60\ \Omega$

$$I = \frac{E}{R_T} = \frac{120}{60} = 2\ \text{A}$$

(b)

$$V_1 = IR_1 = 2 \times 10 = 20\ \text{V}$$

$$V_2 = IR_2 = 2 \times 20 = 40\ \text{V}$$

$$V_3 = IR_3 = 2 \times 30 = \underline{60}\ \text{V}$$

Total voltage drop = 120 V (same as voltage E)

The connection of load elements in series is not commonly found in circuits used in building electrical systems. First, any change in any one of the circuit elements affects the current through all elements. In the extreme, if one element fails (for example, a light bulb), then all the other circuit elements are also turned off. Second, the voltage across each element depends on its relationship with the total circuit resistance. Note that in Example 1.9 the ratio of the voltage drops is the same as the ratio of the resistances. If any of the circuit elements are changed or the number of elements altered, then the voltage across a particular element changes. Thus, it would be impossible to have the circuit elements designed for one specific rated voltage as the required operating voltage would depend on the circuit configuration.

While not normally thought of as a series circuit, one common circuit configuration nevertheless operates on the principle of a series circuit. All circuits have wiring connecting the load to the source. The resistance of the circuit wires is then in series with the load, as shown in Figure 1.4. The resistance of the circuit wires must be kept low enough so that the voltage across the load is within a few percentage points of the source voltage, as illustrated in the following example.

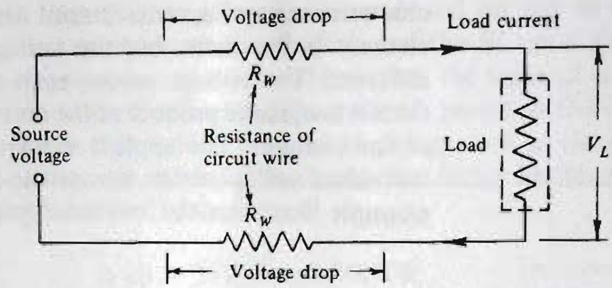


FIGURE 1.4

Practical circuit showing voltage drops in the circuit wires

■ EXAMPLE 1.10

The load in Figure 1.4 will draw a current of 10 A. The source voltage is 120 V. Calculate the maximum resistance R_W of each of the conductors if the voltage across the load V_L is to be within 2.0% of the source voltage.

Solution

The maximum voltage drop permitted is $0.02 \times 120 = 2.4$ V. Therefore, the maximum voltage drop per conductor is 1.2 V. From Equation 1.1,

$$R_W = \frac{V}{I} = \frac{1.2}{10} = 0.12\ \Omega \text{ maximum}$$

While the previous calculation could also be used for small alternating current circuits (for example, 15 amperes), it should be noted that the voltage drop calculation for large feeders is more complicated because of the inductive reactance of the feeder. This is discussed in detail in Section 11.3.

1.2.2 Parallel Circuit

A *parallel circuit* is one in which all the elements are connected between two common points so that there are multiple paths for the current. Figure 1.5 shows a circuit with three elements connected in parallel. The characteristics of a parallel circuit are that the voltage across each element is the same, but that the current through each element can be different. Note that these characteristics are the exact opposite to those for a series circuit. The currents through each element (I_1, I_2, and I_3), from Ohm's law, are inversely proportional to the resistance of each element. The total current I_T is the

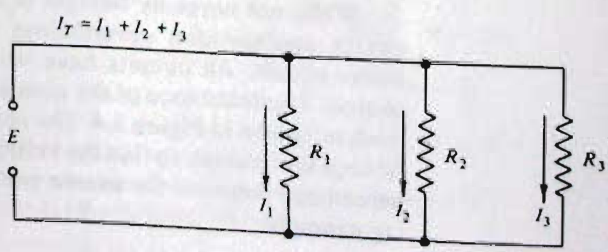


FIGURE 1.5

Parallel circuit with three elements

sum of the individual currents through each element. Finally, the total circuit power is the sum of the individual power requirements of the elements. The following example illustrates the relationships for a parallel circuit.

■ EXAMPLE 1.11

The values of the circuit elements in Figure 1.5 are R_1 = 10 Ω, R_2 = 20 Ω, and R_3 = 30 Ω. The source voltage E is 120 V. Calculate (a) the current through each element, (b) the total circuit current, and (c) the power requirements of each element and the total circuit power.

Solution

(a) $$I_1 = \frac{E}{R_1} = \frac{120}{10} = 12\text{ A};\quad I_2 = \frac{E}{R_2} = \frac{120}{20} = 6\text{ A}$$

$$I_3 = \frac{E}{R_3} = \frac{120}{30} = 4\text{ A}$$

(b) $$I_T = I_1 + I_2 + I_3 = 12 + 6 + 4 = 22\text{ A}$$

(c) $$P_1 = I_1^2R_1 = (12)^2 \times 10 = 1440\text{ W}$$

$$P_2 = I_2^2R_2 = (6)^2 \times 20 = 720\text{ W}$$

$$P_3 = I_3^2R_3 = (4)^2 \times 30 = 480\text{ W}$$

Total power of elements = 2640 W

Total power input to circuit = EI = 120 × 22 = 2640 W

These two power values must be equal.

Note that, even though the resistances of the three elements in the parallel circuit are the same as for the three elements in the series circuit in Example 1.9 and the source voltages are equal, the results are entirely different.

The parallel arrangement is the only practical way of connecting the load elements in a power circuit. In this way, other than the very minor voltage drops in the circuit wiring, the voltage applied across each element is independent of the other elements in the circuit. This is very important, for instance, in lighting systems where individual lights are continually being switched on and off.

With the parallel arrangement, as elements are added the total current increases and hence the total power increases. This power requirement is referred to as the load on the circuit. In subsequent chapters that deal with circuits, you will find very little reference to the resistance (or impedance in alternating current circuits) of the individual circuit elements, but rather the emphasis is on the load that each element adds to the circuit. However, do not lose sight of the fact that as the load increases (that is, as elements are added in parallel) the total equivalent resistance of the circuit is decreasing. Therefore, do not think of the load on a circuit in terms of resistance (or impedance), but rather in terms of power requirements. With a fixed voltage, the power is directly proportional to the current (overlooking the power factor, which is discussed later with regard to alternating current circuits).

1.3 ALTERNATING CURRENT RELATIONSHIPS

Although not specifically mentioned, all the discussions to this point have been based on direct currents. With direct current (dc), the voltage is constant in magnitude and polarity and the current flows constantly in one direction. With alternating current (ac), as the term implies, the voltage is continuously varying in magnitude and polarity, and the current is continuously changing direction. With steady dc circuits, only the resistance need be of concern. With ac circuits, the additional parameters of inductance, capacitance, and power factor must be considered. This, in turn, requires an understanding of sine waves, frequency, rms values, impedance, and phase relationships.

If the use of alternating currents causes extra problems, the first question must then be: Why use ac systems? There are two very important reasons. First, the voltage levels can be easily raised or lowered by means of a transformer, as described in Section 1.7. Second, ac systems allow the use of the squirrel-cage induction motor, which is very simple in construction, requiring no commutator bars and brushes, and the like, as discussed in Section 2.5.

1.3.1 Sine Waves, Cycles, and Frequency

The voltages and currents of ac systems vary in a sinusoidal manner; that is, their waveforms vary according to the sine function of an angle over a linear period of time. Other waveforms could be used (for example, square or sawtooth), but the sine wave is the only waveform with a rate of change that in itself is also sinusoidal. This is shown in Sections 1.4.1 and 1.4.2 with respect to inductance and capacitance.

The shape of the sine wave is obtained from the trigonometric relationship of the sine of each angle throughout the 360° of a complete circle or revolution, as shown in Figure 1.6. In the diagram, the circle is shown divided into 12 equal segments of 30° each. The vertical distance from the zero axis of each 30° segment (that is, the sine of the angle) is projected to outline the waveform. One cycle is the complete change of the varying quantity from zero through a positive peak, through a negative peak, and back to zero, as indicated.

The horizontal axis of the waveform is marked in degrees from 0 to 360. However, the horizontal axis also represents time. The time to complete one cycle is called the *period*. The *frequency* is the

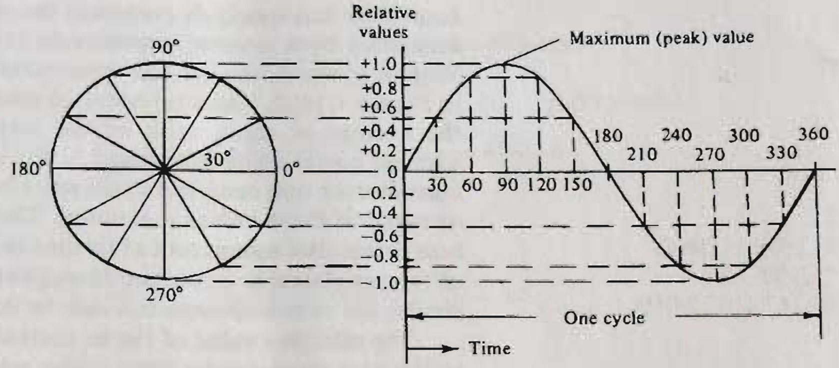


FIGURE 1.6

Development of the sine wave

number of cycles completed in 1 second. The unit for frequency is the hertz (Hz). One hertz equals one cycle per second. The standard frequency for the United States and Canada is 60 hertz. Europe and much of the rest of the world have standardized on 50 hertz. A 60 hertz system is one in which the voltage and current alternate through 60 cycles each second. The period for each cycle is therefore $\frac{1}{60}$ or 0.0167 second.

Since the magnitude of a sine wave voltage or current is continuously varying with time, the magnitude at one specific instant of time is referred to as the *instantaneous value*. For example, at 0°, 180°, and 360°, the instantaneous value, as per Figure 1.6, is zero. At 90°, the instantaneous value has reached its maximum positive value, which is therefore referred to as the *maximum* or *peak* value of the quantity.

1.3.2 Root-Mean-Square Values

Since the use of sine wave alternating voltages and currents is so common, it is desirable to have a method by which their magnitudes can be easily specified. However, in doing so, the fundamental relationships of the volt, the ampere, and the watt as they apply to dc circuits must not be altered.

Referring to the shape of the sine wave, we can see that the average value of an ac current is zero since the negative half cycle exactly matches the positive half cycle. Therefore, the average value cannot be used as a means of specifying the magnitude of the current. The rational method then is to establish an effective value that represents the magnitude of ac current that in terms of power is equivalent to a steady dc current of the same magnitude. The power dissipated by a resistor is expressed in Equation 1.3 as $P = I^2R$. With ac systems, the instantaneous power is also varying, as shown in Figure 1.14(a). The equivalent constant power over one cycle is the average or mean value of the varying power. To obtain the average power using Equation 1.3, the instantaneous values of the current over one complete cycle must be squared, and the average or mean of these values calculated. The effective value of the current is then the square root of this mean value. (Note that the value of the resistance is a constant throughout all these calculations.) A similar set of calculations can also be done for the ac voltage.

The effective value of the ac current and voltage is also known as the *root-mean-square* (rms) *value*, which describes the operation to obtain the value, that is, taking the square root of the mean value of the current or voltage squared. These calculations result in the following relationships:

$$E = \frac{E_{max}}{\sqrt{2}} = 0.7071E_{max} \tag{1.5}$$

$$I = \frac{I_{max}}{\sqrt{2}} = 0.7071I_{max} \tag{1.6}$$

where E and I = rms values
E_{max} and I_{max} = maximum or peak values

Note that no subscript is applied to the rms value as it is understood that, unless otherwise indicated, any reference to an ac voltage or current is to the rms value. The meters installed in ac systems record the rms values of the voltage and current.

EXAMPLE 1.12

Calculate the maximum or peak voltage of a 120 V ac system (the 120 V being the rms value).

Solution

Rearranging Equation 1.5,

$$E_{max} = \sqrt{2} \times 120 = 170 \text{ V}$$

These voltages are shown graphically in Figure 1.7.

With the adoption of the rms values for ac circuits, the relationships developed for dc circuits are still valid. For example, a 120 volt, 100 watt light bulb has the same light output, whether it is connected to a 120 volt ac circuit or a 120 volt dc circuit. All the calculations shown in Examples 1.1 to 1.11 are still valid for ac circuits, providing that the circuits consist only of resistive elements. The effects of inductance and capacitance are discussed in Section 1.4.

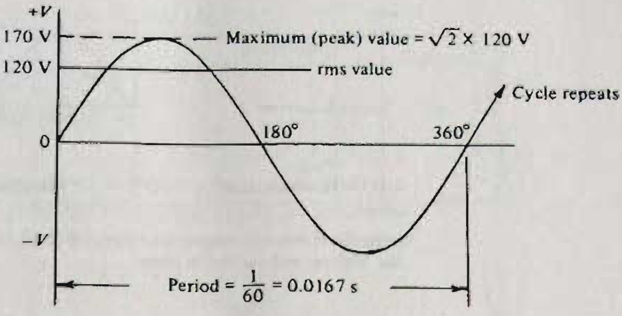


FIGURE 1.7

Voltage waveform for 120 V, 60 Hz system

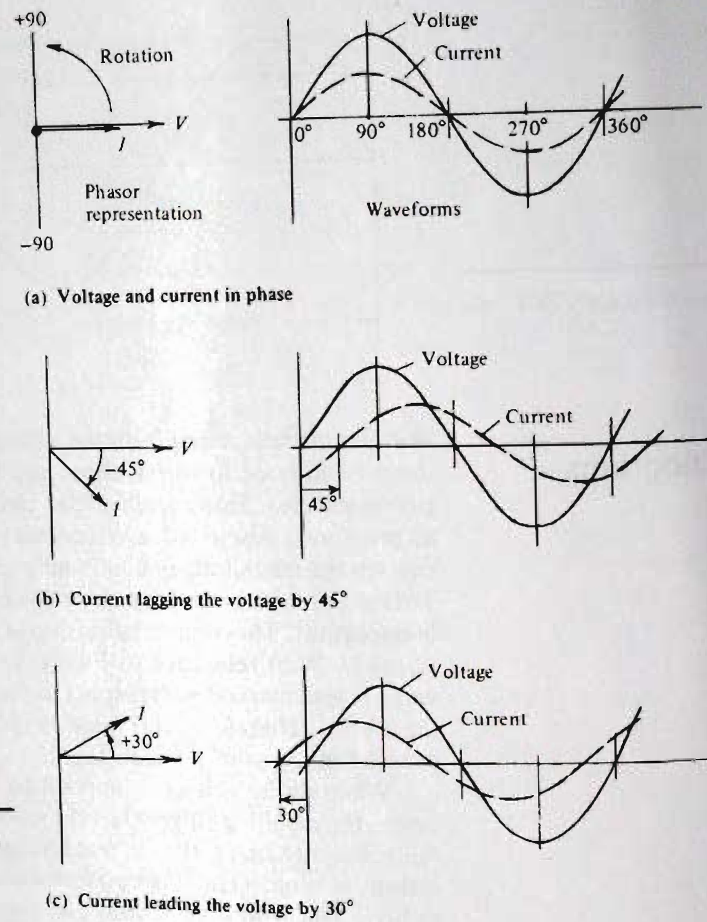
1.3.3 Phasor Diagrams

With dc circuits, since both the voltage and the current are steady, there is no need to worry about any time relationship between the two quantities. However, with ac circuits, the voltage and current, as previously discussed, are time-varying quantities, that is, a quantity whose magnitude is continually changing with respect to time. Therefore, the time relationship between the voltage and the current is important. This time relationship is referred to as the *phase relationship.* With reference to Figure 1.6, the time scale for the sine wave is also marked with respect to the degrees of revolution around the circle. Therefore, this time or phase relationship can be expressed in terms of a *phase angle*.

When an ac voltage is applied to a circuit that has only resistance, the resulting current has the same time relationship; that is, as the voltage changes, the current changes proportionally at the same instant of time. Thus, the two quantities vary together and are said to be *in phase* with each other, as shown in Figure 1.8(a).

Not all circuits, however, are purely resistive in nature. Many circuits have characteristics (to be discussed in Section 1.4) that result in the voltage and current being out of phase with each other; that is, they do not both pass through the zero axis and reach their maximum values at the same instant of time. Figure 1.8(b) shows the case where the current passes through the zero axis after the voltage does and reaches its maximum value after the voltage does. In other words, the current is lagging in time with respect to the voltage and is said to be a *lagging current*. Since each point on the current sine wave is 45° behind the equivalent point on the voltage sine wave, the phase angle is −45°.

Figure 1.8(c) shows the case where the current passes through the zero axis before the voltage and reaches its maximum value before the voltage. In other words, the current is leading in time with respect to the voltage and is said to be a *leading current*. Since each point on the current sine wave is 30° ahead of the equivalent point on the voltage sine wave, the phase angle is +30°. Note that a lagging



(a) Voltage and current in phase

(b) Current lagging the voltage by 45°

(c) Current leading the voltage by 30°

FIGURE 1.8

Phase relationships and phasor diagrams for ac voltages and currents

phase angle is regarded as negative and a leading phase angle as positive.

Up to this point, we have represented ac quantities by means of sine waves. However, a much simpler method is to use the phasor diagram such as shown to the left of each set of sine waves in Figure 1.8. Each quantity is represented by a straight line drawn from a common point, with its length scaled for the magnitude and its direction indicating the phase relationship. It is normal to show the voltage phasor horizontally from left to right as the reference. Where it is necessary to designate the phase relationship of a voltage or current, the polar notation $V\underline{/\theta}$ or $I\underline{/\theta}$ is used. V or I represents the scalor magnitude of the quantity (usually the rms value), and θ represents the phase angle of the quantity with respect to a reference. For example, a 10 ampere current that lags the voltage by 30° is shown as 10 A $\underline{/-30^\circ}$.

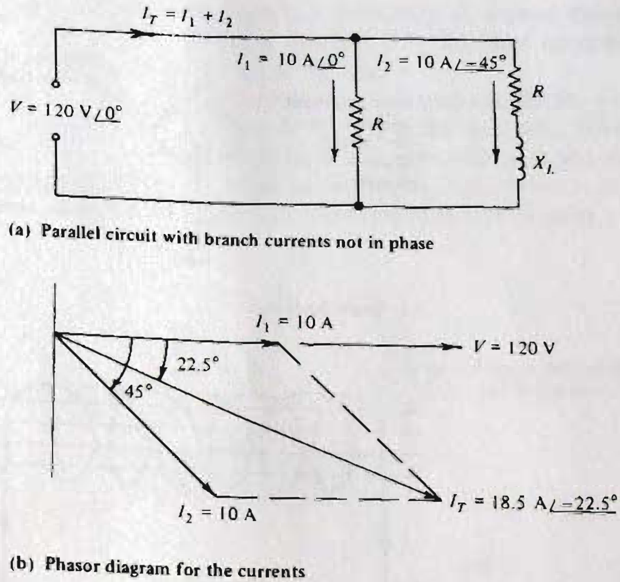


FIGURE 1.9

Addition of two currents that are not in phase

With a parallel circuit, it is possible to have currents in the branches that are not in phase with each other, such as shown in Figure 1.9(a). The method of adding these branch currents to obtain the total current is shown graphically in Figure 1.9(b). Calculations using phasor quantities can also be done using phasor arithmetic. The reader is referred to the books on circuits listed in the bibliography for the methods employed in phasor arithmetic.

1.4 ALTERNATING CURRENT CIRCUITS

When a current flows through a resistor, regardless of whether the current is steady or continually changing in magnitude, all the electrical energy is converted to heat and is therefore lost to the circuit. Such is not the case with ac circuits, which have components with inductance or capacitance. Energy is stored in these components for part of the cycle and then returned to the circuit. As a result, the current is no longer in phase with the voltage, and circuit calculations must be based on the impedance and power factor of the circuit.

1.4.1 Effect of Inductance

When a current flows in a conductor, it creates a magnetic field that completely surrounds the conductor, as shown in Figure 1.10(a). The effect of this field is referred to as *electromagnetism*. The direction of the field, which is at right angles to the direction of the

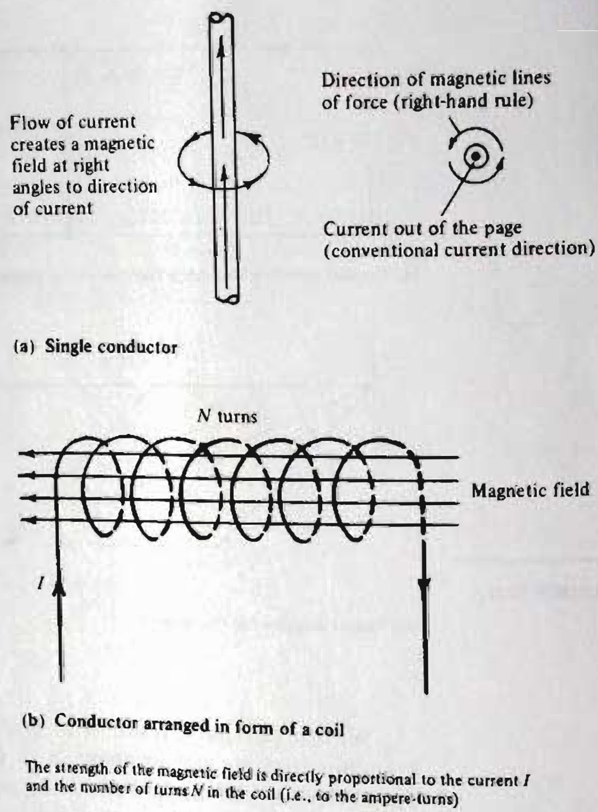


FIGURE 1.10

Magnetic field around a current-carrying conductor

current, is determined by the right-hand rule; that is, with the thumb of the right hand pointing in the conventional direction of the current, the fingers then point in the direction of the magnetic lines of force. When the conductor is wound in the form of a coil, as shown in Figure 1.10(b), the magnetic field is concentrated into a smaller area and becomes much stronger; its strength is a function of the magnitude of the current and the number of turns in the coil (the ampere-turns). With a fixed number of turns, the field strength is proportional to the current.

With direct current, once the current has reached its steady state, the magnetic field remains constant and it has no further effect on the current. In contrast, alternating current is continuously changing, and therefore the magnetic field that it creates is also continuously changing. This changing field induces a voltage that opposes the change of current, a process referred to as *self-inductance* or, for short, *inductance*.

Faraday's law of electromagnetic induction states that the magnitude of an induced emf is proportional to the rate of change of the magnetic flux linkage. One example of this relationship is the electric generator in which a conductor is moved through a magnetic field, as discussed in Section 2.1. Another example is the transformer, as discussed in Section 1.7.

With self-inductance, the induced emf in the conductor is proportional to the rate of change of the magnetic field, which in turn means that the induced emf is proportional to the rate of change of current in the conductor. Figure 1.11(a) shows a theoretical circuit that has only inductance and no resistance. Figure 1.11(b) shows the

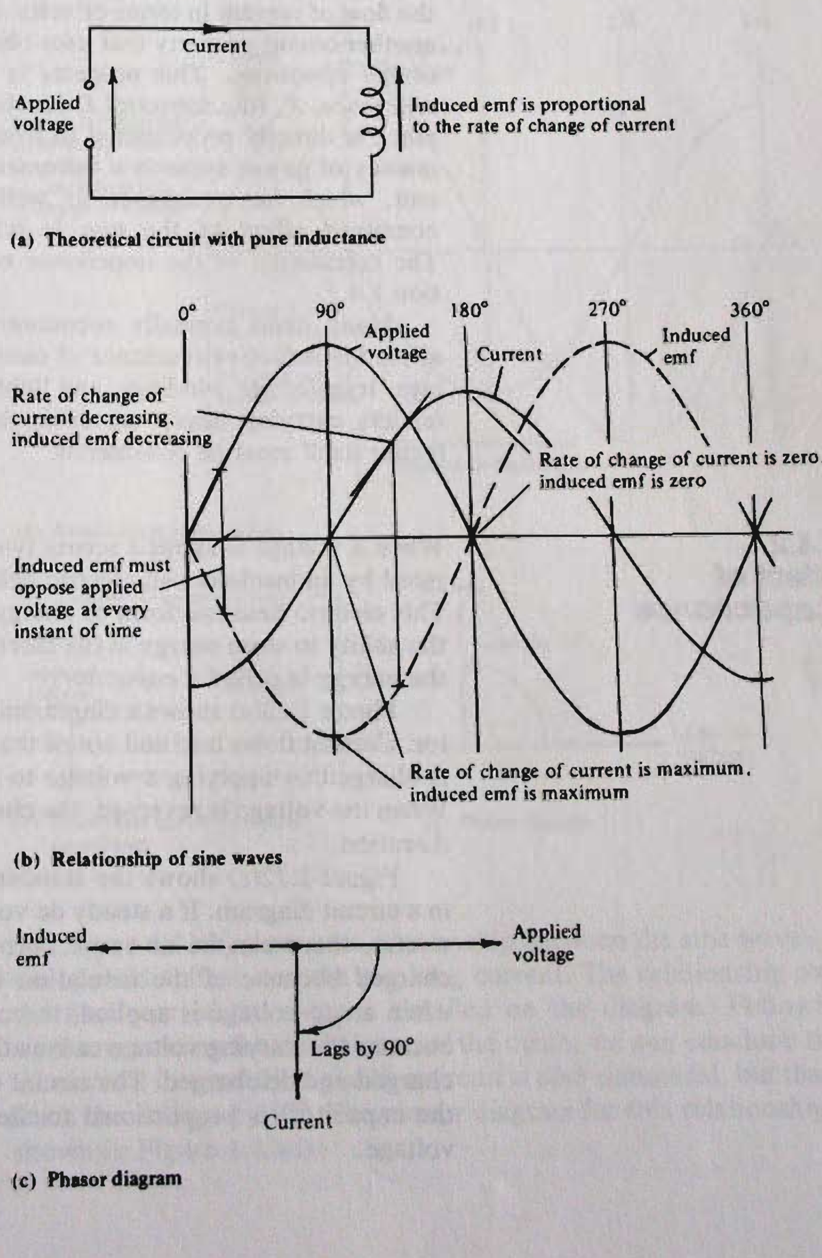


FIGURE 1.11

Phase relationship between voltage and current in a purely inductive circuit relationship between the sine waves of the applied voltage, the induced emf, and the current. Note that the induced emf must oppose the applied voltage at every instant of time. The relationships over part of the cycle are detailed on the diagram. Following similar reasoning over the balance of the cycle, we can conclude that the current in a purely inductive circuit is also sinusoidal, but that it lags the applied voltage by 90°. The phasor diagram for this relationship is shown in Figure 1.11(c).

Rather than consider the opposition of the induced voltage to the flow of current in terms of volts, it can instead be considered as another circuit property that uses ohms as the unit of measurement of the opposition. This property is then referred to as *inductive reactance*, X_L (the subscript L denotes inductance). Inductive reactance is directly proportional to frequency, but with the fixed frequency of power systems it becomes a constant. In a practical circuit, which has resistance as well as inductive reactance, the combined effect of the two is referred to as the *impedance*. The calculation of the impedance of a circuit is covered in Section 1.4.3.

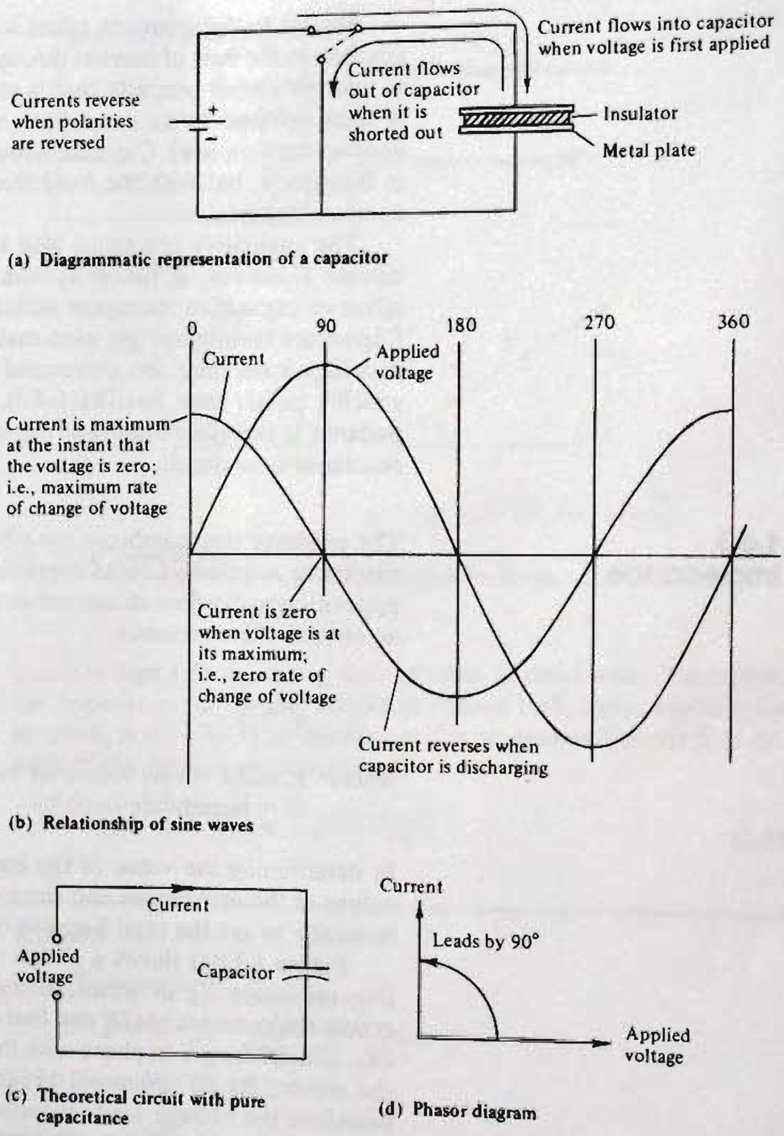
Many items normally encountered in electric power systems affect the inductive reactance of circuits, for example, motor windings, transformer windings, and lighting ballast windings. On large feeders carrying heavy currents, the inductive reactance of the feeder itself must be considered.

1.4.2 Effect of Capacitance

When a voltage is applied across two adjacent parallel plates separated by an insulator, an electric field is set up between the plates. This electric field is a form of energy. *Capacitance* is a measure of the ability to store energy in the electric field. The device that stores the energy is called a *capacitor*.

Figure 1.12(a) shows a diagrammatic representation of a capacitor. Current flows into and out of the capacitor as first the capacitor is charged by applying a voltage to it and then as it is discharged. When the voltage is reversed, the charging current is in the opposite direction.

Figure 1.12(c) shows the standard symbol used for capacitance in a circuit diagram. If a steady dc voltage is applied to the capacitor circuit, there can be no more current flow once the capacitor is charged because of the insulation between the plates. However, when an ac voltage is applied, the capacitor acts like a conductor, because the varying voltage causes the capacitor to be continuously charged and discharged. The circuit current (the charging current of the capacitor) is proportional to the rate of change of the applied voltage.



(a) Diagrammatic representation of a capacitor

(b) Relationship of sine waves

(c) Theoretical circuit with pure capacitance

(d) Phasor diagram

FIGURE 1.12

Phase relationship between voltage and current in a purely capacitive circuit

Figure 1.12(b) shows the relationship between the sine waves of the applied voltage and the resulting current. The relationship over the first part of the cycle is detailed on the diagram. Following similar reasoning for the balance of the cycle, we can conclude that the current in a purely capacitive circuit is also sinusoidal, but that it leads the voltage by 90°. The phasor diagram for this relationship is shown in Figure 1.12(d).

Similar to the approach taken with inductive reactance, the opposition to the flow of current through a capacitor can be considered as another circuit property that is measured in ohms. This property is then referred to as *capacitive reactance*, X_C (the subscript C denotes capacitance). Capacitive reactance is inversely proportional to frequency, but with the fixed frequency of power systems it becomes a constant.

The capacitive reactance also affects the total impedance of a circuit. However, in power systems encountered in buildings, the effect of capacitive reactance within the system itself is negligible. Capacitors themselves are used mainly for power factor correction, in which case they are connected in parallel with the system at specific points (see Section 1.4.4). The following section on impedance is therefore limited to the effect of resistance and inductive reactance in a circuit.

1.4.3 Impedance

The property that combines the effect of the circuit resistance and reactance is referred to as *impedance*, Z. Impedance is the total opposition to the flow of current in an ac circuit. The Ohm's law for ac circuits then becomes:

$$Z = \frac{E}{I} \tag{1.7}$$

where E and I = rms values of voltage and current
Z = impedance in ohms

In determining the value of the impedance of a circuit, the ohmic values of the resistances and reactances cannot just be added arithmetically to get the total because of their phase relationships.

Figure 1.13(a) shows a circuit that has resistance R and inductive reactance X_L in series. From Ohm's law, the voltage drop across the resistance is IR and that across the inductive reactance is IX_L. The IR drop is in phase with the current, but the IX_L drop leads the current by 90° (Figure 1.11; the current lags the voltage, and therefore the voltage leads the current). Figure 1.13(b) shows the phase relationship of these voltage drops and how they must add together to equal the applied voltage. Since the current is the common factor, the resistance R, the inductive reactance X_L, and the impedance can be represented by a right angle triangle, as shown in Figure 1.13(c). This diagram is referred to as the *impedance triangle*.

To facilitate the designation of the components of the impedance triangle, the j operator is introduced. The j operator is used to indicate that an electrical quantity is rotated through 90°, with a positive sign (+) indicating that rotation is counterclockwise and the

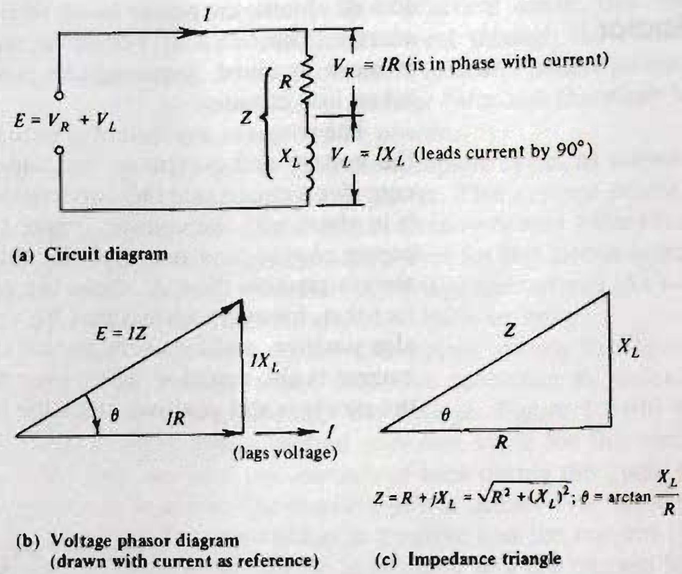


FIGURE 1.13

Impedance triangle for a circuit with resistance and inductance

negative sign (−) indicating that rotation is clockwise. Therefore, the impedance for the *RL* circuit of Figure 1.13, using rectangular notation, is $R + jX_L$. The impedance Z is represented by the hypotenuse of the right angle triangle and:

$$Z = R + jX_L = \sqrt{R^2 + (X_L)^2} \qquad (1.8)$$

■ EXAMPLE 1.13

Refer to Figure 1.13. Assume that $R = 8\ \Omega$, $X_L = 6\ \Omega$, and $E = 120$ V. Calculate the magnitude of the current I and its phase relationship with the voltage.

Solution

From Equation 1.8,

$$Z = 8 + j6 = \sqrt{8^2 + 6^2} = 10\ \Omega$$

From Equation 1.7,

$$I = \frac{120}{10} = 12\text{ A}$$

From the impedance triangle,

$$\theta = \arctan \frac{X_L}{R} = \arctan \frac{6}{8} = 36.9°$$

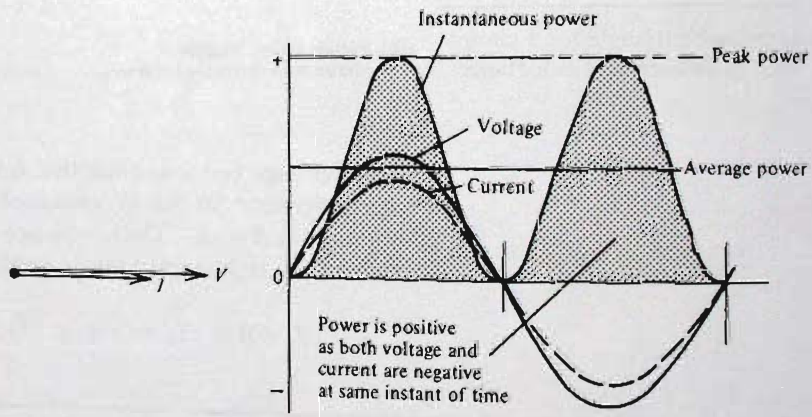
Using polar notation,

$$I = 12\text{ A} \angle{-36.9°} \quad \text{(current lags the voltage)}$$

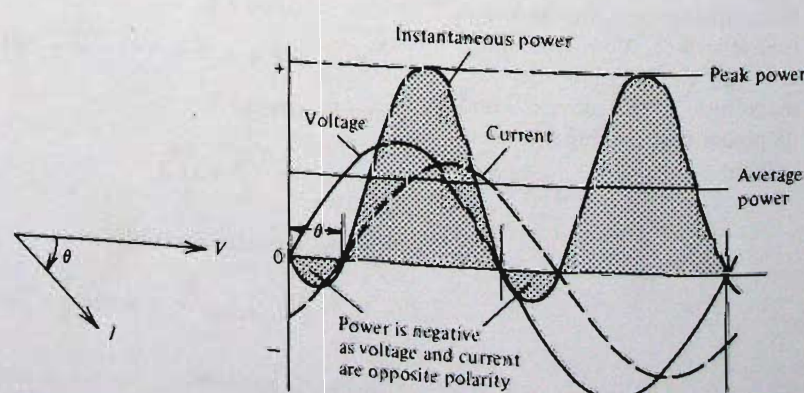
1.4.4 Power Factor

In a dc circuit, the power involved is the product of the voltage and current (Equation 1.2). For ac circuits, the calculation of the power is more involved, requiring the power factor of the circuit to be taken into account.

The power at any instant of time in an ac circuit is the product of the voltage and current at that same instant of time. First, let us consider a circuit that has only resistance, and therefore the current is in phase with the voltage. Figure 1.14(a) shows the instantaneous power plotted over one cycle for this case. Note that the power is always positive (that is, above the zero line). This results from the fact that, for every instant that the voltage is positive, the current is also positive, and for every instant that the voltage is negative, the current is also negative. Thus, even for the second half of the cycle, the power is still positive, since the product of two negative quanti-



(a) Current in phase with the voltage



(b) Current lagging the voltage

FIGURE 1.14

Plots of instantaneous power over one cycle ties is a positive quantity. In a practical sense, this means that, regardless of the direction of current through the resistance, the electrical energy is being converted to heat. Positive power, which is electric power converted to another form and therefore lost to the circuit, is referred to as *active* power.

The average power over the complete cycle, as shown in Figure 1.14(a), is one-half of the peak power. This average power was used in Section 1.3.2 to establish the effective or rms values for the voltage and current. Therefore, the power for this circuit is equal to the product of the rms values of the voltage and current. As we will see, the power factor for this circuit is 100% or unity.

Next, we will consider the circuit shown in Figure 1.13(a), which has resistance and inductive reactance in series, with the result that the current lags the voltage. Figure 1.14(b) shows the instantaneous power plotted over one cycle for this circuit. Note that there are now two periods of time during the cycle where the power is negative. The negative power occurs over those periods of time, first when the voltage is positive and the current is negative and next when the voltage is negative and the current is positive. Negative power represents power that is being returned to the circuit as a result of the collapse of the magnetic field associated with the inductance (energy is stored during the positive portions of the cycle). Negative power is referred to as *reactive* power. Because of the reactive power, the average power over the cycle is less than that shown in part (a) for the same values of voltage and current. Therefore, the product of the rms voltage times the rms current no longer represents the positive or active power in the circuit. The product of the voltage and current is instead called the *apparent* power, since, if the voltage and current only are considered, it appears that the circuit uses this much power. The unit for apparent power is the volt-ampere (VA) or the kilovolt-ampere (kVA), which is equal to 1000 volt-amperes.

Refer to Figure 1.15(a), which shows the phasor relationship between the voltage and current as per Figure 1.14(b). The lagging current can be considered as being made up of two components, a component that is in phase with the voltage and a component that lags the voltage by 90°. The in-phase component is termed the active component since it is associated with the active (positive) power of the circuit. The 90° component is termed the reactive component since it is associated with the reactive (negative) power of the circuit.

Figure 1.15(b) shows the resulting power triangle obtained by multiplying each current component by the voltage. The horizontal side represents the active power in watts, the vertical side represents the reactive power in vars (volt-amperes reactive), and the

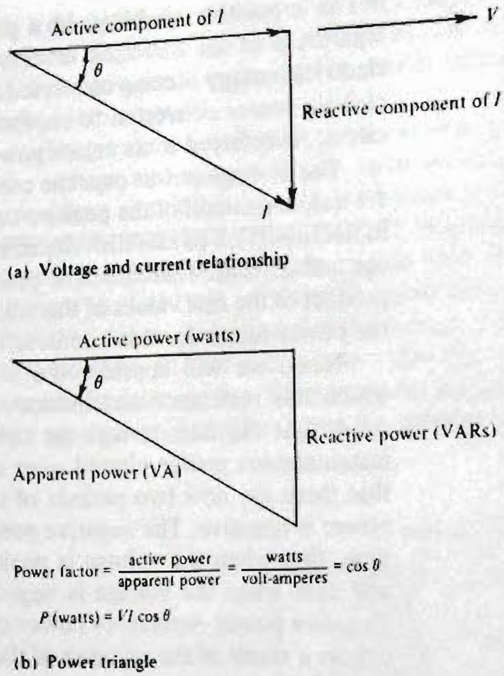


FIGURE 1.15

Power triangle for circuit with lagging power factor

hypotenuse represents the apparent power in volt-amperes. The term *power factor* is used to express the ratio between the active power and the apparent power. Therefore:

$$\text{Power factor} = \frac{\text{active power}}{\text{apparent power}} = \frac{\text{W}}{\text{VA}}$$

From the power triangle, we can see that the power factor is also equal to the cosine of the angle θ, which is also the phase angle between the current and voltage. This then leads to the power relationship for ac circuits:

$$P\ (\text{watts}) = VI \cos \theta \tag{1.9}$$

where $\cos \theta$ is the power factor. Power factor can be expressed as a decimal (for example, 0.80) or as a percentage (80%). Since the current in a circuit with inductive reactance lags the voltage, the power factor is a lagging power factor. For the case where the current leads the voltage, the power factor is a leading power factor. A power factor of 1.0 or 100% is referred to as *unity* power factor. Meters designed to read power in ac systems measure the active power and are therefore wattmeters or kilowattmeters.

■ EXAMPLE 1.14

For a 120 V, two-wire ac circuit, the wattmeter reads 1920 W and the ammeter reads 20 A. Calculate the power factor.

Solution

$$\text{Apparent power} = VI = 120 \times 20 = 2400 \text{ VA}$$

$$\text{Power factor} = \frac{1920}{2400} = 0.80 \quad (80\%)$$

Note that the meter readings in themselves do not indicate whether the power factor is leading or lagging. However, if any item in the circuit is inductive in nature (for example, a motor), then the power factor is lagging.

■ EXAMPLE 1.15

The load on a 240 V, two-wire ac circuit draws 15 A at a lagging power factor of 90%. Calculate the power.

Solution

From Equation 1.9,

$$P = 240 \times 15 \times 0.9 = 3240 \text{ W}$$

Note that the decimal form for the power factor is used.

■ EXAMPLE 1.16

The load on a 240 V, two-wire ac circuit is rated at 5.0 kW, 80% power factor. Calculate the current.

Solution

Rearranging Equation 1.9,

$$I = \frac{P}{V \cos \theta} = \frac{5 \times 1000}{240 \times 0.8} = 26 \text{ A}$$

When designing the circuits and feeders for loads which are rated in watts or kilowatts, it is imperative that the power factor of the load be known. Otherwise, the conductor size chosen may be too small for the actual current that will flow.

As previously mentioned, the reactive power of a system is the power that is alternately being stored in and returned from the magnetic fields associated with the inductive reactance. This power is surging back and forth in the system between the source and the load. The electric utility's meter that records the energy consumed on a customer's premises measures this energy on the basis of active power. However, the reactive power, as we have seen, requires that more current flow in the system than that required for the active power alone. Therefore, the utility assesses a penalty to customers whose systems operate at too low a power factor (for example, less than 90 percent).

For a system with an unsatisfactory power factor, power factor correction should be considered. Refer to Figure 1.12, which shows that a capacitor draws a current that leads the voltage by 90°. Capacitors can therefore be used to improve the power factor since the current they draw is 180° out of phase with the 90° lagging reactive current component of the system [Figure 1.15(a)]. By reducing the reactive component of the power, the load current drawn by the system is reduced. Capacitors can be individually connected to the terminals of equipment that has a poor power factor, such as induction motors (see Section 2.5.1 and Figure 2.15) and ballasts for lighting (see Section 4.2), or one central capacitor bank can be installed at the main service entrance. Synchronous motors can also be used for power factor correction. Section 2.4 and Figure 2.11(c) show that a synchronous motor, when the field is overexcited, operates with a leading power factor.

1.5 SINGLE-PHASE, THREE-WIRE SYSTEMS

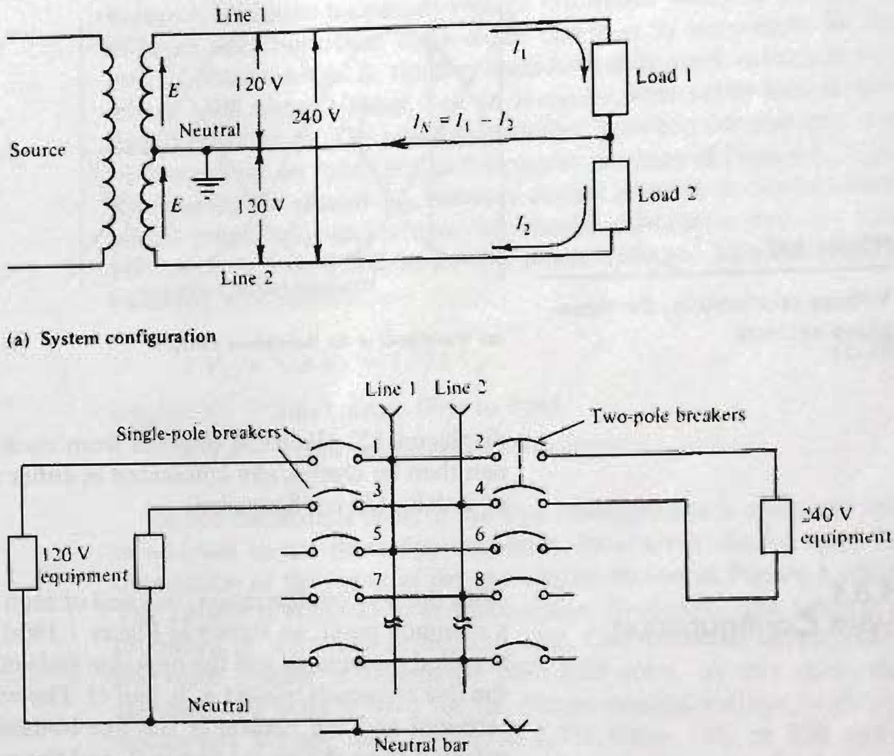
The 120/240 volt, single-phase, three-wire system is the common arrangement used to supply power to individual residences and small commercial buildings. The three-wire configuration is shown in Figure 1.16(a). The diagram indicates that a single-phase transformer with two 120 volt secondary windings is the source. Note that the center connection between the two windings is grounded and that the conductor connected to that point is called the *neutral* since it operates at ground potential. The grounding of systems is fully discussed in Chapter 10.

The instantaneous direction of the line currents I_1 and I_2 are such that the neutral conductor only has to carry the difference between currents I_1 and I_2. When the two line currents are equal, the neutral current I_N is zero. Therefore, one advantage of this system is that the total of loads 1 and 2 can be supplied using only three wires. The second advantage is that two voltage levels are available.

The arrangement of circuits for a panelboard supplied from a single-phase, three-wire system is shown in Figure 1.16(b). For 120 volt equipment, the circuit is connected to one of the lines and the neutral. Two circuits connected to opposite lines can be connected to the same neutral conductor. For 240 volt equipment, the circuit is connected to the two lines through a two-pole breaker and there is no connection to the neutral. Panelboards and branch circuits are discussed in detail in Chapter 12.

1.6 THREE-PHASE SYSTEMS

Three-phase systems are universally used today to generate and transmit large amounts of electrical energy because of their many inherent technical and economic advantages. Initially, the easiest



(a) System configuration

(b) Typical circuit arrangement in a panel

FIGURE 1.16

Single-phase, three-wire system

way to approach the concept of a three-phase system is to assume that three separate sources of emf are used, with each source generating a sine wave voltage that is identical in magnitude but, when compared on a time basis, is 120° out of phase with respect to the others. When combined into one system, each of these sources is then referred to as a phase: phase A, phase B, and phase C.

The sine waves for the three phase voltages are shown in Figure 1.17(a). Phase A is taken as the reference voltage, so it is shown passing through the zero voltage axis at 0° and reaching its maximum positive value at 90°. Each equivalent value of phase B then follows behind in intervals of time equivalent to 120° (one-third of a cycle). Similarly, each equivalent value of phase C follows behind phase A in intervals of time equivalent to 240° (two-thirds of a cycle). The resulting phasor diagram is shown in Figure 1.17(b).

In practice, three-phase power is produced using one generator. The phase emfs are generated by three separate sets of windings, which are mounted around the generator so that they are physically

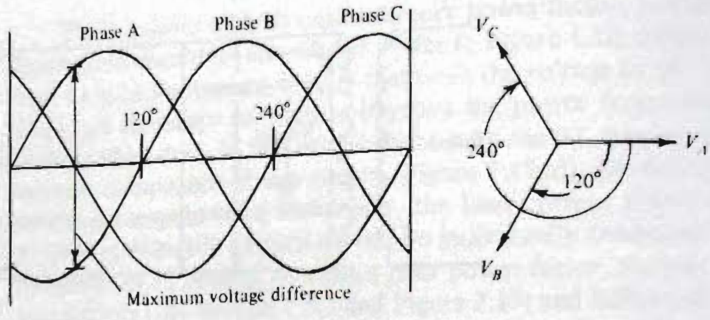


FIGURE 1.17

Voltage relationships for three-phase systems

(a) Waveforms of the three-phase voltages (b) Phasor diagram

displaced 120 electrical degrees from each other. These windings can then be electrically connected in either a wye (Y) configuration or a delta (Δ) configuration.

1.6.1 Wye Configuration

With the wye configuration, one end of each winding is connected to a common point, as shown in Figure 1.18(a). The common point (n) is called the *neutral* and the opposite ends of the windings are called the *line terminals* (points a, b, and c). The voltage between each line terminal and the neutral is the line-to-neutral voltage (commonly referred to as the *phase voltage*), and the voltage between two line terminals is the line-to-line voltage (commonly referred to as the *line voltage*).

The line voltage is not the arithmetical sum of two phase voltages because of the 120° phase relationship. If we refer back to

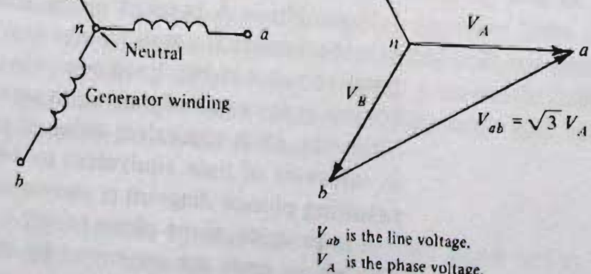


FIGURE 1.18

Wye-connected, three-phase generator

(a) Wye configuration (b) Phasor diagram of voltages

Figure 1.17(a), the maximum voltage difference between two phase voltages does not occur when either one is at its maximum. In the case of phases A and B, the first maximum difference occurs at 60°, where each phase voltage has an instantaneous value that is less than its maximum. The exact relationship between the voltages can be determined by reference to the phasor diagram of Figure 1.18(b). By drawing the phasor V_{ab} between points b and a, it can be determined graphically and proved by phasor arithmetic that the line voltage is $\sqrt{3}$ or 1.732 times the phase voltage. Therefore, in a balanced wye system:

$$V_L = \sqrt{3}\ V_P = 1.732\ V_p \tag{1.10}$$

where V_L = line voltage (line to line)
V_P = phase voltage (line to neutral)

Since the neutral point of the wye configuration is also available in addition to the three line terminals, four wires can be used for connection to the loads in the system, as shown in Figure 1.19(a). The system is referred to as three-phase, four-wire. The neutral is grounded as described in Section 10.2. One common three-phase, four-wire system is designated 208Y/120 volts. In this case, the standard 120 volts is used for the line-to-neutral voltage, with the line-to-line voltage then becoming 1.732 times 120, or 208 volts. Another common system is designated 480Y/277 volts. In this case the standard 480 volts is used for the line-to-line voltage, with the line-to-neutral voltage then becoming 480 divided by 1.732, or 277 volts. It is a significant advantage for each system to have the two voltage levels available. For example, the 208Y/120 volt system provides 120 volts for single-phase loads, such as lighting and small appliances, and 208 volts for single-phase loads, such as electric heaters, and three-phase loads, such as motors.

Figure 1.19(a) shows a wye-connected load supplied from a three-phase, four-wire source. In a balanced system (that is, with identical loads connected to each phase), since the phase voltages are 120° out of phase with each other, the phase currents I_A, I_B, and I_C are also 120° out of phase with each other. The phase current through each load is also the line current that flows through the connecting wiring. The waveforms for the three phase currents are shown in Figure 1.19(b), and the phasor diagram is shown in Figure 1.19(c). The neutral current I_N is the sum of the three phase (line) currents. If the instantaneous values of each phase currents are measured, we can establish the fact that these currents always sum to zero. For example, the instantaneous relative values of the currents at 90° are $I_A = +1.0$, $I_B = -0.5$, and $I_C = -0.5$, which adds up

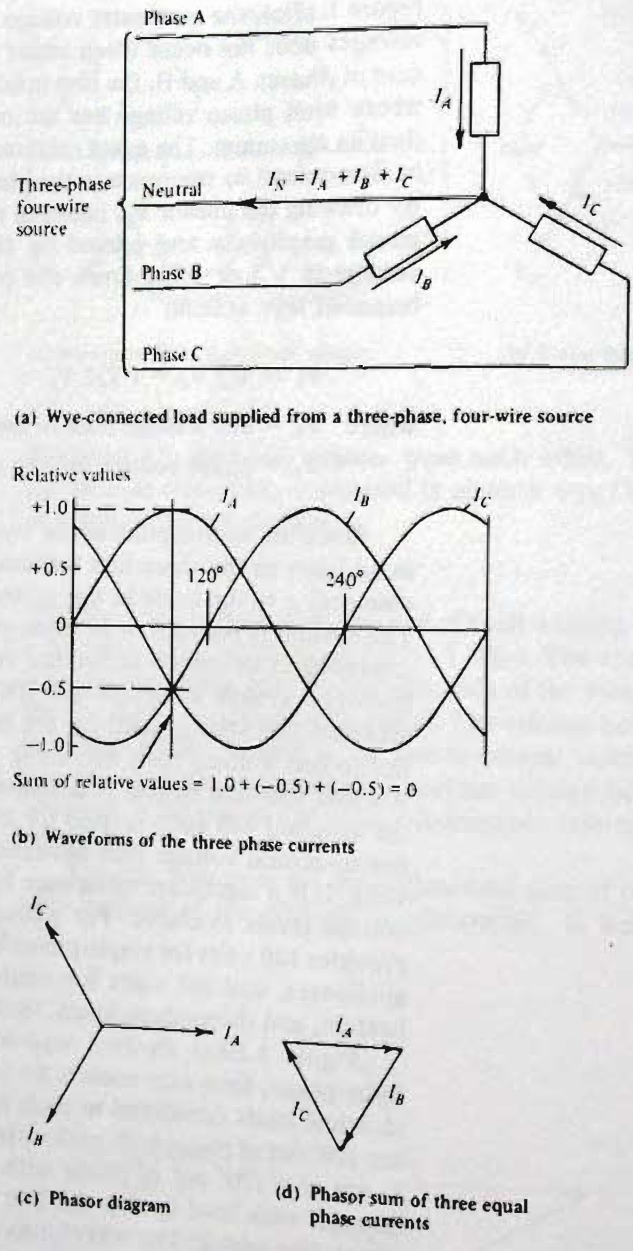


FIGURE 1.19

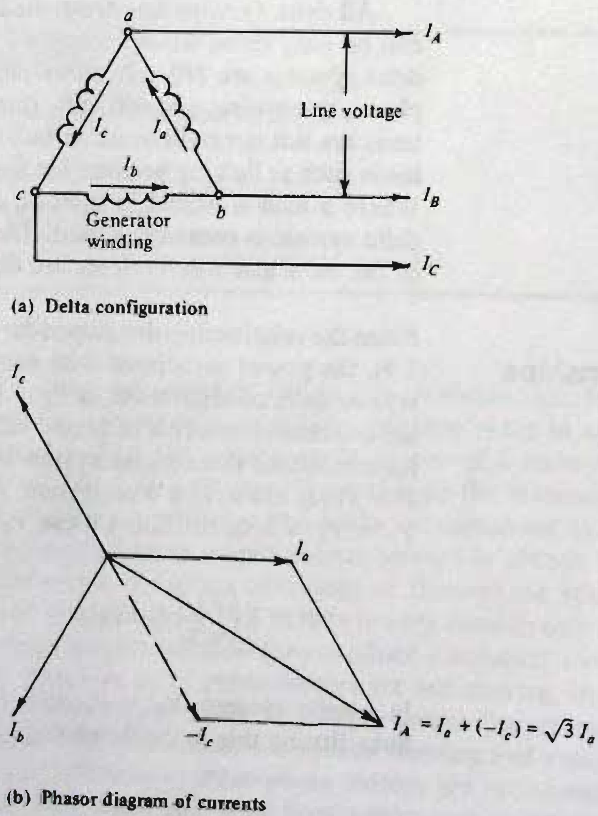
Current relationships for a three-phase, four-wire system

to zero. This can also be verified by adding the phasors for each current end to end, as shown in Figure 1.19(d). The resulting triangle closes, indicating that the three currents sum to zero and therefore the neutral current is zero.

Even if the the load on one phase is disconnected (for example, the phase C load), the neutral current, which is the sum of the other two phase currents (I_A and I_B), is only the same magnitude as each of the phase currents themselves. Therefore, the neutral conductor of the system can be the same size as the phase (line) conductors. Another significant advantage of the three-phase, four-wire system is that three single-phase loads can be supplied using only four wires as compared to the six wires required if three separate two-wire circuits are used. This can result in substantial savings in the cost of the wiring throughout a building. The connection of single-phase branch circuit loads to three-phase, four-wire panelboards is discussed in detail in Section 12.5 and shown in Figure 12.5.

1.6.2 Delta Configuration

With the delta configuration, one end of each phase winding is connected to the end of the adjacent phase winding, as shown in Figure 1.20(a). This configuration is shown electrically in the form of a triangle designated by the Greek letter delta (Δ). The line connec-



(b) Phasor diagram of currents

I_A is the line current.
I_a is the phase current.

FIGURE 1.20

Delta-connected, three-phase generator

tions are then made at the common connection between the phases. The line voltage is the same as the voltage across each winding (that is, the phase voltage). However, the line currents are not the same as the winding or phase currents. For example, as shown in Figure 1.20(b), the line current I_A is the vector sum of the phase current I_a (since it flows toward point *a*) plus the negative of phase current I_c (since it flows away from point *a*). It can be determined graphically and proved by phasor arithmetic that the line current is $\sqrt{3}$, or 1.732, times the phase current. Therefore, in a balanced delta system:

$$I_L = \sqrt{3} I_P = 1.732 I_P \qquad \textbf{(1.11)}$$

where I_L = line current
I_P = phase current

Note that the same relationship holds with regard to a delta-connected load.

All delta systems are designated as being three-wire since there can be only three wires connected to this configuration. Common delta systems are 240 volt, three-phase, three-wire; 480 volt, three-phase, three-wire; and 600 volt, three-phase, three-wire. Delta systems are not normally used in buildings for supplying single-phase loads such as lighting because the system cannot be easily grounded. Where a load is primarily motors, such as in industrial plants, the delta system is commonly used. The advantages and disadvantages of the delta and wye systems are discussed in detail in Chapter 10.

1.6.3 Power Relationships

From the relationship developed for a single-phase circuit (Equation 1.9), the power associated with each individual phase, whether the wye or delta configuration, is $P_P = V_P I_P \cos\theta$, where all parameters are expressed in terms of phase values. Therefore, the total power for a balanced three-phase system is three times the phase power or $P = 3V_P I_p \cos\theta$. In a wye system, $I_P = I_L$, and from Equation 1.10, $V_P = V_L/\sqrt{3}$. Substituting these values in the foregoing gives:

$$P = 3\left(\frac{V_L}{\sqrt{3}}\right) I_L \cos\theta = \sqrt{3}\, V_L I_L \cos\theta$$

In a delta system, $V_P = V_L$ and, from Equation 1.11, $I_P = I_L/\sqrt{3}$. Substituting this in the foregoing gives:

$$P = 3V_L\left(\frac{I_L}{\sqrt{3}}\right) \cos\theta = \sqrt{3}\, V_L I_L \cos\theta$$

Therefore, the same expression can be used, regardless of whether the system is wye or delta:

$$P = \sqrt{3}\, V_L I_L \cos\theta = 1.732 V_L I_L \cos\theta \qquad (1.12)$$

where P = total three-phase power
V_L = line-to-line voltage
I_L = line current
$\cos\theta$ = power factor of the system

EXAMPLE 1.17

A three-phase load with an 80% power factor is supplied by a 208Y/120 system. The line current is 40 A. Calculate the power.

Solution

From Equation 1.12

$$P = 1.732 \times 208 \times 40 \times 0.80 = 11{,}528\ \text{W}$$
$$= 11.528\ \text{kW}$$

EXAMPLE 1.18

A 50 kW load with a 90% power factor is supplied from a 480 V delta system. Calculate the line current.

Solution

Rearranging Equation 1.12,

$$I_L = \frac{P}{1.732 V_L \cos\theta}$$
$$= \frac{50 \times 1000}{1.732 \times 480 \times 0.9} = 66.8\ \text{A}$$

If we refer back to Figure 1.14, it shows that, for a single-phase circuit, the power is pulsating, peaking twice in each cycle. If we were to plot the instantaneous power of a three-phase system, it would be a straight line. Even though the instantaneous power of each phase is pulsating, the peaks are spread out over the cycle, and the sum of these instantaneous powers is always the same value. Therefore, a further advantage of three-phase systems is that the power is constant. This results in very smooth operation with three-phase motors because they produce a constant torque at the shaft. In addition, three-phase motors are self-starting. In contrast, single-phase motors produce a pulsating torque that causes vibrations and noise, and they require a special winding and centrifugal switch to start. Therefore, three-phase motors are recommended for all but the very small fractional horsepower motors. Motors are discussed in detail in Chapter 2.

1.6.4 Third Harmonics

In the previous discussions on ac circuits and systems, it was assumed that the currents that flowed were always sinusoidal. However, that is not always the case. Nonsinusoidal currents result when the iron cores of transformers, motors, and the like, saturate during peak periods of the cycle. This periodic saturation causes the inductance of the associated winding to momentarily decrease, thus permitting a sudden increase in the instantaneous current. A typical waveform of the resulting current is shown in Figure 1.21(a). This distorted waveshape of the current can be reduced to a fundamental sine wave component plus a number of sine wave components at higher frequencies, which are referred to as *harmonics*. The most prominent is usually the third harmonic, which is a sine wave component that has a frequency three times the system frequency (that is, 180 hertz for the 60 hertz system). The fundamental and third-harmonic components are also shown in Figure 1.21(a).

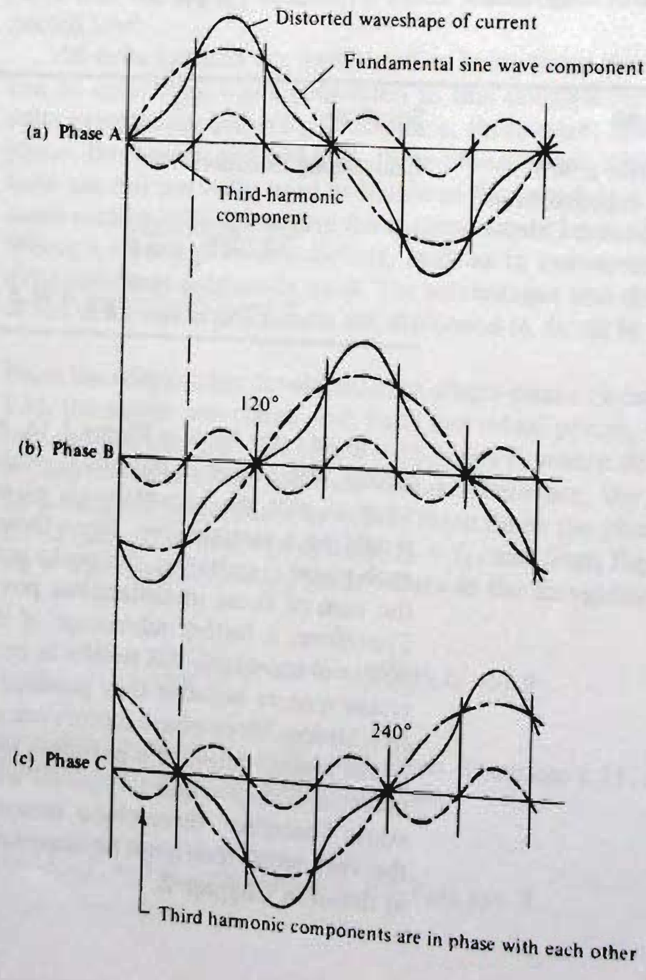


FIGURE 1.21

Third harmonic components on three-phase system

With three-phase, four-wire systems, the third harmonics can cause a problem. Figure 1.21 shows the third harmonics with respect to the currents of each of the three phases. Note that, even though the fundamental components are 120° out of phase with each other, the third harmonics of each phase are in phase with each other. The fundamental current components add up to zero (see Figure 1.19), but the third harmonics do not. They instead add together, and the only path for this current is back through the neutral to the source.

In the design of feeders for many loads, it is assumed that under balanced conditions there will be no current flowing in the neutral conductor. However, for feeders supplying loads that produce third harmonics, such as lighting units equipped with magnetic-core ballasts, the neutral conductor does carry current even under balanced load conditions. This problem is discussed in Section 11.1.5.

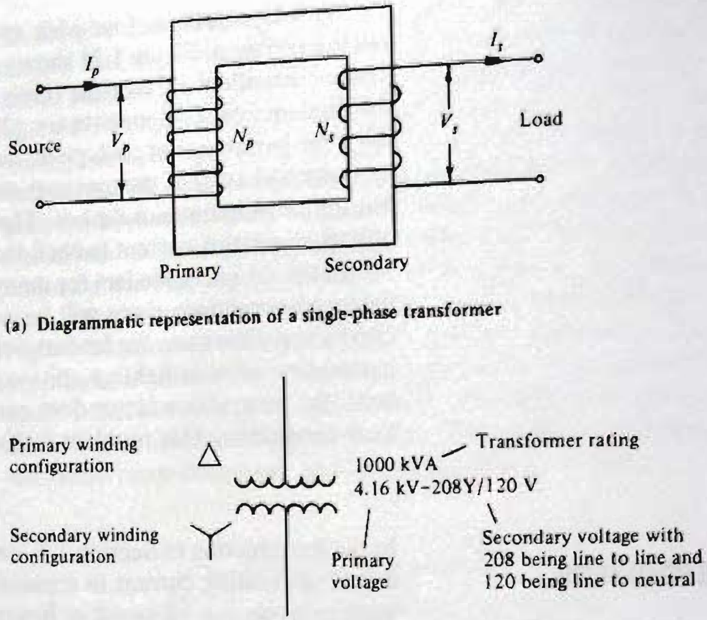
1.7 TRANSFORMERS

In the introduction to Section 1.3, one reason given for the universal use of alternating current to transmit power is the ease with which voltage levels can be raised or lowered as desired. The device used to change voltage levels is the *transformer*. Transformers are used at generating stations to raise the transmission voltages to high levels. This results in much lower line currents and therefore much lower line (I^2R) losses in the transmission lines. At the load end, transformers lower the voltages, first to levels that suit the distribution of power to the customer's premises and, finally, if required, to levels to suit the utilization equipment. Only the basic operation of the transformer is discussed in this section. See Chapter 15 for further details on types of transformers.

The basic single-phase transformer consists of two windings, as shown in Figure 1.22(a). The winding connected to the source of power is referred to as the *primary*, and the winding connected to the load is referred to as the *secondary*. There are no electrical connections between the primary and secondary windings. Energy is transferred through mutual inductance. Transformers work only on alternating current, because a continuously changing current is required in the primary to produce a magnetic flux in the iron core that is also continuously changing. This flux then links with the secondary winding, inducing a voltage that is proportional to the rate of change of the flux. Since the flux varies sinusoidally, the induced voltage also varies sinusoidally.

1.7.1 Voltage, Current, and Power Relationships

The primary and secondary voltages are directly related to the respective number of turns in the windings. For example, in Figure 1.22(a), if the primary winding has 1000 turns and the secondary winding has 100 turns, then the primary voltage is 10 times the



(a) Diagrammatic representation of a single-phase transformer

(b) Method of designating a three-phase transformer on a one-line diagram

FIGURE 1.22

Transformers

secondary voltage. This leads to the following relationship:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} = \alpha \tag{1.13}$$

where V_p = primary voltage
V_s = secondary voltage
N_p = number of turns on the primary
N_s = number of turns on the secondary
α = turns ratio

Note that the turns ratio can be determined from the voltages without knowing the actual number of turns on the windings.

The amount of power that a transformer can continuously carry is largely dependent on the load current. The I^2R losses in the windings create heat, and the load current is restricted by the ability of the transformer to dissipate this heat. Therefore, transformers are rated by their volt-ampere capacity. Large transformers have a kilovolt-ampere or kVA rating. For a single-phase transformer, the rated current is obtained by dividing the volt-ampere rating by the rated voltage of the winding.

Single-phase transformers can be electrically connected to form three-phase transformer banks. However, the growing trend is to combine the individual phase coils into one overall three-phase transformer unit. The primary and secondary windings can be connected in either the wye or delta configuration. The most common arrangement for transformers used in unit substations for buildings is the delta-connected primary and the wye-connected secondary. Figure 1.22(b) shows the method of designating a three-phase transformer on an electrical system diagram.

The power relationships of three-phase transformers must include the $\sqrt{3}$ (1.732) factor as developed for Equation 1.12. Since transformer ratings are in volt-amperes, the power factor does not have to be included and therefore:

$$\text{kVA of three-phase transformer} = \frac{1.732\ V_s I_s}{1000}$$

from which

$$I_s = \frac{\text{kVA} \times 1000}{1.732 V_s} \tag{1.14}$$

where I_s = rated secondary line current
V_s = rated secondary line-to-line voltage

The kilovolt-ampere rating of a transformer is based on the rated output from the secondary. Transformers are very efficient, normally having losses (that is, heat) as low as 1% to 2%. Therefore, the input power at rated loading can be assumed to equal the rated kVA, and the rated primary current can be obtained by using the rated primary voltage V_p in place of V_s in Equation 1.14. Note that as the voltage is stepped down through the transformer the current is stepped up, and vice versa.

■ EXAMPLE 1.19

A single-phase transformer has a 600 V primary and a 120 V secondary. The primary winding has 800 turns. Calculate (a) the number of turns on the secondary and (b) the turns ratio.

Solution

(a) From Equation 1.13,

$$N_s = N_p \times \frac{V_s}{V_p} = 800 \times \frac{120}{600} = 160 \text{ turns}$$

(b) The turns ratio is

$$\alpha = \frac{V_p}{V_s} = \frac{600}{120} = 5$$

Note that the ratio $N_p/N_s = 800/160 = 5$ also.

■ EXAMPLE 1.20

A 100 kVA, three-phase transformer is rated for 480-208Y/120 V. Calculate the rated primary and secondary currents.

Solution

From Equation 1.14,

$$I_p = \frac{100 \times 1000}{1.732 \times 480} = 120.3 \text{ A}$$

$$I_s = \frac{100 \times 1000}{1.732 \times 208} = 277.6 \text{ A}$$

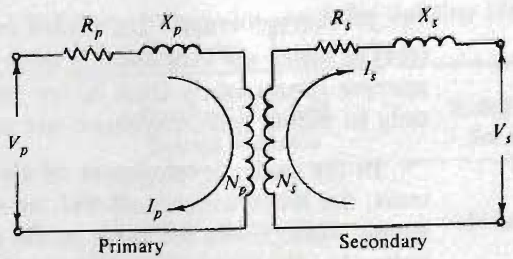
Note that the line-to-line voltage (208 V) must be used to calculate the secondary current. Note also that the ratio of the currents is equal to the inverse of the ratio of the voltages (that is, to the turns ratio).

1.7.2 Equivalent Impedance

So far we have treated the transformer as an ideal device that has no losses. However, as with any device carrying current, the windings of the transformer have resistance, which results in some degree of I^2R losses under load conditions. Also, not all the magnetic flux created by the primary winding links with the secondary winding, and vice versa. The small amount of flux that does not link properly is referred to as the *leakage flux,* which causes an inductive reactance in each of the windings (referred to as *leakage reactance*). Figure 1.23(a) shows the equivalent circuit diagram for a transformer that includes the resistance R and leakage reactance X of each winding. Note that this is a simplified diagram in that the magnetizing component of the primary current is neglected.

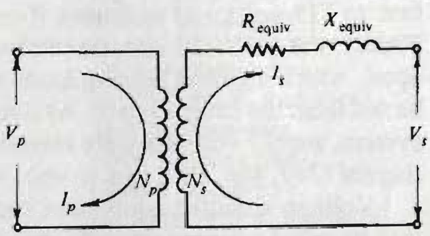
To further simplify the transformer circuit diagram for the purposes of performing system calculations, the total effects of the resistance and leakage reactance can be transferred to either the primary or secondary side of the transformer. Figure 1.23(b) shows the effects transferred to the secondary side. Note that, in transferring the effect of the primary resistance and leakage reactance to the secondary, their value in ohms is divided by the square of the turns ratio (α^2). The reader can refer to one of the electrical machinery and transformer textbooks listed in the bibliography for an explanation of this operation. The combined effect is referred to as the equivalent resistance, leakage reactance, and impedance, respectively. Example 6.3 shows how these equivalent values in ohms can be converted to per unit values for the purpose of calculating fault currents on systems (see Section 6.4).

The equivalent impedance of the transformer results in a voltage drop when the transformer is under load. However, the change in the secondary terminal voltage from full-load to no-load on the transformer, referred to as the voltage regulation, is normally less than 5%.



Note: The magnetizing component of the primary current is neglected.

(a) Simplified circuit diagram of transformer



$$R_{equiv} = R_S + \frac{R_p}{\alpha^2}$$

$$X_{equiv} = X_S + \frac{X_p}{\alpha^2}$$

$$Z_{equiv} = \sqrt{(R_{equiv})^2 + (X_{equiv})^2}$$

$$\alpha = \frac{N_p}{N_s}$$

(b) Equivalent circuit diagram with effects transferred to secondary side

FIGURE 1.23

Equivalent circuit diagram of transformer

1.8 VOLTAGE TERMINOLOGY AND STANDARDS

There have been many different voltage levels used over the 100 years since electric power became universally available, not only around the world but within North America. We still hear references to system voltages such as 110, 115, 220, and 230 volts. Much confusion results from not understanding the terminology that applies to voltages. The following three terms will therefore be defined before we discuss the voltage standards themselves:

1. *Nominal voltage* *The value assigned to a system or part of a system for the purpose of identifying the system*. This term can be applied only to systems, not to equipment. It indicates the desired level of the supply voltage for the system, but the actual voltage at any given point on the system may vary slightly from this nominal voltage within a range that still permits satisfactory operation of the utilization equipment.

2. *Rated voltage* *The value to which all the operating characteristics of a type of equipment are referred*. This term can be applied only to equipment, not to systems. Most equipment can operate satisfactorily within a specified range of voltage variations from the rated value, although there may be some change to the listed design ratings. Motors, for example, have an allowable range of plus or minus 10% from their rated voltage (see Section 2.9).

3. *Voltage class* *This value indicates the maximum voltage level at which the insulation of wiring and equipment is designed to operate continuously* (that is, for years). This term can be applied only to wiring and equipment, not to systems.

In the early development of electrical power distribution systems, the loads were small and the distances short. Therefore, the supply voltage was the same as the equipment voltage, that is, 110 volts. As alternating current systems came into use, higher voltage levels based on multiples of 110 volts became common (220, 440, 550, and so on). However, as systems grew in size, the supply voltages were raised to help overcome the problems of voltage drop, first to 115 volts and multiples thereof (230, 460, 575, and so on). Finally, the 208Y/120 volt, three-phase, four-wire system was developed, which enabled lighting loads and three-phase motors to both be fed from the same system. As a result of the wide adoption of this system, supply voltages were raised again to 120 volts and multiples thereof (240, 480, 600, and so on).

Voltage-sensitive equipment such as lighting was redesigned so that its rated voltage generally matched the increases in the supply voltages. However, for many years, motors, which can tolerate a greater voltage variation, were still designed with rated voltages of 110, 220, 440, 550 volts, and so on, on the basis that the voltage drops inherent in most systems brought the voltage at the motor terminals down close to these values. In the 1960s, a survey of industrial and commercial premises was conducted, which showed that this was not the case; in fact, motors were generally operating on overvoltages. As a result, since the late 1960s, motors have been designed with rated voltages of 115, 230, 460, 575 volts, and so on. Also, since 230 volt motors were no longer suitable for operation on 208 volt systems (as were the 220 volt rated motors), 200 volt ($\sqrt{3} \times$ 115V) rated motors are now available.

The following classifications have been adopted with regard to voltage levels:

- Low voltage: 0 to 1000 V
- Medium voltage: 1001 to 72,500 V
- High voltage: above 72.5 kV up to 242 kV
- Extra-high voltage: above 242 kV

For electrical systems in buildings, only the low and medium voltages (up to 34.5 kilovolts) are used. It should be noted that the *National Electrical Code* (*NEC*)* classifies *low voltage* as ranging

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TABLE 1.1 Voltage Standards for Building Electrical Systems up to 15 Kilovolts

	Standard Nominal System Voltages	Rated Voltages for Motors	Voltage Class
	Single-phase systems:		
	120/240 V, three-wire	115 and 230 V	125 and 250 V[a]
	Three-phase systems:		
Low voltage	208Y/120 V, four-wire	200 V	125 and 250 V[a]
	(240 V, three-wire)	230 V	250 V[a]
	480Y/277 V, four-wire	460 V	600 V
	480 V, three-wire	460 V	600 V
	(600 V, three-wire)	575 V	600 V
Medium voltage	(2400 V, three-wire)	2300 V	5 kV
	(4160Y/2400 V, four-wire)	4000 V	5 kV
	4160 V, three-wire	4000 V	5 kV
	(4800 V, three-wire)	4600 V	5 kV
	(6900 V, three-wire)	6600 V	15 kV
	(13,800Y/7970 V, four-wire)	13,200 V	15 kV
	13,800 V, three-wire	13,200 V	15 kV

[a] Most low-voltage cables and equipment are insulated for a maximum of 600 volts.

System voltages shown without parentheses are preferred.

For a complete listing of standard system voltages, see ANSI C84.1-1982.

up to 600 volts nominal, with higher levels being designated *above 600 volts nominal.*

To minimize the number of different operating voltages used throughout the United States, the American National Standards Institute (ANSI) has issued a list of preferred standard nominal system voltages. These nominal voltages, together with the standard rated voltages for motors and the voltage classes, up to 15 kilovolts are shown in Table 1.1.

SUMMARY

- Current I is the flow of electrons in a circuit, and its unit of measurement is the ampere.
- Voltage V is the electromotive force applied to a circuit, and its unit of measurement is the volt. Voltage can also represent a potential drop across a circuit element.
- Resistance R is the measure of opposition to the flow of current in a circuit, and its unit is the ohm.
- Ohm's law states that $R = V/I$.

- Energy is the ability to do work, and its unit is the joule. Power is the rate of doing work and its unit is the watt.
- Electrical power in watts = volts × amperes.
- The power dissipated by resistance is I^2R.
- Electrical energy is measured in kilowatt-hours:

$$1 \text{ kWh} = 3.6 \times 10 \text{ wattseconds or joules}$$

- Mechanical power is measured in horsepower:

$$1 \text{ hp} = 746 \text{ watts} = 0.746 \text{ kW}$$

- A series circuit provides only one path for the current. The voltage drop across each circuit element is directly proportional to the resistance of the element.
- A parallel circuit provides multiple paths for the current. There is one common voltage across all circuit elements and the current through each element is inversely proportional to the resistance of the element.
- Alternating current systems have currents and voltages that alternate in a sinsusoidal manner.
- Frequency is the number of cycles per second, designated hertz.
- Ac voltages and currents are designated by their rms values where:

$$E = 0.7071\ E_{max}$$

$$I = 0.7071\ I_{max}$$

- The time relationship between an ac voltage and current is designated by a phase angle.
- In a purely inductive ac circuit, the current lags the voltage by 90°.
- In a purely capacitive ac circuit, the current leads the voltage by 90°.
- Inductive reactance X_L is a measure of the opposition to the flow of ac current due to self-inductance, and its unit is the ohm.
- Capacitive reactance X_C is a measure of the opposition to the flow of ac current due to capacitance, and its unit is the ohm.
- Impedance Z is the circuit property that represents the combined effects of resistance and reactance, and its unit is the ohm.
- Ohm's law for ac circuits is $Z = E/I$, where E and I are rms values.
- For a circuit with resistance and inductive reactance:

$$Z = R + jX_L = \sqrt{R^2 + (X_L)^2}$$

where $+j$ is an operator that indicates that the quantity is rotated 90° counterclockwise.

- Power factor is the ratio of the active power to the apparent power and is expressed as a decimal or a percentage:

$$\text{Power factor} = \cos\theta$$

where θ is the angle between the current and voltage.

- Power in a single-phase ac circuit is P (watts) $= VI\cos\theta$.
- The 120/240 volt, single-phase, three-wire system provides two voltage levels, and two 120 volt loads can be supplied using only three wires.
- In a three-phase, wye-connected system, $V_L = \sqrt{3}V_P$, where L is the line value and P is the phase value.
- The three-phase, four-wire, wye-connected system provides two voltage levels. Three single-phase loads can be supplied using only four wires.
- In a three-phase, delta-connected system, $I_L = \sqrt{3}\,I_P$.
- The power in a balanced three-phase system is

$$P\ (\text{watts}) = \sqrt{3}\,V_L I_L \cos\theta$$

- The third harmonics in a three-phase system add together, and therefore a neutral current flows in a four-wire system, even under balanced conditions.
- Transformers are used to raise and lower voltage levels:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} = \text{turns ratio } \alpha$$

where p is primary value and s is secondary value.

- For a three-phase transformer,

$$\text{kVA} = \frac{\sqrt{3}\,V_s I_s}{1000}$$

- The equivalent impedance of a transformer represents the total effect of the resistances and leakage reactances of the windings as referred to one side of the transformer.
- Nominal system voltages represent the desired voltage of the power source and are in multiples of 120 volts.
- Rated voltages represent the ideal operating voltages of equipment. Motors are rated in multiples of 115 volts.

- Voltage class represents the level to which wiring and equipment are insulated.
- Low-voltage systems range from 0 to 1000 volts. The maximum standard at the present time is 600 volts nominal.
- Medium-voltage systems range from 1001 to 72,500 volts. The maximum standard voltage normally used within buildings is 34,500 volts nominal.

QUESTIONS

1. Describe in basic terms what the current in an electric circuit represents and state its unit of measurement.
2. State the difference between a conductor and an insulator.
3. What is the electron moving force called and how is it measured?
4. What is the alternative to the ohm for the unit for resistance?
5. Explain the distinction between emf and voltage drop.
6. State the difference between the source and the load in a circuit.
7. What is the alternative to the watt for the unit for power?
8. List the differences between a series circuit and a parallel circuit.
9. For a power circuit, explain why it is normal to have load elements connected in parallel rather than in series.
10. What is the advantage of having ac currents and voltages vary in a sinusoidal manner?
11. State the relationship between frequency, period, and cycles.
12. Why are the rms values of the current and voltage used for circuit calculations?
13. Explain phase relationship.
14. Why are phasor diagrams used?
15. Explain how inductance affects an ac circuit.
16. Explain how capacitance affects an ac circuit.
17. Explain why the impedance of a circuit cannot be calculated by simply adding arithmetically the numerical values of the resistances and reactances.
18. Explain why the power factor must be included when calculating the power in watts for an ac circuit.
19. How can a lagging power factor on an electrical system be improved?
20. What are the advantages of the single-phase, three-wire system as compared to a two-wire system?
21. What are the advantages of the three-phase, four-wire system as compared to a two-wire, single-phase system?
22. State the difference between a wye system and a delta system.
23. For a wye system with a phase voltage of 120 volts, explain why the line voltage is 208 and not 240 volts.
24. Explain why the relationship $P = 1.732 V_L I_L \cos \theta$ applies to both the wye and delta systems.
25. Explain why third harmonics can cause a problem on a four-wire wye system.
26. What is the significance of the turns ratio of a transformer?
27. State what is meant by the equivalent impedance of a transformer.
28. State the differences between nominal voltage, rated voltage, and voltage class.

PROBLEMS

1. If 240 V ac is applied to a two-wire circuit and the current is measured at 16 A, calculate the impedance of the circuit.
2. Calculate the voltage drop across an impedance of 10 Ω when an ac current of 5 A is flowing through it.

3. Calculate the current drawn by a single-phase load that has an impedance of 20 Ω when connected to a 120 V ac source.
4. Calculate the power being supplied to a two-wire, 120 V ac circuit that draws 15 A. The load on the circuit is purely resistive.
5. Calculate the resistance of a circuit element if the power being dissipated is 800 W when 10 A ac current is flowing through it.
6. Calculate the cost of operating a 500 W heater for 10 h if energy costs 6 cents/kWh.
7. Refer to Figure 1.3. The values of R_1, R_2, and R_3 are 5, 8, and 12 Ω, respectively. Calculate the applied voltage E when 8 A is flowing in the circuit.
8. Refer to Figure 1.5. The values of R_1, R_2, and R_3 are 15, 20, and 24 Ω, respectively. The current through R_1 is 8 A. Calculate (a) the applied voltage E and (b) the total circuit current I_T.
9. The peak value of an ac sinusoidal voltage is 679 V. Calculate its rms value.
10. Refer to Figure 1.9(a). Assume that current I_1 is 15 A $\angle 0°$ and I_2 is 20 A $\angle -30°$. Determine the total circuit current I_T.
11. A 240 V, single-phase load has a resistance of 10 Ω and an inductive reactance of 5 Ω. Calculate (a) the impedance of the load, (b) the power factor of the load, and (c) the power consumed by the load.
12. Calculate the current drawn by a 120 V, single-phase load, rated at 2.0 kW, 90% power factor.
13. Refer to Figure 1.16(a). Assume that load 1 is rated at 3.0 kW, 100% power factor, and load 2 is rated at 2.4 kW, 100% power factor. Calculate the neutral current.
14. A three-phase, 90% power factor load draws a line current of 30 A from a 480Y/277 V system. Calculate the power drawn from the system.
15. Calculate the line current drawn by a 10.0 kW, unity power factor load supplied from a 208Y/120 V, three-phase system.
16. Calculate the line current drawn by a 25.0 kW, 80% power factor load supplied from a 480Y/277 V, three-phase system.
17. Calculate the turns ratio of a 10 kVA, 2400-120 V, single-phase transformer.
18. Calculate the rated primary and secondary currents of a 500 kVA, three-phase transformer rated at 4160-480Y/277 V.

2 Electric Motors

OBJECTIVES

After studying this chapter, you will be able to:

- Identify the factors involved in electromagnetic energy conversion.
- Recognize the different types of motors.
- Explain how each type basically functions.
- Identify typical applications for each type.
- Identify the advantages of each type.
- Identify the disadvantages of each type.

INTRODUCTION

The electric motor is an energy converter. Energy is initially delivered to a building (or generated within) in the electrical form because of the ease with which the electrical energy can be transmitted throughout the building to the exact point where the energy is ultimately required. The electric motor then converts this electrical energy to mechanical energy. The motor is connected to a driven machine for the purpose of moving air (supply and exhaust fans), moving liquids (pumps), moving objects (elevators, conveyors), compressing gases (air compressors, refrigerators), forming materials (production equipment), and so on. In large industrial plants, motors can account for upward of 90% of the total electrical load. In large commercial buildings, motors can still account for more than 50% of the total electrical load.

The selection of the type of motor for a particular application depends first on the form in which the electrical energy is delivered to the motor: direct current (dc), alternating current (ac), single or three phase. Next the selection depends on the requirements of the driven equipment: constant or variable speed, load cycles, starting and acceleration of the load, and so on. Finally, the selection depends on the environment in which the motor is to operate: normal, where an open-type ventilated enclosure is acceptable; hostile, where a totally enclosed motor must be used to prevent the free exchange of air between the inside and outside of the motor; or hazardous, where an explosion-proof enclosure must be used to prevent fires and explosions.

The main classifications of motors are as follows:

- DC motors
  - Shunt
  - Series
  - Compound
- AC motors
  - Three phase: synchronous or induction
  - Single-phase induction: split phase or capacitor start

Each type is first discussed as to its method of operation and characteristics. The summary at the end of the chapter then lists the general applications and the advantages and disadvantages of each type.

The transmission of electrical energy using alternating current is now universal. As a result, ac motors account for the majority of the motors used in buildings and industry. Therefore, the discussions in this chapter will focus primarily on the ac motors, with dc motors being discussed only to introduce motor principles and to show their good speed control characteristics.

2.1 ELECTRO-MECHANICAL ENERGY CONVERSION

To study the conversion of electrical energy to mechanical energy, or vice versa, we must look at the relationships between the electromotive force induced in a conductor, the current flow through the conductor, the magnetic field surrounding the conductor, the motion of the conductor, and the mechanical force on the conductor.

Let us first consider the conversion of mechanical energy to electrical energy (that is, generator action). Figure 2.1 shows a conductor moving through a magnetic field. From Faraday's law of induction, the voltage induced in the conductor is directly proportional to the strength of the magnetic field and the velocity of the conductor. A practical application of this is the dc generator, as shown in Figure 2.2. The generated voltage E can be expressed as:

$$E = K\phi S \tag{2.1}$$

where K = a machine constant
ϕ = strength of the magnetic field
S = rotational speed of the machine

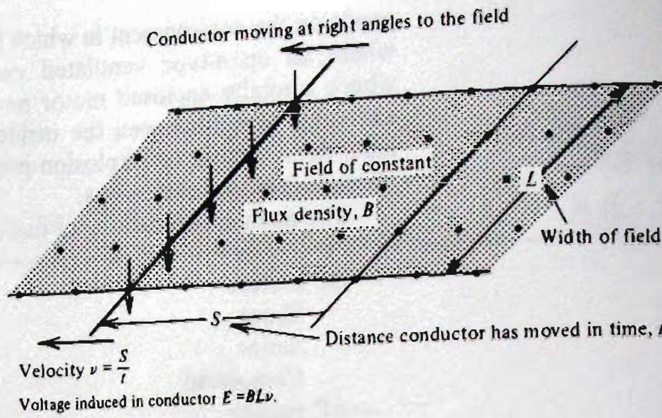


FIGURE 2.1

Conductor moving through a magnetic field

This relationship is equally applicable to a motor, because a motor also has conductors moving in a magnetic field and therefore has an internal generated voltage.

Next consider the conversion of electrical energy to mechanical energy (that is, motor action). Figure 2.3 shows a conductor in a magnetic field. The mechanical force produced on the conductor is proportional to the strength of the magnetic field and to the current in the conductor. If the conductor is placed on the rotor of a motor in the form of a loop, as shown in Figure 2.4, then the force on the conductor produces rotating motion. The important factor now becomes the turning effort or the *torque*. Torque is the product of the force F and its radial distance from the center of rotation R. The torque T produced by a motor is expressed as:

$$T = C\phi I \tag{2.2}$$

where C = machine constant
ϕ = strength of the magnetic field
I = current through the conductors

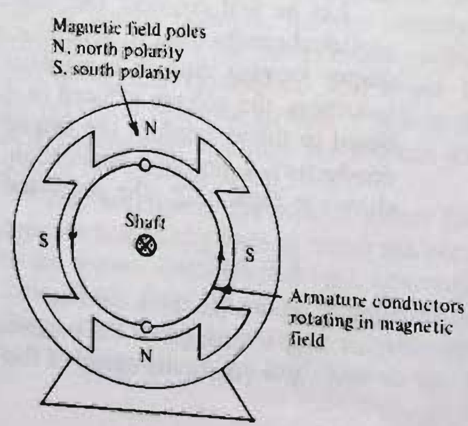


FIGURE 2.2

Elementary four-pole dc generator or motor

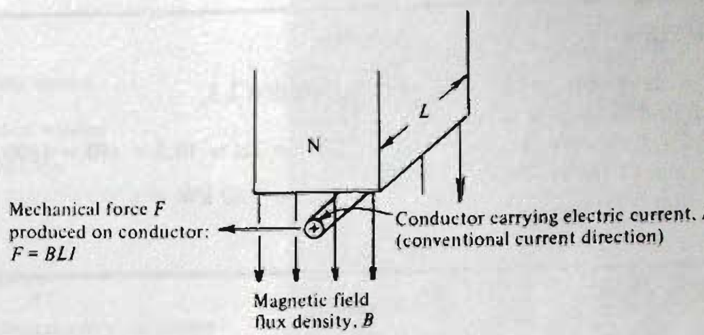


FIGURE 2.3

Force produced on a conductor in a magnetic field

Power is the rate of doing work (see Section 1.1.4). In the Systeme International (SI), the mechanical power output of the motor is expressed as:

$$P = T\omega \tag{2.3}$$

where P = power in watts
T = torque in newton-meters (N · m)
ω = angular velocity in radians per second (rad/s)

Remember that the watt is equally a measure of mechanical power (1 horsepower = 746 watts; Equation 1.4).

In the English system, the mechanical output of the motor is expressed as:

$$\text{Horsepower} = \frac{TS}{5252} \tag{2.4}$$

where T = torque in pound-feet (lb-ft)
S = speed in revolutions per minute (rpm)
5252 = necessary conversion factor

The following examples illustrate these relationships.

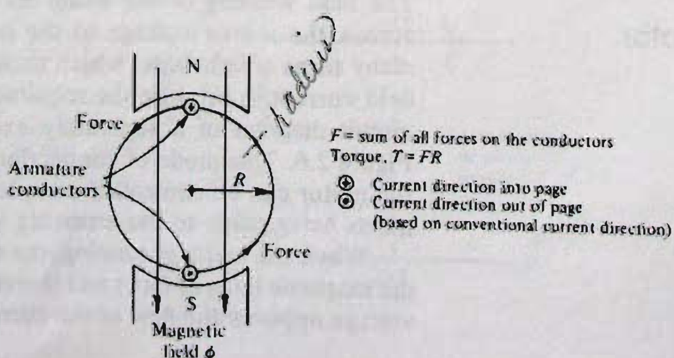


FIGURE 2.4

Torque produced by motor

■ **EXAMPLE 2.1**

A motor is developing a torque of 10.5 N · m at a speed of 180 rad/s. Calculate the power output of the motor using SI units.

Solution

From Equation 2.3,

$$P = T\omega = 10.5 \times 180 = 1890 \text{ W}$$
$$= 1.89 \text{ kW}$$

■ **EXAMPLE 2.2**

A motor is rated at 10.0 hp with a full load speed of 1750 rpm. Calculate the full load torque of the motor using English units.

Solution

Rearranging Equation 2.4 gives

$$T = \frac{\text{horsepower} \times 5252}{S} = \frac{10.0 \times 5252}{1750} = 30.0 \text{ lb-ft}$$

2.2 DIRECT CURRENT MOTORS

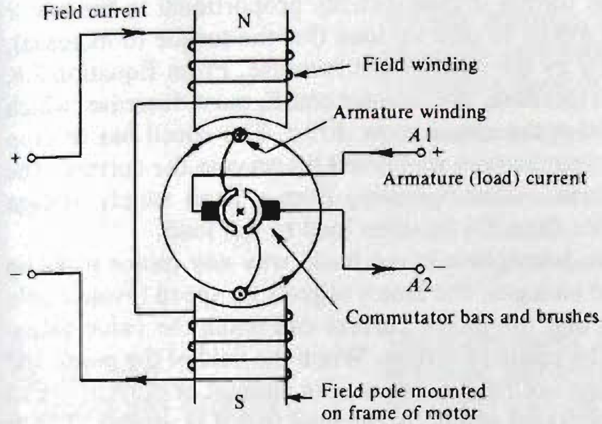
The direct current (dc) motor has two sets of windings: (1) the field winding, which is mounted on the frame, and (2) the armature winding, which is mounted on the rotor. Figure 2.5(a) shows a simplified connection diagram for the two sets of windings, and Figure 2.5(b) shows a cutaway view of the motor. The field current controls the strength of the magnetic field (see Figure 1.10). The armature winding carries the load current of the motor. The armature conductors rotate alternately under a north pole and then under a south pole. The commutator acts like a switch to reverse the individual conductor currents so that the torque is constant in the one direction.

Direct current motors are classified according to the mode of connection of the field winding with respect to the armature winding, that is, shunt, series, or compound.

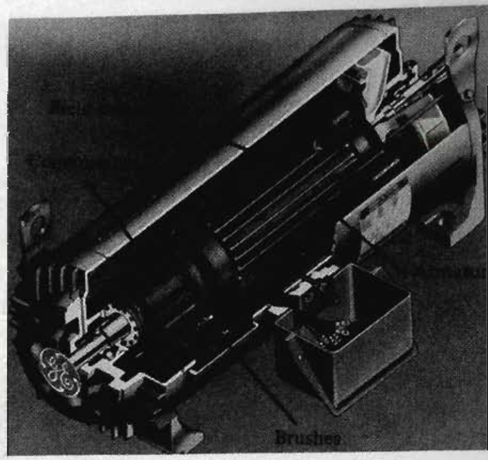
2.2.1 Shunt Motor

The field winding of the shunt motor is designed for connection across the source voltage to the motor. The winding consists of many turns of light wire, which then requires only a relatively small field current to produce the required magnetic flux. The equivalent circuit diagram of a separately excited shunt motor is shown in Figure 2.6. This mode of connection is preferred so that the field of the motor can be controlled completely independent of any adjustments being made to the armature voltage.

When the motor is running, the armature conductors are cutting the magnetic lines of force and therefore a voltage is generated. This voltage opposes the flow of the current through the armature and is



(a) Simplified connection diagram



(b) Cutaway view

FIGURE 2.5

Direct current motor

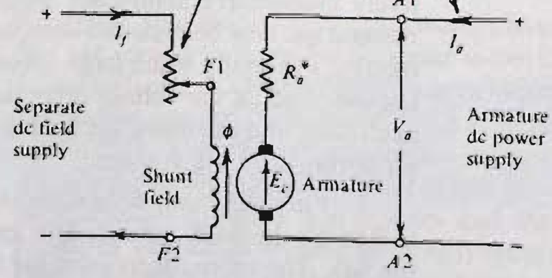
referred to as the *counter* emf, shown on the diagram as E_c. Using the circuit laws as outlined in Chapter 1, the equation for the armature circuit becomes:

$$V_a = I_a R_a + E_c \tag{2.5}$$

Solving for the armature current gives:

$$I_a = \frac{V_a - E_c}{R_a} \tag{2.6}$$

Assume that the motor is operating with a constant magnetic field (that is, the field current is constant). From Equation 2.1, the counter emf E_c is then directly proportional to the speed. From



$^*R_a$ represents total resistance of armature.

FIGURE 2.6

Equivalent circuit diagram of a dc shunt motor separately excited

Equation 2.2, the torque is then directly proportional to the motor current. For the motor to pick up load (for the torque to increase), the current drawn by the motor must increase. From Equation 2.6, for the current to increase, the counter emf E_c must decrease, which in turn requires that the motor slow down. The speed has to drop only slightly for there to be a significant increase in the current. The speed of a dc shunt motor operating from a fixed supply voltage decreases no more than 5% from no load to full load.

The previous description is the basic way any motor picks up load. As the load changes, the motor adjusts its speed (even if only momentarily) so that the motor current can reach the value necessary to develop the required torque. When the field of the motor and the applied voltage are held constant, the amount of current drawn by the motor is dictated solely by the load that it is driving. This is discussed further in Section 2.9.

2.2.2 Speed Control of Shunt Motors

The dc shunt motor is most often used where a variable-speed drive is required. From Equation 2.1, $E_c = K\phi S$. Substituting for E_c in Equation 2.5 and solving for the speed gives:

$$S = \frac{V_a - I_a R_a}{K\phi} \tag{2.7}$$

This relationship shows that there are three ways to control the speed of the shunt motor:

1. *Increase the armature circuit resistance, R_a.* This is done by connecting resistance into the circuit external to the motor. As resistance is added, the speed of the motor decreases, the exact amount being dependent on the load current I_a of the motor. This method has two major disadvantages: (1) It is inefficient because of the heat loss in the added resistors, and (2) the speed of the motor varies as the load on the motor varies.

2. *Vary the supply voltage, V_a.* With the development of relatively inexpensive solid-state variable-voltage power sources, this method has now become the accepted way to control the speed of dc motors, especially when large speed changes are required. Neglecting the effect of the voltage drop across the armature I_aR_a, which is negligible, and assuming the field ϕ is constant, the speed is directly proportional to the voltage.

3. *Vary the shunt field current.* The amount of flux ϕ is controlled by the field current. The speed is inversely proportional to the flux. Therefore, decreasing the field current causes the motor to speed up and, conversely, increasing the field current causes the

motor to slow down. The field current can easily be controlled by an external rheostat, as shown in Figure 2.6. Since the field current is relatively very small, the heat loss in the rheostat is not significant. Solid-state devices are also used for field control.

Variable-speed drive systems generally incorporate both methods 2 and 3. Large changes of speed are made by varying the armature voltage, and very precise speed settings are made by controlling the field current. Most applications of dc motors today are for variable-speed drives because of their superior characteristics.

2.2.3 Series and Compound Motors

The series motor has the field winding connected in series with the armature, as shown in Figure 2.7. Since the field winding carries the full motor load current, the winding consists of a few turns of heavy wire. The magnetic flux is now dependent on the load current, with the result that the torque and speed characteristics are quite different from those of the shunt motor. Refer to Equation 2.2. With the flux ϕ also dependent on I_a, the torque is directly proportional to the square of the load current. Refer to Equation 2.7. With the flux ϕ in the denominator, the speed is inversely proportional to the load current when V_a is held constant. This gives the motor a very high torque at low speeds and high currents, and a low torque at high speeds and low currents. These characteristics are very desirable for the traction motors used to drive trains and electric buses and for other applications requiring high starting torques. The starter motor on your car is a series motor. However, the use of series motors in buildings is very rare other than in battery-operated mobile equipment.

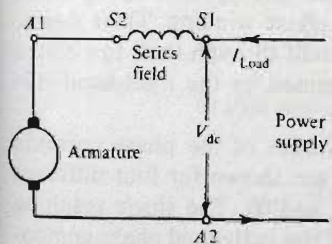


FIGURE 2.7

Direct current series motor

The compound motor uses a combination of the shunt and series windings, giving it higher starting torques than a comparable shunt motor and greater speed drops under load. However, ac motors are available with similar characteristics, so the use of compound motors in buildings or for industrial applications is rare.

2.3 POLYPHASE ALTERNATING CURRENT MOTORS

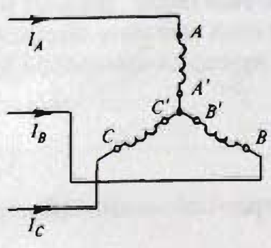
Polyphase alternating current (ac) motors have many characteristics that are similar to those for dc shunt motors, but there are several major differences. Electrically, commutation is not required with alternating current. Mechanically, the armature winding is mounted on the frame and the field winding is mounted on the rotor, which is the reverse of the arrangement for the dc motor. It makes no difference whether the field is stationary and the armature conductors rotate, or vice versa, as long as there is relative motion between the two. Since no commutation is required for ac motors, it makes sense to place the higher voltage, higher current armature windings on the frame (stator), where fixed connections can be made. The field winding, on the other hand, requires only a fraction of the power. In the case of the synchronous motor, the collector ring and brush assembly required for the electrical connections to the rotor can be relatively much smaller.

2.3.1 Rotating Magnetic Field

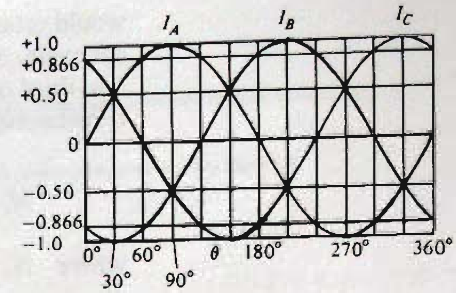
Before the operation of polyphase motors can be explained, it is necessary to understand the phenomenon of the rotating magnetic field. It is hard to imagine that pulsating currents flowing through fixed coils produce a field that is constant in strength and that rotates around the frame. For the explanation, refer to Figure 2.8, which shows a simplified arrangement of three armature coils mounted on the stator. Each coil is located 120° from the other around the stator, as shown in part (c). The coils are connected to the three-phase power supply as shown in part (a) so that their currents are 120° out of phase with each other (see Section 1.6.1 and Figure 1.19). The relative instantaneous values of the currents over one full electrical cycle are similarly shown in Figure 2.8(b). The positive sign indicates that the current is flowing toward the neutral at that instant of time, and the negative sign indicates that the current is flowing away from the neutral at a later instant of time. ϕ_A, ϕ_B, and ϕ_C represent the components of flux set up by each phase winding. Their magnitude is directly proportional to the current through their respective windings, and their direction is determined by the right-hand rule (see Section 1.4.1 and Figure 1.10).

The directions and relative magnitudes of the phase currents and of the magnetic flux components are shown for four different instants of time Figure 2.8(c), (d), (e), and (f). The single resulting magnetic field ϕ_{RES} is the vector sum of the individual phase components. Note that in each case the relative magnitude of ϕ_{RES} remains constant at a value of 1.5, but that the position of this field moves. The rotation of the field in mechanical degrees is the same as the electrical degrees covered in the cycle. The time span covered is 90° or one-quarter of a cycle, and the field has moved 90° or one-quarter of a revolution in a clockwise direction. The constant field is very desirable as it results in a constant torque being developed by three-phase motors, giving them very smooth running and quiet operation.

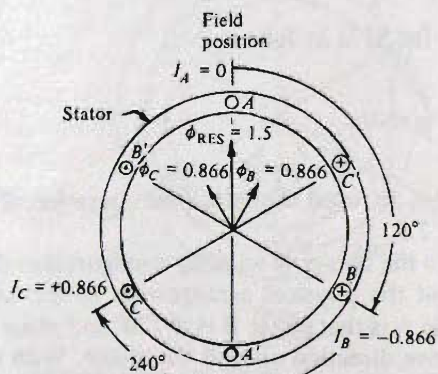
With the two-pole configuration (that is, there is one resulting north pole and one resulting south pole) shown in Figure 2.8, the field will complete one full revolution around the stator for every one cycle of the electrical system. If we were to analyze the performance of a motor wound to produce a resulting field having two north poles and two south poles (a four-pole motor), then the field



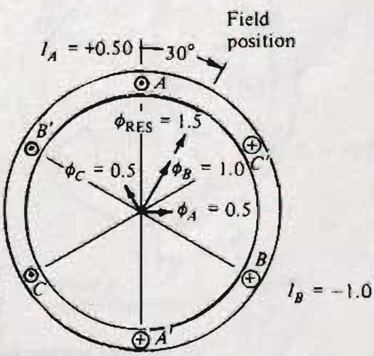
(a) Connections to armature coils



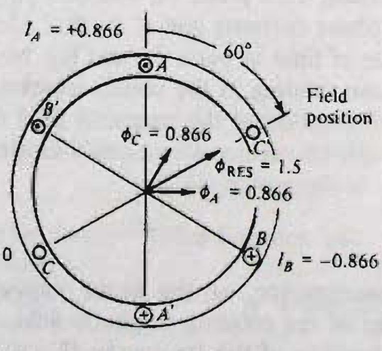
(b) Relative values of phase currents



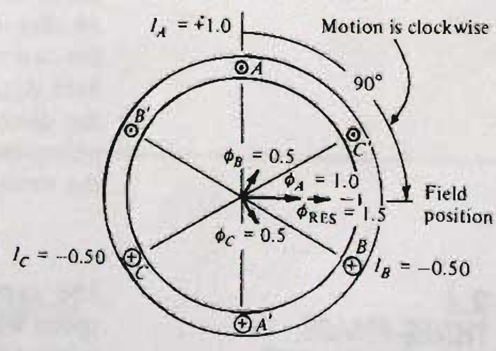
(c) Field position when θ = 0°



(d) Field position when θ = 30°



(e) Field position when θ = 60°



(f) Field position when θ = 90°

FIGURE 2.8

Rotating magnetic field of a three-phase ac motor

would rotate only one-half of a revolution for each complete electrical cycle. Similarly, for a six-pole motor, the field would rotate only one-third of a revolution for each complete electrical cycle. Thus, a relationship for the English system is established as follows:

$$N_s = \frac{120f}{P} \text{ rpm} \tag{2.8}$$

where N_s = synchronous speed of a motor (the speed of rotation of the field)
f = frequency of the electrical system
P = number of poles

The relationship for SI is as follows:

$$\omega_s = 4\pi \frac{f}{P} \text{ rad/s} \tag{2.9}$$

These relationships are used to analyze the operation of ac motors in Sections 2.4 and 2.5.

Refer again to the two-pole winding configuration shown in Figure 2.8. Note that the physical arrangement of the windings with reference to phase A is that phase B is at 120° and phase C is at 240°, both in a clockwise direction around the stator. With this arrangement, the field rotates in a clockwise direction. Let us reverse the electrical connections to two of the phase windings, as shown in Figure 2.9(a). Now phase B is 120° and phase C is 240° in a counterclockwise direction from phase A. The directions and relative magnitudes of the phase currents and of the flux components are shown for two instants of time in parts (b) and (c). Note that the resulting field ϕ_{RES} is now rotating in the counterclockwise direction. Thus, the direction of rotation of the magnetic field (and that of a three-phase motor) can be reversed by simply interchanging any two of the three lines to the motor.

2.4 THREE-PHASE SYNCHRONOUS MOTORS

The synchronous motor, as the name implies, synchronizes its speed with that of the rotating magnetic field. Since this speed of rotation is a function of the frequency (Equations 2.8 and 2.9), a particular synchronous motor with a fixed number of poles and connected to a fixed frequency will operate at an absolutely constant speed regardless of the load. This characteristic can be a very desirable feature for certain types of loads.

The following examples show the speeds of operation of two motors having different numbers of poles and operating on different frequencies.

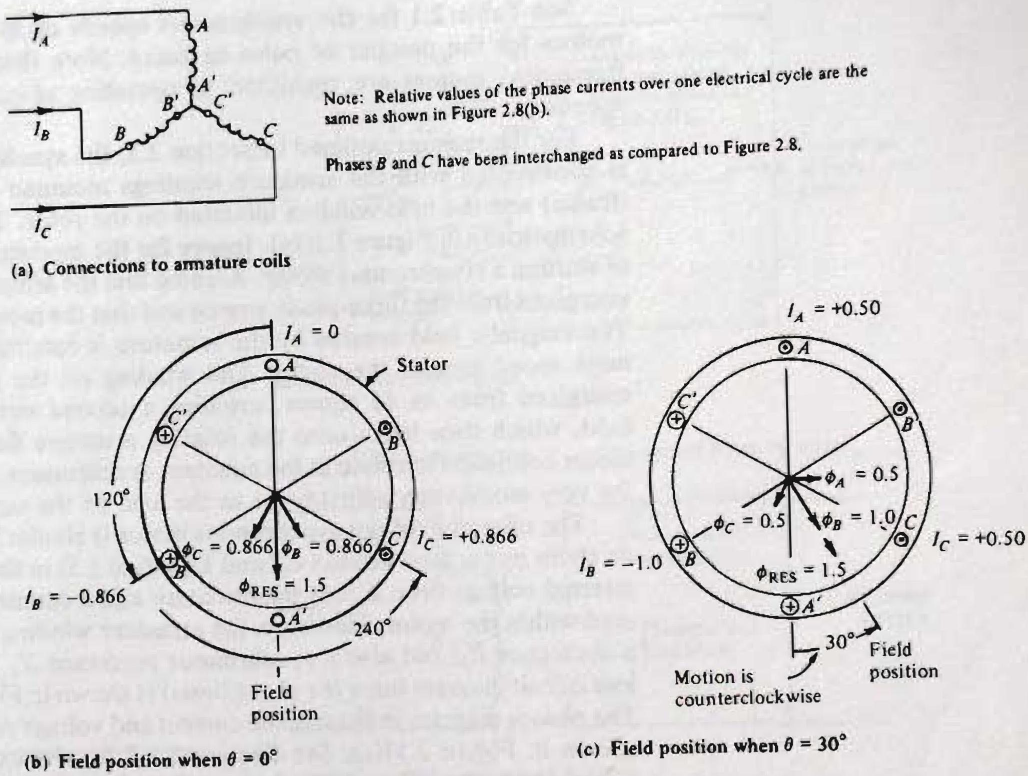


FIGURE 2.9

Direction of rotation of field compared to Figure 2.8

■ EXAMPLE 2.3

A synchronous motor has four poles and is operated from a 60 Hz, three-phase supply. Calculate the speed in rpm.

Solution

Using Equation 2.8,

$$N_s = \frac{120 \times 60}{4} = 1800 \text{ rpm}$$

■ EXAMPLE 2.4

A synchronous motor has six poles and is operated from a 50 Hz, three-phase supply. Calculate the speed in rad/s.

Solution

Using Equation 2.9,

$$\omega_s = 4\pi \frac{50}{6} = 104.7 \text{ rad/s}$$

See Table 2.1 for the synchronous speeds of 50 and 60 hertz motors for the number of poles as listed. Note that with a fixed frequency, motors are restricted to operating at certain specific speeds.

For the reasons outlined in Section 2.3, the synchronous motor is constructed with the armature windings mounted on the stator (frame) and the field winding mounted on the rotor. This is shown schematically in Figure 2.10(a). Ignore for the moment the problem of starting a synchronous motor. Assume that the armature has been energized from the three-phase source and that the motor is running. The magnetic field created by the armature is rotating at synchronous speed around the stator. The winding on the rotor is next energized from its dc source, creating a second strong magnetic field, which then locks onto the rotating armature field. Thus the motor continues to rotate at the constant synchronous speed except for very momentary adjustments as the load on the motor changes.

The operation of the synchronous motor is similar to that of the dc shunt motor (see Section 2.2 and Equation 2.5) in that there is an internal voltage drop across the armature and a counter emf generated within the motor. However, the armature winding not only has a resistance R_a, but also a synchronous reactance X_s. The equivalent circuit diagram (on a per phase basis) is shown in Figure 2.10(b). The phasor diagram indicating the current and voltage relationship is shown in Figure 2.11(a). See Section 1.3.3 for the explanation of phasor diagrams. The phasor sum of the voltage drops across the armature (I_aR_a and I_aX_s) plus the counter emf E_c must be equal to the voltage applied to the armature V_a.

Similar to the dc shunt motor, as the load on the motor increases the armature current must increase in order to produce the required

TABLE 2.1 Synchronous Speeds of Alternating-Current Motors

Number of Poles	Synchronous Speeds 50 Hz rpm	50 Hz rad/s	60 Hz rpm	60 Hz rad/s
2	3000	314.2	3600	377.0
4	1500	157.1	1800	188.5
6	1000	104.7	1200	125.7
8	750	78.5	900	94.2
10	600	62.8	720	75.4
12	500	52.4	600	62.8
16	375	39.3	450	47.1
20	300	31.4	360	37.7

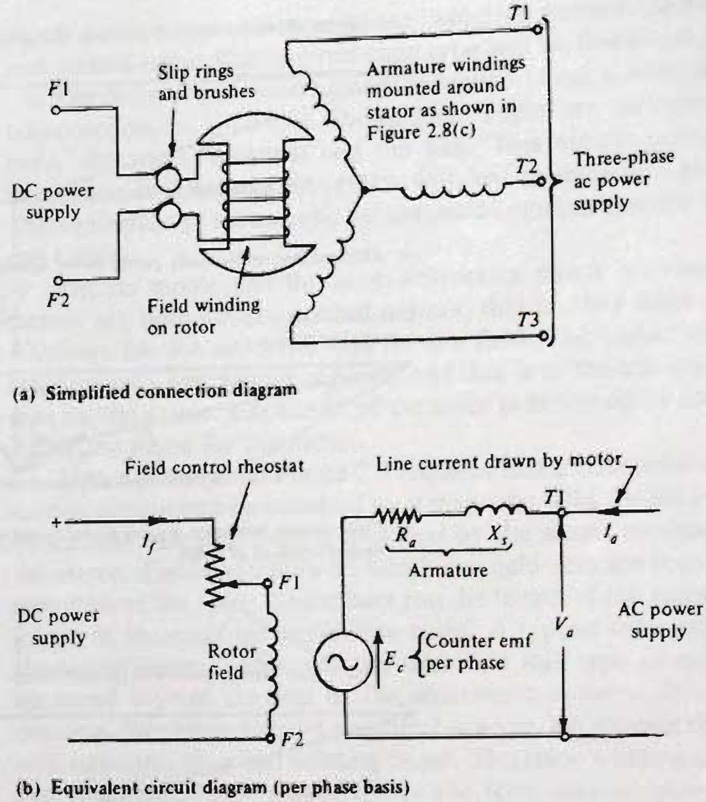


FIGURE 2.10

Three-phase synchronous motor

torque. This requires that the counter emf E_c must change. However, unlike the dc motor, the synchronous motor cannot permanently change speed. It only slows down momentarily, which changes the position of the rotor with respect to the rotating magnetic field. This change in the phase relationship between V_a and E_c allows the current to increase. Once the motor has adjusted to its new load, it then resumes rotating at its synchronous speed. Thus, like all motors, the synchronous motor adjusts to the load demands of the driven equipment by drawing more or less current from the power supply. However, unlike other motors, it does not vary its speed with load. If the motor is overloaded beyond its ability to maintain the speed, it pulls out of synchronism and must be immediately shut down.

There is a second major characteristic of the operation of the synchronous motor. Refer again to Figure 2.11(a). This phasor diagram shows the condition when the armature current I_a is in phase with the applied voltage V_a; that is, the motor is operating at unity (100%) power factor (refer to Section 1.4.4). Parts (b) and (c) show

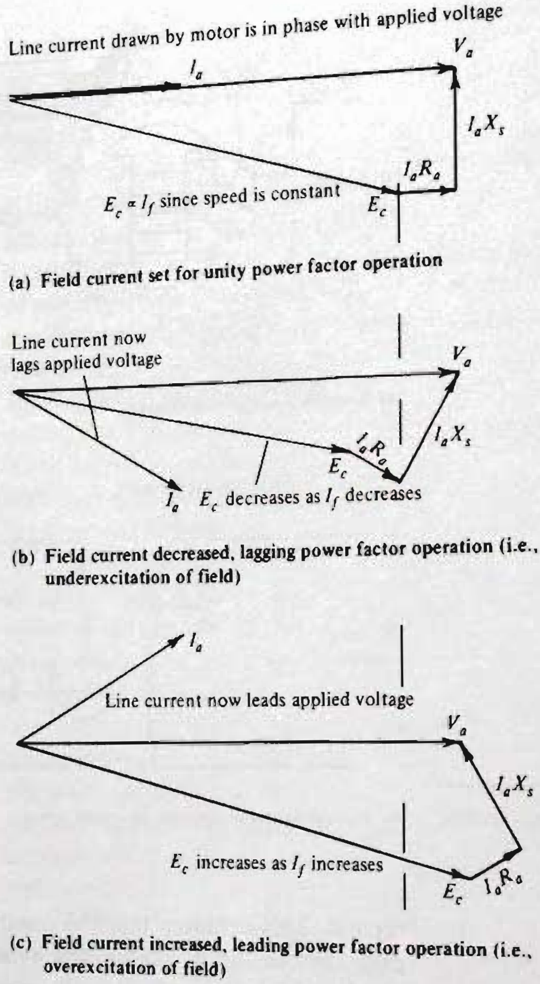


FIGURE 2.11

Operation of synchronous motor with constant load, but with varying field current

what happens when the dc rotor field current is varied with a constant load on the motor. When the field current is decreased, the motor operates at a lagging power factor, and when it is increased, the motor operates at a leading power factor. Thus the power factor at which the motor operates can very simply be controlled by adjusting the relatively small dc field current. This is a tremendous advantage where large motors are operating on a system. A synchronous motor not only drives the load, but it can be used for power-factor correction on the system.

The synchronous motor is not inherently self-starting. The usual method of overcoming this problem is to superimpose a degree of squirrel-cage winding onto the rotor [see Figure 2.13(a)]. Thus the motor is started as a squirrel-cage motor, and when the rotor is almost up to speed, the dc field is applied and the motor then runs as a synchronous motor.

2.5 THREE-PHASE INDUCTION MOTORS

There are two types of three-phase induction motors: squirrel cage and wound rotor. The squirrel-cage type will be discussed first.

The three-phase, squirrel-cage induction motor is very simple in construction, as shown in Figure 2.12. There are no commutator bars, slip rings, brushes, and the like. This simple construction results in a much lower cost motor with less maintenance problems. The squirrel-cage motor is by far the most common electric motor in use today.

The dc motor and the ac synchronous motor previously discussed are both doubly excited motors; that is, they have separate windings for the armature and for the field. The induction motor requires only one source of power and that is to the armature windings on the stator. Excitation of the rotor is achieved by induction, hence the name for the motor.

Motor action as in Figure 2.3 requires that a conductor carrying an electric current be acted on by a magnetic field. In the induction motor, the magnetic field is provided by the armature windings on the stator. The conductors on which the field acts are bars that are mounted on the rotor. These bars run the length of the rotor and are joined at the ends by conducting rings. A typical rotor winding is shown in Figure 2.13(a). At the time that this type of motor first appeared toward the end of the nineteenth century, it was very common for people to have a squirrel as a pet. To provide these pets with exercise, they had rotating cages. The rotor winding construction resembled these cages. Hence the term squirrel cage was selected for this type of motor to differentiate it from the wound-rotor induction motor (see Section 2.5.4).

For small- and medium-sized squirrel-cage motors, the rotor bars and end rings can be cast in one piece using aluminum. This results in much lower production costs in comparison to motors

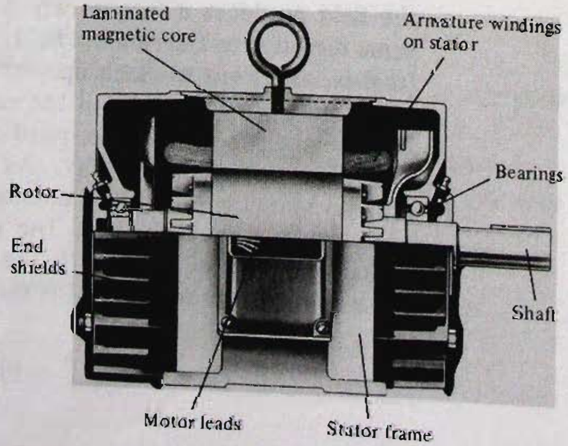
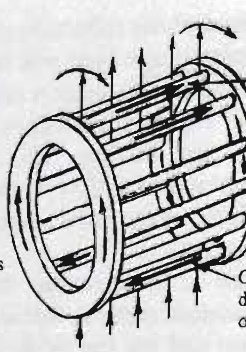
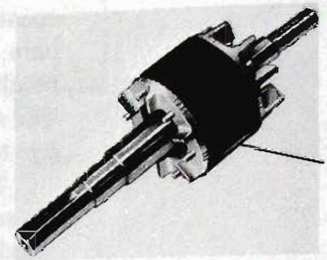


FIGURE 2.12

Cutaway view of squirrel-cage induction motor



(a) Squirrel-cage rotor winding



(b) Fully assembled rotor mounted on shaft

FIGURE 2.13

Rotor for squirrel-cage induction motor

requiring wound rotors. To have as strong a magnetic field as possible, the rotor bars must be surrounded by a laminated magnetic core. Figure 2.13(b) shows the complete rotor assembly mounted on the shaft. The rotor bars themselves are not visible as they are just beneath the surface of the laminated magnetic core, but the end rings are visible. The protrusions on the end rings act like a fan to circulate air through the motor for cooling.

2.5.1 Running Characteristics of Squirrel-Cage Motors

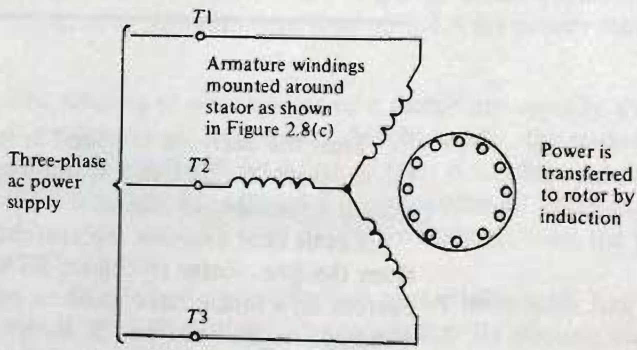
To begin to understand how the three-phase induction motor operates, we must return to the rotating magnetic field as described in Section 2.3.1. The armature windings on the stator are arranged as shown in Figure 2.8(c). The instant that the motor is energized from its three-phase source, the currents through the windings establish the rotating magnetic field. With the rotor standing still, this rotating field sweeps past the rotor bars. This action induces a voltage, which in turn causes current to flow in the bars. See Figure 2.13(a) for the paths of the rotor current. The interaction of the rotor current with the field produces a torque, which starts the rotor turning in the same direction as the rotating field. As the rotor comes up to speed (that is, as it tries to catch up with the rotating field), the relative speed between the field and the rotor decreases. To differentiate between the two speeds, the speed of rotation of the field is referred to as the *synchronous speed* N_s. As per Equation 2.8, N_s is constant for a given motor with a fixed number of poles when operated from a constant frequency (60 Hz). The difference between N_s and the actual speed of the rotor S_R is the *slip*. The relative speed of the rotor with respect to the field is then expressed as:

$$\% \text{ Slip } (S) = \frac{N_s - S_R}{N_s} \times 100 \qquad (2.10)$$

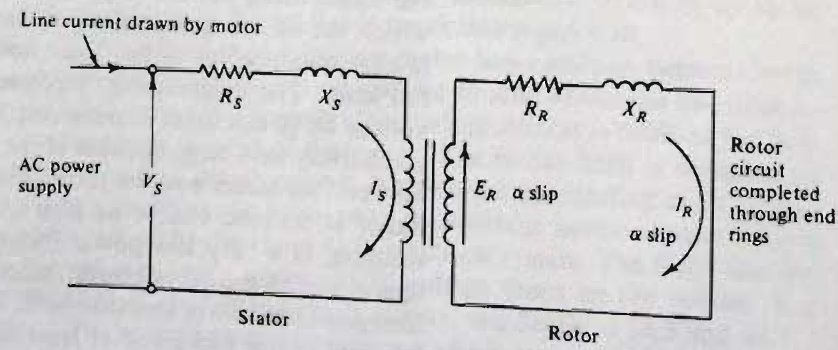
The speed of the rotor can never exactly reach the synchronous speed. There must always be some slip in order to produce the necessary current in the rotor bars to keep the motor turning.

The simplified connection diagram for the squirrel-cage induction motor is shown in Figure 2.14(a), and the equivalent circuit diagram (on a per phase basis) is shown in Figure 2.14(b). The induced voltage in the rotor E_R is a function of the slip, which in turn means that the rotor current I_R is a function of the slip. As the load on the motor increases, the torque produced by the motor must also increase. From Equation 2.2, the rotor current must increase, which then means that the slip must increase. Thus, the motor has to slow down to the point where the increase in torque is sufficient to match the new load demand. The change in speed is slight, as shown by the following examples.

$T = C\phi I$



(a) Simplified connection diagram



(b) Equivalent circuit diagram (per phase basis)

FIGURE 2.14

Three-phase, squirrel-cage induction motor

■ **EXAMPLE 2.5**

A four-pole, 60 Hz induction motor is operating with a slip of 2.0%. Calculate the actual speed of the motor.

Solution

From Equation 2.8,

$$N_s = \frac{120 \times 60}{4} = 1800 \text{ rpm}$$

Rearranging Equation 2.10,

$$S_R = 1800 - \frac{2.0 \times 1800}{100} = 1764 \text{ rpm}$$

■ **EXAMPLE 2.6**

The load on the motor in Example 2.5 is now doubled. Calculate the new speed of motor.

Solution

The slip was 1800 − 1764 = 36 rpm. This must increase to 2 × 36 = 72 rpm. The new speed is 1800 − 72 = 1728 rpm.

Thus the decrease in speed in the previous examples is only on the order of 2%. The slip at full load should not exceed 5% for the typical squirrel-cage motor.

Let us next examine the current that the induction motor draws from the line. Refer to Figure 2.14(b). By transformer action, any current flow in the rotor must be reflected into the stator (primary) winding. As the load on the motor increases, the rotor current increases and therefore the stator current increases. However, this reflected current from the rotor is only one component of the stator or line current. Since there is no separate field winding for an induction motor, the line current must also have a component to provide the magnetizing current to produce the field. Refer to Figure 2.15, which shows the components of the line current both at no load (motor spinning free of any load) and at full load (motor producing full load). The magnetizing component of current lags the applied voltage by 90 electrical degrees (see Section 1.4.1). This component is relatively very large because of the air gaps in the magnetic circuit between the stator and the rotor. Therefore, the line current of the motor at no load can be as high as 50% of the full-load current, resulting in a very low power factor. At full load, the motor still operates with a lagging power factor. Small motors may have full-load power factors of less than 80%. Large motors are better, having full-load power factors of at least 90%. This lagging power factor operation is one of the major disadvantages of the induction motor.

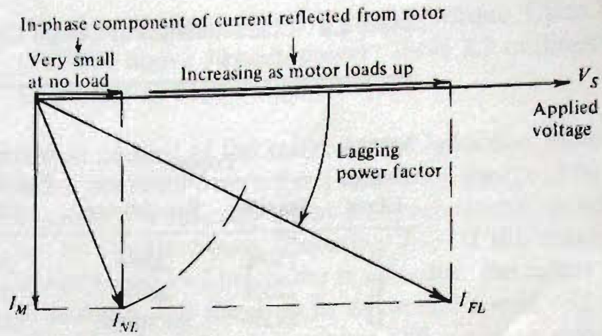


FIGURE 2.15

Running currents of induction motor

I_M, magnetizing component of current, very large because of air gaps in motor. Constant regardless of load.
I_{NL}, no-load line current of motor, up to 50% of I_{FL}.
I_{FL}, full-load line current of motor.

It is usually the major cause of power factor problems on electrical systems in buildings (see Section 1.4.4 for power factor).

2.5.2 Starting Characteristics of Squirrel-Cage Motors

The starting characteristics of a motor are equally as important as their running characteristics. Mechanically, the motor must be able to break the driven load free to start it turning and then be able to rapidly accelerate up to full speed within 15 seconds. Electrically, the motor must not draw excessive currents from the power system when starting.

The squirrel-cage induction motor inherently has good starting and accelerating torque characteristics. Its starting torque is generally greater than its full-load running torque. As the motor accelerates, its developed torque increases, reaching a maximum at approximately 80% of the synchronous speed. The maximum torque is also known as the *breakdown torque*. A motor, once it is up to speed, can successfully withstand a temporary mechanical overload up to its maximum torque before it will break down and stall.

The squirrel-cage induction motor has a starting current that is low enough to usually permit starting directly across the line (that is, with full voltage). Typically, the starting current is 600% of the full-load running current of the motor. The motor itself is designed to withstand this inrush current during a normal starting cycle. However, a problem can arise when a particular motor accounts for a good part of the total load on an electrical system. The 600% starting current may cause unacceptable voltage drops on the system. For methods of starting induction motors, see Sections 14.2 and 14.4.

The starting torque and current of a motor are often referred to as the *locked-rotor* torque and current since, at the instant of start-

TABLE 2.2 Characteristics of Design Classes for Squirrel-Cage Induction Motors

NEMA Design Class	Torque[a] Starting	Torque[a] Breakdown	Maximum Full-Load Slip	Starting Current[b]	Name/ Characteristic
B	150%	200%	5%	600%	General purpose
C	225%	200%	5%	600%	High torque
D	275%	At stand-still	15%	600%	High torque, High slip
F	125%	160%	5%	400%	Low starting current, Low torque

[a] Average value expressed as a percentage of full-load running torque.

[b] Maximum value expressed as a percentage of full-load running current.

Starting values apply for motors started full voltage.

Note: Exact values vary for each design class depending on horsepower rating and number of poles.

ing, the rotor is in effect locked into position. These values are measured by actually locking the rotor so that it cannot turn.

The exact values of the starting torque, the maximum torque, and the starting current of a squirrel-cage induction motor can be controlled by the design of the rotor bars. For example, if the resistance of the rotor bars is increased, the starting torque increases and the starting current decreases. However, offsetting these gains are the disadvantages of high full-load slip and lower efficiency because of the extra heat produced in the rotor bars. Another approach is to install two sets of bars on the rotor (a double squirrel-cage design). One set comes into action during starting, giving a higher starting torque and a lower starting current. The other set comes into action when the motor is up to speed, giving a normal full-load slip and efficiency. However, this type of construction increases the cost of the motor considerably.

Squirrel-cage induction motors are classed according to their starting torque, breakdown torque, full-load running slip, and starting current. These classes are designated as design classes B, C, D, and F. Design class A was assigned to the original squirrel-cage motor. The class B design has a slightly modified rotor, which results in a lower starting current while still providing the normal running characteristics. Therefore, the class A motor is no longer in general use, and the class B motor has been designated as the general-purpose motor. The class C design uses the double squirrel-cage rotor. The class D design uses rotor bars with higher than normal resistance. The class F design gives the lowest starting current, but this results in a low starting torque. Class F motors are only available above 30 horsepower. Table 2.2 outlines the general characteristics of each design class.

2.5.3 Speed Control of Squirrel-Cage Motors

Speed control of the squirrel-cage induction motor is not practical when operated from a fixed frequency source. The running speed of the motor is basically set by its synchronous speed, which in turn is set by the frequency (Equation 2.8). If the voltage applied to the motor is reduced below the rated value, the motor will start to slip a little more, but the drop in the actual speed will be slight. On the other hand, the motor current will increase significantly with the possibility that the motor will overheat. Also, there is no possibility of controlling the speed through field control, as the induction motor has no separate field winding.

$N_s = \frac{120f}{P}$ (rpm)

The speed of an induction motor can be changed by changing the number of poles (Equation 2.8). However, this results in large step changes. For example, if a motor is connected for four-pole operation on 60 hertz, it will run just below its synchronous speed of 1800 rpm. If the electrical connections to the stator windings are now changed by external switching so that eight-pole operation is obtained, then the motor will operate at half the speed. The synchronous speed of the motor has been changed to 900 rpm. Two-speed motors are often used to drive such loads as fans so that two different levels of air movement can be selected. Four-speed motors are also available that have additional combinations of winding connections, but these all add to the cost of the motor and the switching becomes quite complicated.

The only method of obtaining satisfactory stepless speed control of the squirrel-cage induction motor is by varying the frequency of the power source. The adjustable frequency controller used for this purpose rectifies the ac power to dc and then inverts the dc to a variable frequency and voltage output. While the inexpensive, standard squirrel-cage motor can be used, the adjustable frequency controller is costly. However, present development work is lowering the cost of controllers. Adjustable frequency controller and squirrel-cage motor packages are now becoming cost effective compared with other systems, such as variable dc voltage controller and dc motor packages. The adjustable frequency controller is complex and requires highly trained personnel to maintain. At the present time, due to limitations in technology, applications are restricted to 500 horsepower and below.

2.5.4 Wound-Rotor Motor

The wound-rotor induction motor differs from the squirrel-cage motor in that the rotor windings are not shorted out internally in the rotor. The electrical connections to the rotor windings are instead brought out via slip rings and brushes to terminals on the frame of the motor. Thus, the rotor circuit is accessible, and external resistance can be added to each phase as desired in order to change the starting torque and starting current or the full-load running speed of the motor.

For example, resistance can be added so that the maximum torque is developed at the instant of starting, thereby at least doubling the starting torque. At the same time, the starting current of the motor is considerably reduced. Then, as the motor comes up to speed, the added resistance can progressively be reduced so that maximum torque output is maintained during acceleration. Once up to speed and with all the resistance shorted out, the motor runs as a normal squirrel-cage motor.

On the other hand, once the motor is running, external resistance can be added to the rotor circuit for the purpose of controlling the speed of the motor. When the resistance of the rotor is increased with a constant load on the motor, the slip increases in direct proportion to the resistance. Thus, the motor slows down. The speed can therefore be controlled by varying the resistance. However, there are two major disadvantages to this method of speed control. First, the speed regulation is very poor. As the load on the motor decreases, the motor speeds up toward its synchronous speed, and it will only slow down again as load is added. Second, the efficiency of the motor is drastically reduced as the motor slows down because of the amount of heat that is dissipated in the resistors. For example, if sufficient resistance is added to slow the motor down to half speed, then approximately 50% of the total power input to the motor is wasted in heat from the resistors.

The wound-rotor motor is much more expensive than the squirrel-cage motor. The construction of the wound type of rotor is much more complicated than the cast type for the squirrel cage. The added ring and brush assembly also adds to the maintenance of the motor. The use of the wound-rotor motor for speed control has declined in recent years because of the development of dc and ac variable-speed drive systems. However, the wound-rotor motor continues to be used for applications involving high inertia loads, where high starting and accelerating torques combined with low starting currents are required.

Very recently, there has been some revival of interest in the use of the wound-rotor induction motor for speed control with the development of the slip energy-recovery system. With this system, the previously wasted rotor energy is regenerated and fed back into the supply lines, thus increasing the overall efficiency of the drive system. The solid-state circuitry required for the regeneration is quite complex, but further development work may make this an acceptable means of speed control in the future.

2.6 SINGLE-PHASE ALTERNATING CURRENT MOTORS

Single-phase motors are normally made in sizes up to 10 horsepower at 230 volts. However, the full-load current for a motor this size is 50 amperes. It could have a starting current of up to 300 amperes, and the problems that this would cause on most single-phase systems would be extreme. Therefore, single-phase motors should only be considered where three-phase power is not available or for very small fractional horsepower loads where it is not convenient to provide three-phase power.

The most commonly used type of single-phase motor is the induction motor. Unfortunately, single-phase induction motors are not inherently self-starting as are three-phase induction motors. Also, they are not as smooth running nor generally as efficient as three-phase motors.

To understand why single phase motors are not inherently self-starting, refer to Figure 2.8. If we look at the magnetic field that is set up by a single winding only (winding $A - A'$), the flux created by this winding, ϕ_A, does not rotate but remains on a fixed line (that is, horizontal). The flux increases in one direction for the first part of the cycle as shown in parts (c) to (f). If the analysis of the behavior of the flux were carried on for a full cycle, ϕ_A would then decrease back to zero and reverse its direction for the last half of the cycle. Thus the flux created by a single winding only pulses back and forth on a fixed line. This would not create a torque in the rotor of the motor to start it. Instead, there would be a loud vibration as the rotor is buffeted back and forth by the reversing field. If the rotor were to be mechanically spun, then the motor would continue to run. There would be a pulsating torque created each half-cycle in the same direction. The momentum of the rotor would carry it through the zero torque points that occur each time the current reverses. Therefore, a single-phase motor runs satisfactorily once it has started turning.

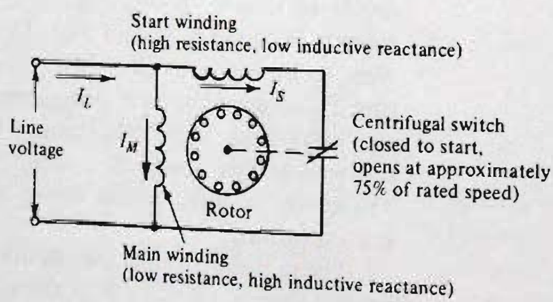
The pulsating torque causes the single-phase motor to run much noisier than is the case with three-phase motors. Other than this, single-phase induction motors run in a very similar manner and display similar torque and speed characteristics as for three-phase, squirrel-cage induction motors. The synchronous speeds are as shown in Table 2.1, and the speed control characteristics and comments in Section 2.5.3 also apply.

Before a single-phase motor will start on its own, there must be some component of rotating flux created in order to produce a starting torque. The two requirements for creating a rotating field as per Section 2.3.1 are (1) that there be windings physically displaced from each other around the stator and (2) that the currents through the windings be out of phase with each other. The standard single-phase induction motor therefore has a second winding called the start winding placed at 90° to the main winding. There are two different methods of then obtaining the phase difference in the currents.

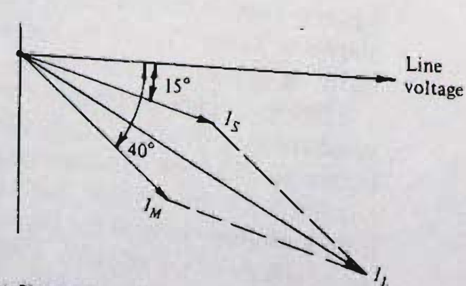
2.6.1 Resistance Split-Phase Starting

The resistance split-phase method of starting obtains the phase difference in the currents by designing the two windings to have different resistances and inductive reactances. Refer to Figure 2.16. The main winding has low resistance and high inductive reactance, whereas the start winding has the opposite. Thus, the current through the main winding I_M lags the applied voltage by a greater angle than does the current through the start winding I_S, as shown in part (b). The phase difference of some 25° between the two currents is sufficient to create a starting torque of at least 150% of the full-load running torque. The motor employing this type of starting has become known simply as the *split-phase* motor.

Once the motor is up to 75% of its synchronous speed, a centrifugal switch on the shaft opens a contact, disconnecting the start winding from the circuit. The start winding is not rated for continuous service. The motor then continues to run on the main winding. The centrifugal starting switch can be a source of trouble over the life of the motor. If the switch fails to open at the end of the starting



(a) Simplified connection diagram



(b) Phase relationship at instant of starting

FIGURE 2.16

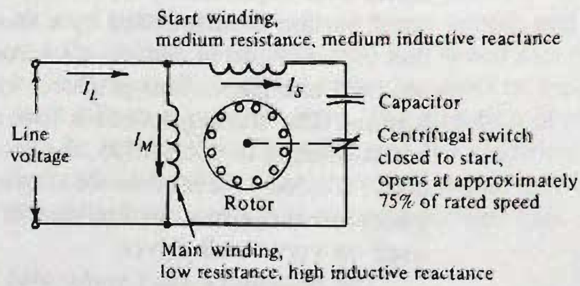
Resistance split-phase induction motor starting (motor is referred to as a *split-phase* motor) cycle, the start winding will burn out. If the switch does not close properly when the motor comes to a stop, the motor will not start the next time it is energized.

In addition to its relatively lower starting torque, the other disadvantage of this type of motor is its high starting current. The current I_L [Figure 2.16(b)] drawn by the motor during the starting cycle is the phasor sum of the two winding currents, which as shown is large.

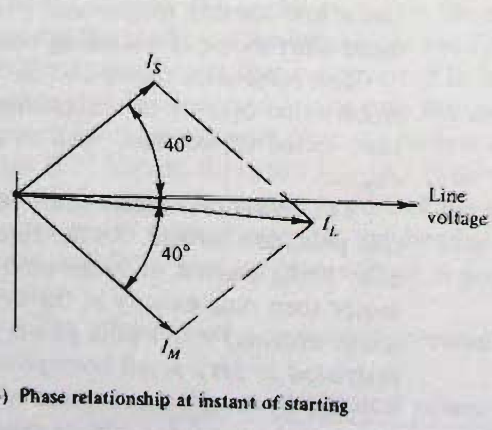
The single-phase induction motor cannot be reversed by simply reversing the two line connections to the motor. The direction of current through the start winding only must be reversed. The leads from the start winding have to be connected to a reversing switch.

2.6.2 Capacitance Split-Phase Starting

The capacitance split-phase method of starting uses a capacitor to obtain the phase difference between the two currents. Refer to Figure 2.17. The main winding is still highly inductive and its current lags the applied voltage, similar to the split-phase motor. With a capacitor in the start winding circuit, I_S is shifted so that it leads the applied voltage as shown in part (b). The phase difference between



(a) Simplified connection diagram



(b) Phase relationship at instant of starting

FIGURE 2.17

Capacitance split-phase induction motor starting (motor is referred to as a *capacitor-start* motor) the two currents now approaches 90°, thus creating a much higher starting torque, up to 450% of the full-load running torque. In addition, the starting current is lower. As shown in part (b), the phasor sum I_L of the two winding currents is much lower than is the case with the resistance split-phase method of starting. The motor employing the capacitance split-phase method of starting has become known simply as the *capacitor-start* motor.

The capacitor-start motor also employs a centrifugal switch to disconnect the start winding and the capacitor at the end of the starting cycle. Therefore, the split-phase and capacitor-start motors perform exactly the same once they are running. The capacitor-start motor costs more because of the capacitor. It is selected for applications where a high starting torque and low starting current are required.

2.6.3 Other Types of Single-Phase Motors

The shaded-pole motor and the reluctance-start motor are two types of single-phase motors that use means other than phase splitting to produce some degree of rotating magnetic flux in order to start.

The *shaded-pole motor* has only the one main winding. Each stator pole is physically divided into a large and small section. The small section is surrounded by a short-circuited coil. The result is a flux that is distorted and moves across the face of the pole when the motor is energized. This produces enough torque to start the motor turning. The starting torque is low and the efficiency of the motor when running is poor. Also, the motor cannot be reversed electrically. Shaded-pole motors are restricted to very small ratings, up to $\frac{1}{4}$ horsepower. However, because of their low cost, they are widely used on very small drives.

The *reluctance-start motor* also has only the one main winding. The stator pole tips are modified so that the flux in the air gaps is distorted, thereby creating some degree of rotating flux. The motor has a low starting torque and poor running efficiency. The reluctance-start motor is becoming obsolete.

The reluctance motor and the hysteresis motor are single-phase motors that operate at synchronous speed. They are used for constant-speed applications such as recording instruments and timing devices.

The *reluctance motor* has a rotor that is physically modified so that poles are formed. As the rotor approaches synchronous speed after being started, it locks onto the rotating magnetic field. The motor then runs exactly at the synchronous speed. The reluctance motor operates with a poor power factor and at a low efficiency. It is restricted to very small horsepower ratings.

The *hysteresis motor* uses a permanent magnet for the rotor, which locks the rotor into its synchronous speed. It is restricted to very small horsepower ratings. This is the common synchronous motor used in clocks.

Finally, the last type of single-phase motor to be discussed, the *universal motor,* does not use the induction principle. It is in fact the series motor. Refer to Figure 2.7, which is the circuit diagram for the dc series motor. This type of motor will also work on alternating current. Since the armature current and the field current are one and the same, they both reverse at the same time. The reversal of the armature current is canceled by the reversal of the field, and therefore the developed torque is constant in the one direction. Because of its ability to operate on both dc and ac, this motor is called the universal motor. The major problem with ac operation is the much higher hysteresis and eddy-current losses in the magnetic core. The universal motor must be especially designed to handle these losses so that the motor will not overheat. It is generally restricted to smaller ratings.

The most common use for this type of motor is for portable tools, such as drills and skillsaws, and portable household appliances, such as vacuum cleaners. The universal motor is used because a high output can be obtained from a relatively small frame operating at high speeds for short periods. This motor is not restricted to operating at synchronous speeds and can be designed for speeds as high as 20,000 rpm. The speed can be controlled over a wide range using variable series resistors or more recently by solid-state silicon-controlled units. The direction of rotation of the motor can be reversed by interchanging the electrical connections to the series field winding. The universal motor has the disadvantage of requiring maintenance of the commutator bars and brushes.

2.7 EFFICIENCY OF MOTORS

The efficiency of any type of equipment is the ratio of the useful output power as compared to the total input power. In the case of electric motors, the useful output is the mechanical power developed at the shaft, and the input is the total electrical power delivered to the motor. Power that is converted to heat within the motor and power that is consumed just to turn the motor itself are considered losses. Heat losses result from the current flowing through the windings (I^2R losses, Equation 1.3) and from the hysteresis and eddy-current losses in the magnetic core of the motor. Mechanical power losses result from friction at the bearings and brush contacts, if used, and from windage losses (it takes power just to spin the rotor in air).

The efficiency of a motor is expressed as:

$$\%\ \text{Efficiency} = \frac{\text{mechanical power output}}{\text{electrical power input}} \times 100 \qquad \textbf{(2.11)}$$

Electric motors can be very efficient, with large motors having efficiencies as high as 95%. However, the trend in the design of electric motors, especially the smaller horsepower, squirrel-cage induction motors, was to provide as much horsepower rating for a given physical size of motor as possible. Competitive factors in the marketplace require manufacturers to keep their costs as low as possible. This is done in part by keeping the amount of magnetic material in the motor to a minimum and by using the smallest conductors possible for the windings. Unfortunately, this all increases the heat losses and lowers the efficiency of the motor. The increased operating temperature of the motor is made possible by better insulating materials. In the past with power costs low, the lower price for the motor was traded off against the increase in power consumption.

Energy shortages in the 1970s, however, resulted in considerable increases to the cost of electrical energy. Using a motor with a higher efficiency (lower losses), even though it costs more, can be beneficial. Manufacturers are now offering energy-efficient electric motors. The lower losses are the result of using more and better steels in the magnetic core and larger diameter copper (rather than aluminum) wire in the windings. The following example shows the advantage of using energy-efficient motors.

■ EXAMPLE 2.7

A 20 hp motor is to operate 4000 h/yr at 100% load. An energy-efficient motor has an efficiency of 91.5% as compared to 89.1% for the standard motor. Assume that the energy-efficient motor costs \$770, the standard motor costs \$630, and energy costs 5.0 cents per kWh. Calculate the payback period for the energy-efficient motor.

Solution

From Equation 1.4,

$$20 \text{ hp} = 20 \times 0.746 = 14.92 \text{ kW output}$$

From Equation 2.11, the input power to the two motors is:

$$\text{Std. motor} = \frac{14.92 \times 100}{89.1} = 16.75 \text{ kW}$$

$$\text{EE motor} = \frac{14.92 \times 100}{91.5} = 16.31 \text{ kW}$$

The cost of energy consumed (see Section 1.1.4) is:

$$\text{Std. motor} = 16.75 \times 4000 \times \$0.05 = \$3350$$

$$\text{EE motor} = 16.31 \times 4000 \times \$0.05 = \underline{\$3262}$$

$$\text{Energy savings for EE motor} = \$88$$

$$\text{Difference in cost of motors} = \$770 - \$630 = \$140$$

Time to pay back extra cost of energy efficient motor is

$$\frac{140}{88} = 1.6 \text{ years}$$

With a payback period as short as 1.6 years, it makes sense to purchase the higher cost motor. The assumed cost of 5.0 cents per kilowatt-hour is very conservative. The example also assumed a cost premium of 22% for the energy-efficient motor. No doubt competition will lower this premium in the future.

In evaluating an electric motor for purchase, the efficiency quoted by the manufacturer should be one of the most important factors that is considered.

2.8 FRAME SIZES AND ENCLOSURES

The frame size indicates the main physical dimensions of a motor. The National Electrical Manufacturers Association (NEMA) has established frame sizes in an attempt to standardize the dimensions of motors. Thus, motors of different manufacturers, but with the same frame size, can be readily interchanged. The frame size is designated by up to three numbers followed in some cases by a letter. The first two numbers indicate the height of the shaft above the motor mounting plate. Since this also sets the overall width of the motor, the space crosswise between the bolt holes on the mounting plate is fixed. The third number is a code for the length of the motor, which in turn sets the space lengthwise between the bolt holes.

The original frame sizes, beginning in 1928, also set the shaft diameters. However, with the development of new types of insulation and with improved designs over a period of time, it was possible to provide higher horsepower ratings in a given frame size. This increased power required a larger diameter of shaft for a particular frame size, which is indicated by a letter after the frame number. The letter U refers to new ratings initiated in 1953, and the letter T refers to a further rerating of motors initiated in 1964.

An example of a frame size designation is 254T. The height of the center line of the shaft above the mounting plate is 6.25 inches (one-quarter of 25), and the bolt holes for mounting the motor are spaced 10.0 inches across and 8.25 inches lengthwise. The shaft size is in accordance with the 1964 rerate program and is 1.625 inches in diameter. Thus, any other motor with the same frame size can be physically interchanged with this motor.

NEMA frame sizes are at present based on the dimensions being in inches. An attempt is being made to standardize motor frame sizes with the International Standards Organization (ISO) metric-dimensioned sizes, but progress toward this is slow.

Motors must operate in a wide range of environmental conditions from reasonably dry and clean to wet, dusty, or corrosive. A number of different types of motor enclosures are available. Each is designed to provide adequate protection for the motor and a degree of operating safety relative to the particular environment in which the motor is to operate. The two basic types of motor enclosures are the *open* type and the *totally enclosed* type, as shown in Figure 2.18.

In the open-type motor, a free exchange of air is permitted between the surrounding atmosphere and the interior of the motor. The air is circulated by means of fans formed on each end of the rotor assembly. Open-type motors may be further classed as drip proof or splash proof. The ventilating openings of drip-proof motors are constructed so that liquids or solid particles falling on the motor at angles up to 15° from the vertical will not interfere with the successful operation of the motor. Splash-proof motors can handle liquid or solid particles splashed on the motor at angles up to 100° from the vertical.

In the totally enclosed motor, there is no free exchange of air between the surrounding atmosphere and the interior of the motor. Totally enclosed motors may be either nonventilated or fan-cooled, as shown in Figure 2.18. The nonventilated motor is cooled solely by the radiation of heat from the surface of the motor. The fan-cooled motor has a fan that is external to the main enclosure and blows air along cooling fins on the outer surface of the motor housing to increase the rate of heat dissipation. In addition, totally enclosed motors can be classed as explosion proof, for use where hazardous gases or vapors are present, and dust and explosion proof, for use where dust is present. The dust may be either the type that can be ignited or the type that can cause explosions.

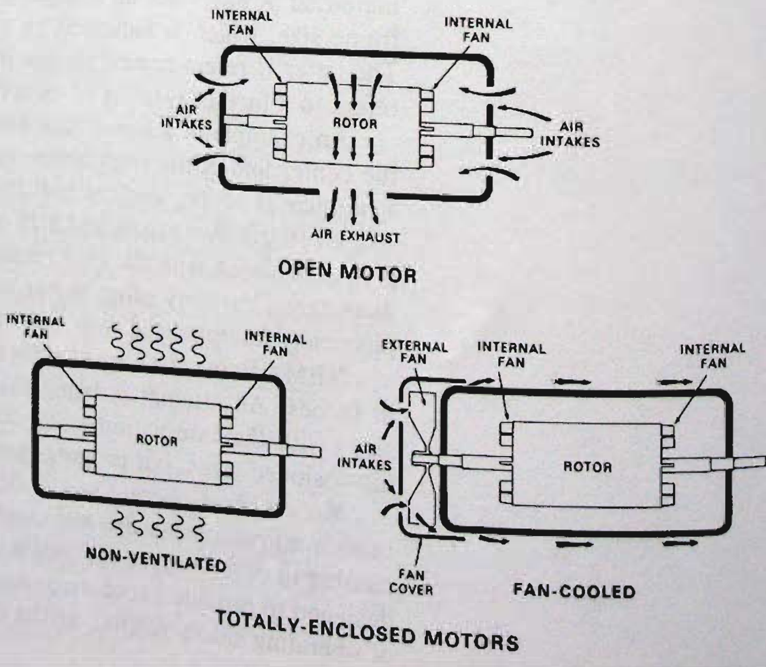


FIGURE 2.18

Basic types of motor enclosures

2.9 RATINGS OF MOTORS

When selecting a motor for a particular application, the most important criterion is the amount of mechanical power that the motor can produce at the shaft. Therefore, motors are rated by their mechanical power output, not by their electrical power input. For many years, the mechanical power has been rated in horsepower. However, the Systeme International (SI) recommends the use of the watt as the unit for mechanical power, in addition to its use for electrical power, which results in motors being rated in kilowatts. This unfortunately can lead to confusion in that the kilowatt rating can mistakenly be taken for the input electrical power to the motor. Because of losses in the motor as discussed in Section 2.7, the input power is higher than the output power. The term horsepower, because of its instant recognition as referring to the mechanical power output, will in all probability be used for many years to come.

It must be clearly understood what the horsepower rating of a motor means. As previously discussed, a motor picks up load by adjusting its speed, even if only momentarily, so that the current can increase to the value necessary to develop the required torque. Therefore, with a constant voltage, the current drawn by a motor from the power source is dictated solely by the load that the motor is driving. As the load and hence the line current increase, more heat is generated within the windings by the I^2R losses. The motor is designed to expel a certain amount of heat by circulating air through the windings. The horsepower rating (the rating stamped on its nameplate) is the amount of power that the motor can deliver continuously without seriously overheating. The motor can easily produce more power than its rated horsepower, but if it does so for more than a short period of time, the temperature within the motor will increase to the point that the insulation will start to deteriorate and eventually fail.

Some motors, however, are designed to take some degree of loading above their nameplate horsepower rating. This is indicated by the *service factor*. When the voltage and frequency are maintained at the nameplate values, the motor may be loaded up to the horsepower obtained by multiplying the rated horsepower by the service factor shown on the nameplate. For example, a 10.0 horsepower, general-purpose, open-type motor with a service factor of 1.15 can be continuously loaded up to 11.5 horsepower. Many other motors (for example, the totally enclosed type) have service factors of 1.0, which means that they cannot be continuously loaded beyond their nameplate horsepower.

Other nameplate ratings are as follows. The rated voltage is the voltage that should be applied to the terminals of the motor in order to get rated output from the motor. See Section 1.8 for definitions of voltages and for voltage standards. For alternating current motors operating on a fixed frequency, if the voltage is varied too far from the rated value, the line current increases, losses within the motor increase, and the motor can overheat. Therefore, the actual voltage applied to the motor must be within plus or minus 10% of the rated value in order to obtain satisfactory operation of the motor. The rated line current is the amperes that the motor will draw from the power system when delivering rated horsepower with rated voltage and frequency applied. This is also referred to as the full-load current of the motor. The rated speed is the speed at which the motor will run when delivering rated horsepower with rated voltage applied. For the alternating current induction motor, this speed is about 3% below the synchronous speed, because the motor must slip in order to produce the required power (see Section 2.5.1).

The allowable temperature rise is the maximum amount by which the internal temperature of the motor can rise above the ambient temperature. The term ambient means the air that immediately surrounds the motor and that is used for cooling the motor. For a general-purpose motor with class B insulation, the maximum rise is 90°C from an ambient temperature of 40°C. An ambient temperature above 40°C affects the ability of the motor to cool itself and therefore reduces its ability to produce the rated horsepower.

In the case of ac motors, the source frequency must exactly match the nameplate frequency of the motor if it is to operate satisfactorily at its rated conditions. The United States and Canada have standardized on 60 hertz, but most other parts of the world use 50 hertz.

Refer to Section 430-7 of the *National Electrical Code* for a complete listing of the information that is required to be shown on the nameplate of a motor.

A motor must be carefully selected to match the electrical characteristics of the power supply and the mechanical requirements of the load that it will be driving. It is especially important to match the horsepower requirements. An undersized motor will either overheat or trip its overload protective devices and shut down. On the other hand, an oversized motor will be operating at only partial load. The efficiency of the typical motor starts to decrease quite rapidly for loads below 80% of rated. This lower efficiency results in wasted energy and increased energy costs. For squirrel-cage induction motors, the partial loading means that the motor will also be operating at a poorer power factor than if fully loaded.

Tables 13.1 and 13.2 list the standard horsepower ratings and full-load currents for single-phase and three-phase ac motors (up to 200 horsepower), respectively. These values are used for the design of branch circuits and feeders for motors.

SUMMARY

The following is a summary of the advantages, disadvantages, and general applications of the types of motors covered in this chapter.

- Direct current motors (general). The transmission of electrical energy using alternating current is now universal, and therefore any dc motor requires rectifying equipment to provide the dc power. This added cost, coupled with the higher cost of the dc motor, precludes their use for general applications where a constant-speed drive is to be used. DC motors are only used for special applications such as those indicated for the specific types.
- Shunt dc motor
  - — Advantages
    - Very flexible and accurate speed control characteristics.
    - Wide range of operating speeds.
    - Very precise speed regulation.
    - Flexible starting and accelerating torques.
    - Competitive prices for complete speed-control package, including motor and rectifier for converting three-phase ac power.
    - Very good efficiency for the speed-control package.
  - — Disadvantages
    - Requires maintenance of brushes and commutators.
    - Speed controller complex to maintain.
  - — Typical drive applications: where variable-speed drives are required for paper machines, printing presses, rolling mills, elevators, hoists, and machine tools.
- Series dc motor
  - — Advantages
    - Very high starting torques.
    - High torques at low speeds for acceleration.
    - Low torques at high constant speeds.
  - — Disadvantages
    - Requires maintenance of brushes and commutator.
    - Motor can run away if disconnected from its load.
  - — Typical drive applications: traction motors for trains, electric buses, and mobile battery-operated equipment.
- Compound dc motor. The torque and speed characteristics of the compound motor can be matched by ac induction motors, which are cheaper. Today, compound motors are not normally used.

- Three-phase synchronous motor
  - Advantages
    - Runs exactly at synchronous speed.
    - Power factor can easily be controlled.
    - More efficient than induction motors.
  - Disadvantages
    - Generally more expensive than induction motors.
    - Requires maintenance of brushes and slip rings.
    - Requires separate dc power supply for field.
  - Typical drive applications
    - Where an absolutely constant speed is mandatory.
    - Where using the motor for power-factor correction saves the cost of the capacitor installation otherwise required.
    - For large drives above 1000 hp and below 450 rpm, the synchronous motor can be less expensive.

- Three-phase, squirrel-cage induction motor
  - Advantages
    - Very simple in design, rugged, and reliable.
    - No brushes and commutators to maintain.
    - Generally the least expensive of all motors.
    - Two- and four-speed motors available.
    - Runs at almost constant speed.
    - Can be started directly across the line.
  - Disadvantages
    - Runs at a lagging power factor even at full load.
    - High no-load currents (up to 50% of full load).
    - Very poor power factor at light loads.
    - Stepless speed control by variable frequency can be more expensive than other speed-control methods and equipment is complex to maintain.
  - Typical drive applications
    - General-purpose design class B motors, where normal starting torques and currents are acceptable; fans, centrifugal pumps, rotary compressors.
    - Design class C motors, where high starting torques are required; reciprocating pumps and compressors, crushers.
    - Design class D motors, where high starting torques and high full-load slips are required for high-peak intermittent loads with flywheels; punch presses, shears, bending rolls.

Design class F motors, where lower than normal starting currents are required and the lower starting torques are acceptable; fans, blowers.

- Wound-rotor induction motor

— Advantages

Very high starting torques combined with low starting currents can be obtained by varying the rotor circuit resistance when starting.

Speed can be controlled by varying the external rotor circuit resistance when running under load.

— Disadvantages

Cost of motor is high.

Requires maintenance of brushes and slip rings.

Very poor speed regulation with added resistance.

Very poor efficiency with added resistance.

— Typical drive applications: for high inertia loads where high starting and accelerating torques are required, but where normal starting currents would cause severe problems; large compressors, large cranes, conveyors, ballmills.

- Single-phase ac induction motor

— Advantages

Generally inexpensive.

Has good starting torque.

More convenient to supply single-phase 120 and 240 V power to small, fractional-horsepower drives.

— Disadvantages

Requires maintenance of centrifugal starting switch.

Pulsating torques, noisy operation.

Starting currents for the larger ratings can cause problems on most single-phase systems.

— Typical drive applications

Machine tools, refrigerators, oil burners, exhaust fans, washing machines, dryer blowers, pumps.

Split-phase motors are used where normal starting torques are acceptable; up to $\frac{3}{4}$ hp

Capacitor-start motors are used where high starting torques are required; up to 10 hp

- Other single-phase motors
  - — Shaded-pole motors are low cost but inefficient. They are used for low power drives such as record players, portable fans, dishwasher pumps, and typewriters.
  - — Synchronous motors (reluctance and hysteresis) operate exactly at synchronous speed and are used for clocks, appliance timers, and recording instruments.
  - — Universal motors can operate up to 20,000 rpm, have a high output in a relatively small frame, and can be speed controlled. They are used for portable tools and appliances such as drills, skillsaws, vacuum cleaners, sewing machines, and office machinery. The brushes and commutator require maintenance.

QUESTIONS

1. What is the relationship between the voltage, the magnetic field, and the speed of a generator?
2. What is the relationship between the torque, the magnetic field, and the current of a motor?
3. What is the relationship between the horsepower, the torque, and the speed of a motor?
4. What are the two basic sets of windings associated with the dc motor?
5. What are the three ways to control the speed of a dc motor?
6. How does the connection of the field winding for a series dc motor differ from that of the shunt dc motor?
7. What is the relationship between the synchronous speed, the frequency, and the number of poles for an ac motor?
8. How is the direction of rotation of a polyphase ac motor reversed?
9. With a fixed frequency, why are ac motors restricted to running at certain specific speeds?
10. Explain the significance of the term synchronous speed.
11. Both the dc motor and the ac synchronous motor are doubly excited motors. How does the induction motor differ in this respect?
12. Why is the basic induction motor referred to as a squirrel cage?
13. Why are squirrel-cage motors less costly to produce than motors requiring wound rotors?
14. What is meant by the term slip?
15. Why does the induction motor have a very poor power factor when running lightly loaded?
16. Explain the significance of design classes B, C, D, and F with regard to squirrel-cage induction motors.
17. What is the limitation of the method that changes the speed of an induction motor by changing the number of poles?
18. How is stepless speed control of a squirrel-cage induction motor obtained?
19. What is the major difference in construction between the squirrel-cage and the wound-rotor motor?
20. Why does the single-phase induction motor require a starting winding?
21. What is the difference between the split-phase and the capacitor-start motor with regard to method of starting?
22. What is the difference between the split-phase and the capacitor-start motor with regard to starting characteristics?
23. List the other types of single-phase motors with regard to method of starting and running.
24. Describe the losses associated with electric motors.
25. State what the efficiency of a motor indicates.
26. What does the frame size of a motor indicate?
27. The frame size of a motor is 215T. What is the

height of the center line of the shaft above the mounting plate? What is the significance of the T designation?

28. What is the difference between an open motor and a totally enclosed motor?
29. What does the nameplate horsepower rating of a motor mean?
30. What is the significance of the rated voltage of a motor?
31. What does a service factor of 1.15 indicate?
32. What does the rated line current of a motor indicate?
33. What is meant by the allowable temperature rise?
34. Why are dc motors not used for general constant-speed drive applications?
35. List suitable applications for dc motors?
36. List two major reasons why three-phase synchronous motors are used.
37. What are the two major advantages of squirrel-cage induction motors?
38. What is the major disadvantage of squirrel-cage induction motors?
39. What is the major type of application for the wound-rotor induction motor?
40. When three-phase power is available, why are three-phase induction motors preferable to single-phase motors?

PROBLEMS

1. A 20 hp motor has a full-load speed of 1150 rpm. Calculate its full-load torque.
2. A motor is producing 50 lb-ft of torque at 870 rpm. Calculate the horsepower output of the motor.
3. Calculate the synchronous speed of a 60 Hz, eight-pole motor in (a) rpm and (b) rad/s.
4. Calculate the slip of a 60 Hz, four-pole induction motor with a speed of 1740 rpm in (a) rpm and (b) percent.
5. A 60 Hz, six-pole induction motor has a full-load slip of 3.0%. Calculate its rated speed.
6. Calculate the full-load efficiency of a 50 hp, three-phase, 460 V motor that has a rated line current of 65 A at a power factor of 90%. (Use Equation 1.12 for power input.)
7. Refer to Example 2.7. The 20 hp motor is to operate for 6000 h/yr at an average of 80% of its rated horsepower. The cost of energy is 8.0 cents/kWh. Calculate the payback period for the energy-efficient motor.
8. A 30 hp motor is to operate 5000 h/yr at 100% load. An energy-efficient motor has an efficiency of 92.5%, compared to 90.0% for the standard motor. Assume that the energy-efficient motor costs $1100, the standard motor costs $900, and energy costs 6.0 cents/kWh. Calculate the payback period for the energy-efficient motor.

3 Lighting Fundamentals

OBJECTIVES

After studying this chapter, you will be able to:

- Identify the factors involved in the seeing process.
- Discuss light and how the eye determines color.
- Use the terminology of lighting.
- Calculate lighting quantities.
- Read an intensity distribution curve.

INTRODUCTION

The design of the lighting for an indoor working environment is considered to be more of an art than a science. The fundamental requirement is to provide sufficient light for the performance of visual tasks to enable the person to do these tasks efficiently and accurately, yet at the same time to create a comfortable environment with a minimum of eye strain and fatigue. Since the eye responds to the light reflected from an object, this becomes a very individual response with a great many variables to consider.

However, the primary objective of Chapters 3, 4, and 5 is to cover the *science* of lighting, that is, the use of well-established criteria to determine the *quantity* of light required to provide adequate levels of illumination for the average person under normal conditions. Only brief mention can be made of the equally important but far more nebulous requirement of the *quality* of lighting. This involves the comfort of the seeing environment and is only fully understood by lighting designers after years of experience.

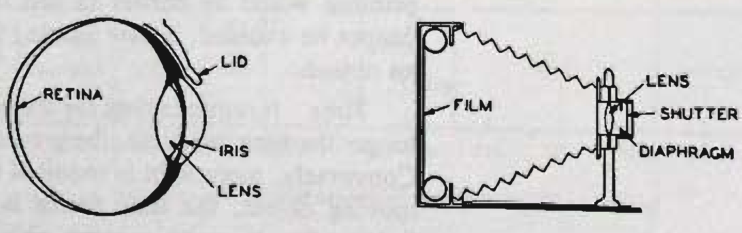
3.1 FACTORS INVOLVED IN SEEING

The study of lighting must begin with a brief discussion of the eye and the seeing process, since the purpose of lighting is to make vision possible. Vision, the sense of sight, perceives the form, size, color, distance, and movement of objects. The eye is a marvelous organ with the ability to react efficiently to a wide variety of conditions. A simple comparison between the eye and a camera is shown in Figure 3.1(a). The characteristics that enable the eye to perform are discussed next.

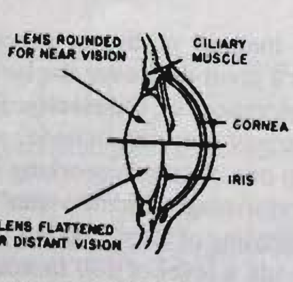
Accommodation This process enables the eye to focus on an object regardless of the distance. It does this by adjusting the curvature of the lens with the ciliary muscles. For focusing on near objects, the lens must be rounded by the contraction of the muscles; conversely, when focusing on distant objects, the lens must be flattened, as shown in Figure 3.1(b).

Adaptation This process enables the eye to adjust to a wide range of lighting levels, on the order of 1 million to 1. In very dim light the pupil opens wide, while in very bright light the pupil contracts to a much smaller size. Adaptation also involves photochemical changes in the retina. As we all have experienced, the process of adaptation takes time, particularly when going from a bright area to a dark area. The lighting designer must always take this into consideration when lighting adjacent areas.

Spectral luminous response The eye creates the sensation of color by responding to the different wavelengths of light. Unfortunately, the eye is not equally sensitive to the energy of all wavelengths. For the normal eye, the greatest response is in the center of the visible spectrum, which is the yellow-green region, while the least response is at the extremities of the visible spectrum, the red and blue regions. Thus red or blue objects must be lighted to a higher



(a) Comparison between the eye and the camera



(b) Focusing of the eye

FIGURE 3.1

The human eye

level than yellow or green in order for the eye to respond to them equally.

Since the eyes must continually adjust to the conditions imposed on them, eye fatigue will result if they must do this too often and too quickly. Therefore, poor quality or insufficient quantity of light can seriously affect a person's ability to perform efficiently.

External to the eye are additional factors that affect the seeing process.

Size of object One concept easily accepted is that the larger the object the more easily it can be seen. Visual acuity is a measure of the smallest detail that can easily be seen. It is a function of the visual angle, that is, the angle subtended at the eye by the object. By bringing a small object closer to the eye, a person is increasing the visual angle in order to see it more clearly. Increasing lighting levels will markedly increase visual acuity.

Brightness of object This depends both on the amount of light striking an object and the proportion of the light that is reflected from it in the direction of the eye. Naturally, a dark-colored object reflects less light and is harder to see than a light-colored object with the same lighting levels. Therefore, a dark object requires more lighting for it to be seen as clearly as a light object.

Contrast Equally important in clearly seeing an object is the contrast between it and its immediate background. As an example, the print on this page is dark lettering against a near white background. If the same printing were on dark gray paper, then the printing would be harder to see. Where poor contrast conditions cannot be avoided, higher lighting levels are required to clearly see an object.

Time It requires time for the eye to properly see an object. The longer the time available, the greater the detail that the eye can see. Conversely, more light is required for rapid seeing. In the case of a moving object, the time factor is particularly important. Higher lighting levels make moving objects appear to be moving more slowly.

Our manner of living, especially in the Western World, has changed a great deal over the last 100 years, due in no small part to the development of the electric light source. It has changed from a life of largely working outside, with activities confined to daylight hours, to one of largely working indoors under artificial lighting and often performing difficult visual tasks. Direct sunlight provides a level of lighting of from 5,000 to 10,000 footcandles. An overcast day can provide a level of 500 footcandles. Therefore, the present recommendation of an average of 75 footcandles for office lighting is not that high by comparison.

3.2 LIGHT AND COLOR

In the most basic terms, light is that portion of the electromagnetic spectrum to which the eye responds. This visible energy is an exceedingly small part of the total spectrum, which ranges from cosmic rays with extremely short wavelengths (1×10^{-14} meter) to electric power frequencies with wavelengths in hundreds of kilometers, as shown in Figure 3.2. The visible portion lies between 380 and 770 nanometers (the nanometer, nm, is a unit of wavelength equal to 1×10^{-9} meter or one-billionth of a meter).

The color of light is determined by its wavelength. Visible energy with the shortest wavelengths (380 to 450 nm) produce the sensation of violet and those with the longest wavelengths (630 to 770 nm) produce the sensation of red. In between lie blue (450 to 490 nm), green (490 to 560 nm), yellow (560 to 590 nm), and orange (590 to 630 nm). The region with slightly longer wavelengths immediately adjacent to the red end of the visible spectrum is known as the *infrared*, and the region with slightly shorter wavelengths immediately adjacent to the violet end of the visible spectrum is the *ultravi-*

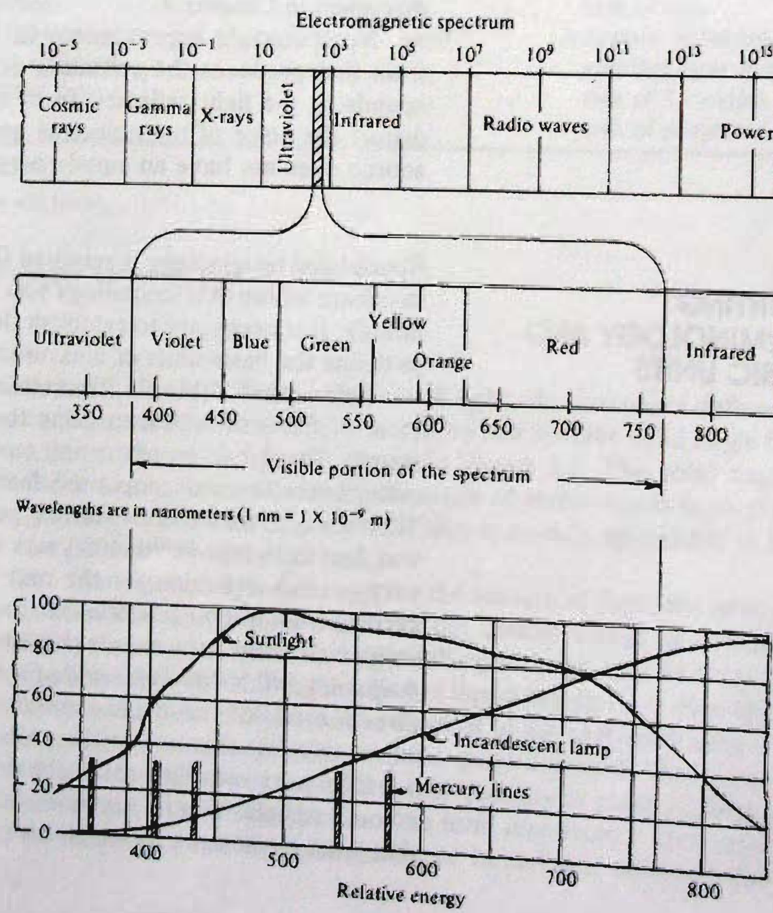


FIGURE 3.2

Electromagnetic spectrum

olet. Neither of these is visible to the human eye; but their effect on humans is very important, and neither can be ignored in lighting applications. For instance, the incandescent light bulb produces a large percentage of infrared energy, which can be very uncomfortable to anyone exposed to it continuously for even a few hours. Conversely, the mercury vapor lamp can produce ultraviolet energy, some of which can be beneficial, but the balance of which can be very harmful.

Light sources can have continuous spectrums; that is, they produce some energy in all wavelengths across the visible spectrum. Or they can have line or band spectrums, in which case energy is produced in only a few separate groups of wavelengths. Also, most light sources do not have equal-energy spectrums, that is, equal quantities of energy in all wavelengths. Refer to Figure 3.2. The incandescent lamp has a continuous spectrum, but it is high at the red end and low at the blue end. The mercury vapor lamp has a line spectrum with its output concentrated in a few specific areas mainly at the blue end of the spectrum. These and other light sources are fully discussed in Chapter 4.

Noon sunlight approximates an equal-energy continuous spectrum that produces the sensation of white light. Since the eye responds to the light reflected from an object, the light source can distort the color of the object as perceived by the eye if the light source does not have an equal-energy continuous spectrum.

3.3 LIGHTING TERMINOLOGY AND BASIC UNITS

Specialized terminology is required for any technology, and to communicate within that technology you must be familiar with the terminology. It is necessary to establish the meaning of all new terms and to define the basic units of measurement. This is done in Table 3.1.

Referring to Table 3.1, the starting point has to be the establishment of the means of measuring the light output or intensity of a source. The definition of the unit *candela* as shown is only approximate, because most people are familiar with the ordinary candle. This was also the obvious starting point when the electric light bulb was first introduced over 100 years ago. However, there must be a very precise definition for the unit candela, as all other units are derived from it. *One candela is defined as the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 × 10^{12} hertz and of which the radiant intensity in that direction is 1/683 watt per steradian*. Now you can see why it is easier to relate this unit to the ordinary candle.

The next criterion to establish is a means of measuring the amount of light (that is, luminous flux). Since light is not something that you can measure by weight or volume, another approach has to

TABLE 3.1 Lighting Terminology and Basic Units

Quantity	Quantity Is a Measure of	Symbol	Unit SI	Unit English	Definition of Unit
Luminous intensity (candlepower)	Ability of source to produce light in a given direction	I	Candela (cd)		Approximately equal to the luminous intensity produced by a standard candle
Luminous flux	Total amount of light	ϕ	Lumen (lm)		Luminous flux emitted in a solid angle of 1 steradian by a 1 candela uniform point source
Illuminance (illumination)	Amount of light received on a unit area of surface (density)	E	Lux (lx)	Footcandle (fc)	One lumen equally distributed over one unit area of surface
Luminous exitance	Density of light reflected or transmitted from a surface	M	lm/m^2	lm/ft^2[a]	A surface reflecting or emitting 1 lumen per unit of area
Luminance (brightness)	Intensity of light per unit of area reflected or transmitted from a surface	L	cd/m^2	cd/in.^{2}	A surface reflecting or emitting light at the rate of 1 candela per unit of projected area

1 meter (m) = 3.28 ft; 1 cd/m^2 = 3.14 lm/m^2

1 m^2 = (3.28)^2 = 10.76 ft^2; 1 cd/in.^{2} = 452 lm/ft^2

1 fc = 10.76 lx

[a] Formerly "footlambert," which is no longer a preferred term.

be used. The unit for the amount of light, the *lumen*, is defined by equating it to the luminous flux emitted in a specific solid angle from a point source of light, as shown in Figure 3.3. The solid angle is defined as one *steradian* since the angle of projection in both planes is 1 radian. Fortunately, this definition is equally applicable in both the SI and English systems.

Having established the unit for the amount of light, the next step is to establish a measurement for the concentration or density of light, that is, the amount of light falling on each unit of area. This could be likened to having 1 gallon of liquid in a can and then spilling the liquid all over the floor. The amount of liquid in each case is the same, but its concentration may be quite different. Since the eye responds to the density of light, this quantity is most important in the design of a lighting system. The term *illuminance* then refers to the lighting levels that should be or have been obtained for the

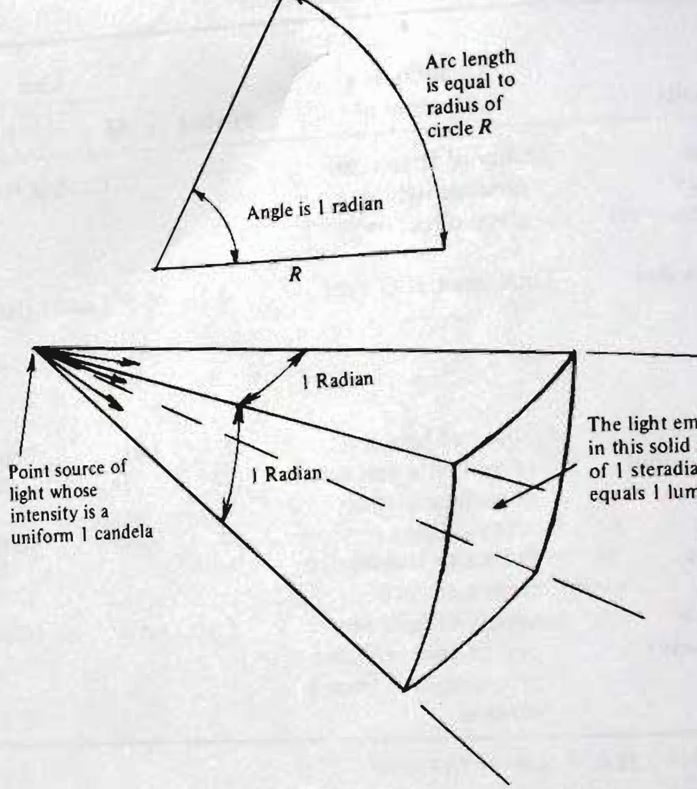


FIGURE 3.3

Definition of the unit lumen

lighting of a particular area. (The term illuminance, which is a more precise term, has replaced the more familiar term *illumination*.)

Unfortunately, since the unit of area depends on the system of measurement, there is a difference between the unit of illuminance for the SI system and that for the English system, as noted in the table. To indicate the same level of illuminance, the numerical value of *lux* (SI) is approximately 10 times the numerical value of *footcandles* (English). As an example, 1000 lux very closely equals 100 footcandles (see Example 3.1).

In Section 3.1, reference was made to the levels of lighting provided by sunlight and to the levels recommended for office lighting. The unit used was the footcandle, because the important criterion to compare is the amount of light per unit of area, and not just the total amount of light.

The final quantity to establish is a measure of the amount of light reflected from or transmitted through a surface, as shown in Figure 3.4. The density of light that leaves the surface is referred to as *luminous exitance* and is also expressed in lumens per unit of area. Since some of the light energy is normally absorbed by the surface material as it is reflected or transmitted, the luminous exitance is

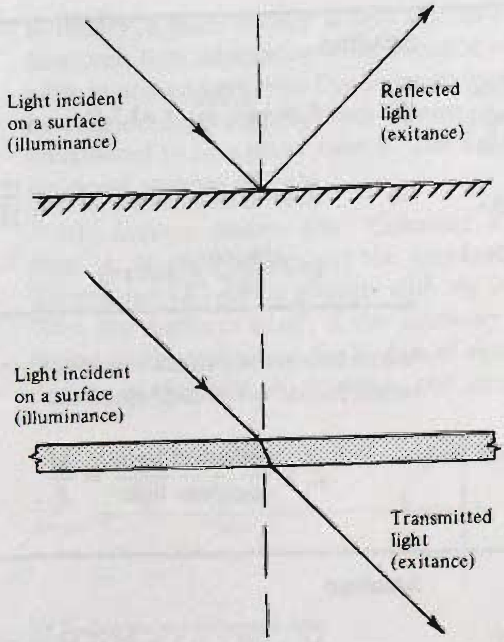


FIGURE 3.4

Reflected and transmitted light

less than the incident light, that is, the light that is received on the surface. The reflectance and transmittance factors, which indicate the ratio of light that is reflected or transmitted, are defined in Section 3.4. In the English system, the unit for luminous exitance was formerly called a footlambert, rather than lumen per square foot, in order to differentiate it from the footcandle, which is also given in lumens per square foot.

The luminous exitance is a measure of the brightness of an object, and it is brightness to which the eye responds. This brightness can also be expressed in a second way: the reflected or transmitted light can be considered as a new source of light, with the unit of measurement expressed as the intensity of light per unit of area. This quantity is then referred to as *luminance*, and it is particularly useful in expressing the brightness of a light source that transmits light energy through a diffusing glass envelope, such as an inside-frosted incandescent lamp.

3.4 RELATIONSHIPS OF QUANTITIES

From the definition of illuminance (E) as shown in Table 3.1, the relationship between E, the total amount of light (luminous flux, ϕ), and the area over which the light is to be spread (A) can be expressed as:

$$E = \frac{\phi}{A} \tag{3.1}$$

■ EXAMPLE 3.1

In a room 12 by 20 ft, the total light incident on the horizontal workplane is 10,000 lm. Calculate the illuminance on the workplane in (a) English units and (b) SI units.

Solution

(a) $$E = \frac{10{,}000}{12 \times 20} = 41.7 \text{ fc}$$

(b) $$\text{Area of room in metric} = \frac{12 \times 20}{3.28 \times 3.28} = 22.3 \text{ m}^2$$

$$E = \frac{10{,}000}{22.3} = 448.4 \text{ lx}$$

When luminous exitance is concerned with reflected light, the reflectance factor (ρ) is expressed as:

$$\rho = \frac{\text{reflected light}}{\text{incident light}} = \frac{M}{E} \tag{3.2}$$

■ EXAMPLE 3.2

A sheet of paper has a reflectance factor of 70%. It is illuminated to 50 fc. Calculate the luminous exitance of the surface of the paper.

Solution

$$M = \rho E = 0.7 \times 50 = 35 \text{ lm/ft}^2 \quad \text{(footlamberts)}$$

When luminous exitance is concerned with transmitted light, the transmittance factor (τ) is expressed as:

$$\tau = \frac{\text{transmitted light}}{\text{incident light}} = \frac{M}{E} \tag{3.3}$$

■ EXAMPLE 3.3

A piece of white diffusing glass has a transmittance factor of 50%. The surface nearest to the light source is illuminated to 30 fc. Calculate the luminous exitance on the far side of the glass.

Solution

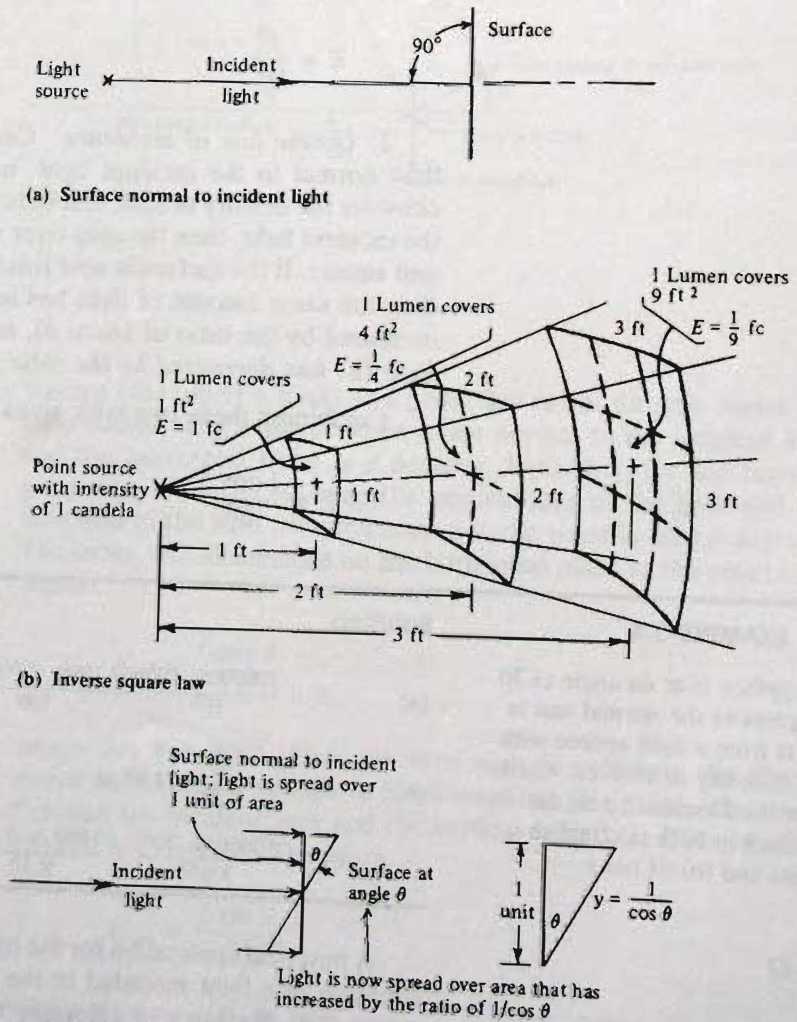
$$M = \tau E = 0.5 \times 30 = 15 \text{ lm/ft}^2 \quad \text{(footlamberts)}$$

Both the reflectance and the transmittance factors result in a relationship expressed as M/E, but it must be remembered that the first is concerned with reflected light from a surface and the second is concerned with light transmitted through a surface (see Figure 3.4).

3.5 LAWS FOR POINT SOURCES OF LIGHT

In theory, a point source of light should have zero area. In practice, however, light emanating from a source whose dimensions are negligible in comparison with the distance from which it is observed may be considered as coming from a point. A clear incandescent lamp is considered to be a point source. The following are the laws governing point sources of light.

1. *Inverse square law* Consider a surface that is normal to (that is, at right angles to) the incident light as in Figure 3.5(a). Illuminance (E) *varies directly with the intensity of the light source*. With the distance fixed, if the intensity is doubled, then the light falling on the surface is doubled, and since the area is the same, the density of the light (E) doubles, and so on. Illuminance also *varies*



(a) Surface normal to incident light

(b) Inverse square law

(c) Cosine law of incidence

FIGURE 3.5

Laws for point sources of light

inversely with the square of the distance from the light source. Refer to Figure 3.5(b). From the definition of luminous flux (ϕ), the amount of light falling on a surface 1 foot away from a point source of light having 1 candela of intensity is 1 lumen. If we now consider a surface 2 feet away from the source, the same amount of light falls on a surface that is 2 feet on each side, or 4 square feet, because of the diverging light rays. Therefore, the density of light (E) is only $(1/2)^2$ or one-quarter as much as for the 1 foot distance. Similarly, for a distance of 3 feet, the same amount of light would fall on an area of 9 square feet, and the density of light is only one-ninth as much. Thus, there is a relationship that varies inversely as the square of the distance. This applies equally if the distance is considered in meters. Combining the previous two statements yields:

$$E = \frac{I}{D^2} \tag{3.4}$$

2. *Cosine law of incidence* Consider a surface that is other than normal to the incident light, as in Figure 3.5(c). If we first consider the density of light that falls on the surface when normal to the incident light, then the area over which the light is spread is one unit square. If the surface is now rotated an angle θ from the normal, then the same amount of light has to spread over an area that has increased by the ratio of $1/(\cos\theta)$, and therefore the *density of the light* (E) *has decreased by the ratio of* $\cos\theta$.

Combining these two laws gives the following relationship:

$$E = \frac{I\cos\theta}{D^2} \tag{3.5}$$

■ EXAMPLE 3.4

A surface is at an angle of 30 degrees to the normal and is 10 ft from a light source with an intensity of 1000 cd. Calculate the illuminance on the surface in both (a) English units and (b) SI units.

Solution

(a) $$E = \frac{1000(\cos 30°)}{10^2} = \frac{1000 \times 0.866}{100} = 8.66 \text{ fc}$$

(b) $$10 \text{ ft} = \frac{10}{3.28} = 3.05 \text{ m}$$

$$E = \frac{1000(\cos 30°)}{3.05^2} = \frac{1000 \times 0.866}{9.30} = 93.1 \text{ lx}$$

A practical application for the previous laws is the very common situation of a light mounted in the ceiling of a room, as shown in Figure 3.6. We wish to calculate the illuminance on a horizontal

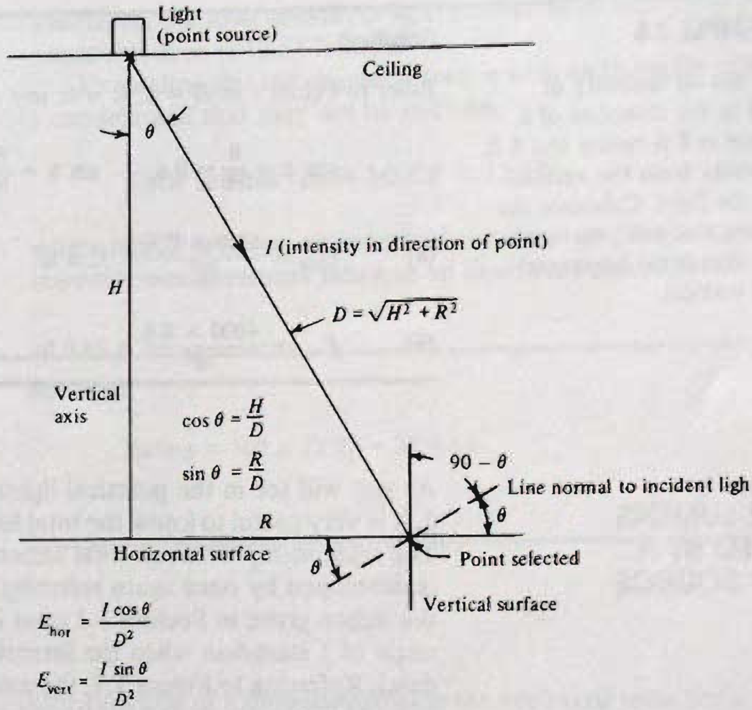


FIGURE 3.6

Calculation of horizontal and vertical illuminance

surface (the top of a desk) at a point that is not directly under the light source. The angle between a line normal to the incident light and the horizontal plane is θ degrees. Note that, by the laws of geometry, the angle between the vertical axis of the light and the direction of the light from the source to the point is also θ degrees. Therefore, the illuminance on the horizontal plane at the point chosen is:

$$E_{hor} = \frac{I \cos \theta}{D^2} \tag{3.6}$$

where $\cos \theta = H/D$. Also, we may wish to calculate the illuminance on a vertical surface (a blackboard) at this point. The angle between the incident light and the vertical surface is $(90 - \theta)$. But $\cos (90 - \theta)$ is $\sin \theta$. Therefore:

$$E_{vert} = \frac{I \sin \theta}{D^2} \tag{3.7}$$

where $\sin \theta = R/D$. In both cases, $D = \sqrt{H^2 + R^2}$.

■ **EXAMPLE 3.5**

A light has an intensity of 4000 cd in the direction of a point that is 8 ft below and 6 ft horizontally from the vertical axis of the light. Calculate the illuminance at this point on a surface that is (a) horizontal and (b) vertical.

Solution

Refer to Figure 3.6: $H = 8$; $R = 6$; and $D = \sqrt{8^2 + 6^2} = 10$ ft

$$\cos\theta = \frac{8}{10} = 0.8; \qquad \sin\theta = \frac{6}{10} = 0.6$$

(a) $$E_{hor} = \frac{4000 \times 0.8}{10^2} = 32.0 \text{ fc}$$

(b) $$E_{vert} = \frac{4000 \times 0.6}{10^2} = 24.0 \text{ fc}$$

3.6 TOTAL LUMENS EMITTED BY A LIGHT SOURCE

As you will see in the practical lighting layout problems in Chapter 5, it is very useful to know the total lumens emitted by a light source. The relationship between total lumens and the intensity of a source is developed by once again referring to the definition of the unit of the lumen given in Section 3.3 (that is, the light emitted in the solid angle of 1 steradian when the intensity of the light source is 1 candela). Referring to Figure 3.7, the amount of light on the one square unit of area on the surface of the sphere is then 1 lumen. The surface area of a sphere is:

$$\begin{aligned} \text{Area} &= 4\pi R^2 \\ &= 4\pi, \quad \text{when } R \text{ is one unit} \\ &= 12.57 \end{aligned}$$

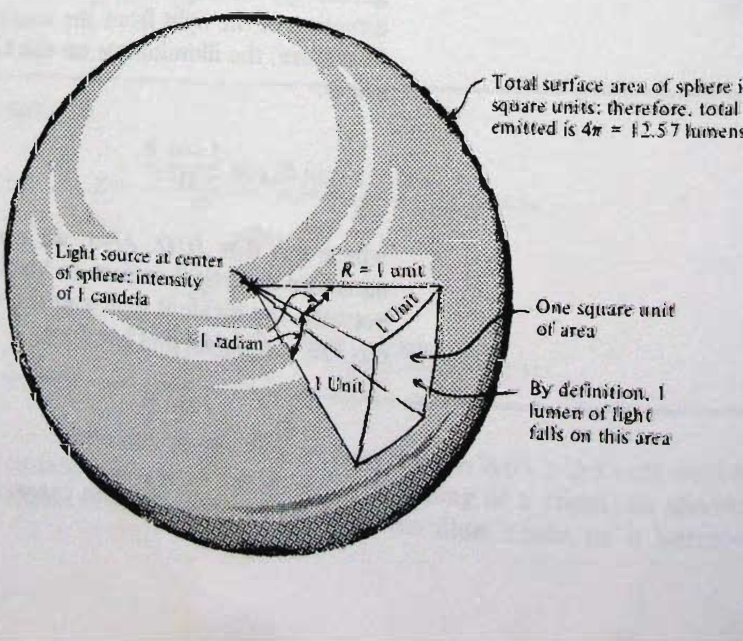


FIGURE 3.7

Total lumens emitted by a light source

Therefore, the total amount of light emitted in all directions from a 1 candela source is 12.57 lumens.

Expanding this to consider a source with an intensity other than 1 candela and that may not be uniform:

$$\text{Total lumens } (\phi) = \text{MSCP} \times 12.57 \tag{3.8}$$

where MSCP is the *mean spherical candlepower* (the mean of many intensity measurements taken in all directions from the source).

■ EXAMPLE 3.6

A light source has a mean intensity of 300 cd. Calculate the rating of the source in lumens.

Solution

$$\text{Rating} = 300 \times 12.57 = 3770 \text{ lm}$$

3.7 INTENSITY DISTRIBUTION CURVES

One function of a *luminaire* (this is the preferred term for a lighting fixture) is to project the light produced by the source in a particular pattern. As an example, a luminaire using an incandescent lamp that is flush mounted in a ceiling may have a reflector mounted above the bulb so that as much light as possible is directed downward toward the work area below. However, the beam pattern may be concentrated as shown in Figure 3.8(a), or it may be wide, as shown in Figure 3.8(b). When selecting a luminaire for a lighting system, it is important to know its distribution pattern.

As part of catalogue information, a manufacturer will provide an *intensity distribution curve* for each luminaire. This curve shows the intensity at every angle around the complete 360 degrees, usually in the vertical plane through the axis of the luminaire. However, instead of plotting these values on the standard rectangular graph, they are plotted on a graph using polar coordinates; that is, the angles are arranged in a circle, starting with zero degrees at the bottom representing the center axis of the luminaire, and the values of the intensity at each angle are scaled using concentric circles around the zero point at the center. Figure 3.9 is an example of an intensity distribution curve. This curve represents a luminaire that projects some light upward from the luminaire, very little from the sides, and the majority downward. Since there is an upward component of light, this luminaire would be suspended from the ceiling.

The advantage of using the polar coordinate form of graph is that the pattern of light output from the luminaire is immediately

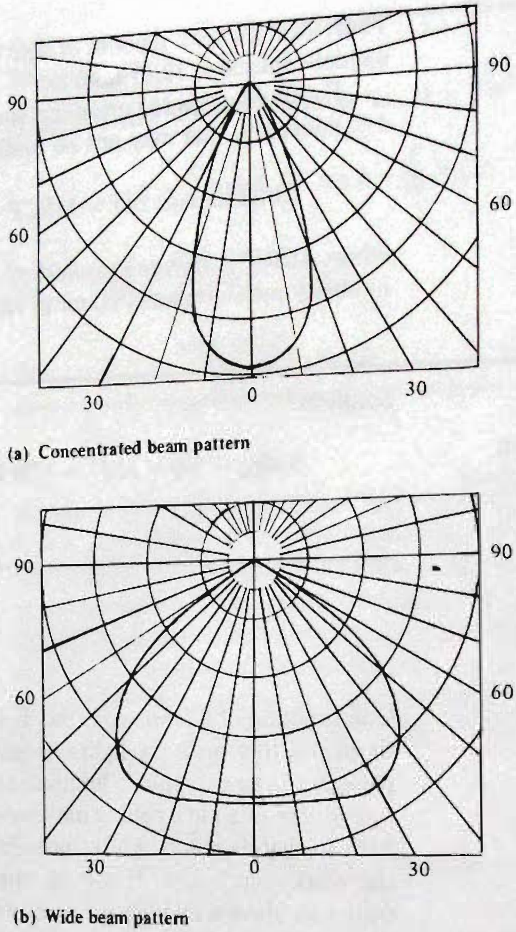


FIGURE 3.8

Comparison of beam patterns for luminaires

apparent. Figure 3.9 also shows an example of a specific value of intensity; for example, at an angle of 21 degrees, the intensity of the projected light is 1400 candelas.

Only one curve is required for a luminaire with a symmetrical distribution pattern, that is, a luminaire with the same pattern in all planes around the vertical axis. A luminaire with a point source of light such as the incandescent lamp would be an example. However, luminaires using the long fluorescent lamp cannot have a symmetrical distribution pattern. It is therefore necessary for the graph to show at least three distribution patterns, one for a plane normal to the lamps, the second for a plane parallel to the lamps, and the third for a plane at 45 degrees to the lamps.

Luminaires are classified on the basis of their distribution patterns, that is, on the relative amount of light projected upward and/or downward from the luminaire. These classifications are discussed in detail in Section 5.4.

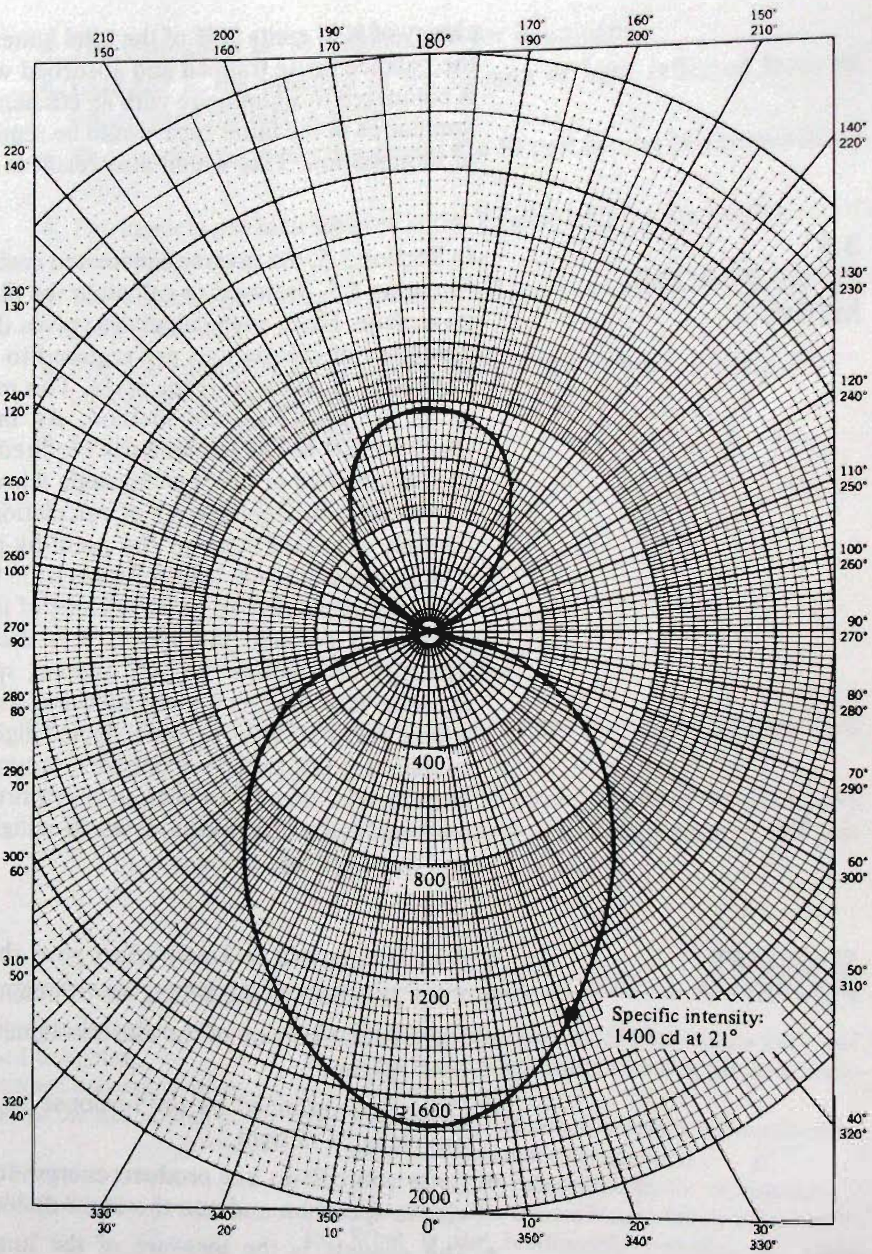


FIGURE 3.9

Example of an intensity distribution curve

Finally, from the intensity distribution curves, the manufacturer can determine the efficiency of a luminaire, which is a very important measure of its performance. The efficiency indicates the proportion of the total lumens emitted by the luminaire as compared to the total lumens produced by the lamps. Thus a luminaire with an efficiency of 90% emits 90% of the total lumens produced by the lamps, the balance being trapped and absorbed within the luminaire. If this is compared to a luminaire with an efficiency of only 60%, then more luminaires of the latter type would be required to give the same level of illumination. This would also result in higher energy costs.

3.8 POINT-BY-POINT METHOD

In Section 3.5, the inverse square and cosine laws, as represented by Equation 3.5, are used to calculate the illuminance at a single point on a plane. Since each calculation gives the value at only one point, a number of calculations are required to determine the illuminance at a series of points over the plane. This method is therefore referred to as the point-by-point method. An intensity distribution curve (Section 3.7) of the luminaire is required to obtain the intensity of the light source at the specific angle θ involved in each calculation.

Besides the multiplicity of calculations required, there are two inherent disadvantages to the point-by-point method; it does not take into account any light reflected from the surfaces of a room, and it is only applicable to point sources of light. Therefore, the lumen method as covered in Chapter 5 is the preferred way to handle lighting calculations for an indoor space. The point-by-point method, however, is widely used for outdoor lighting calculations where there is little or no reflected light and the light source is usually a point source. Computer programs are available for performing the many calculations required by the point-by-point method for such applications as streetlighting, sports field lighting, and floodlighting.

SUMMARY

- Poor lighting can seriously affect your ability to perform efficiently.
- Your response to the seeing environment is very individual.
- Light is that portion of the electromagnetic spectrum to which your eyes respond.
- Color is determined by the response of your eyes to the different wavelengths of light.
- Light sources do not produce energy equally in all regions of the visible spectrum and can therefore distort your response to color.
- The candela is the measure of the luminous intensity of a light source.
- The lumen is the measure of the luminous flux (light).
- Illuminance is the measure of the density of light falling on a surface. It represents the level of illumination.
- The lux is the SI unit for illuminance.

- The footcandle is the English unit for illuminance.
- Exitance is the measure of the density of light reflected from or transmitted through a surface.
- The candela per meter squared is the SI unit for the brightness of an object.
- The candela per inch squared is the English unit for the brightness of an object.
- The reflectance factor is the ratio of the amount of light reflected from a surface.
- The transmittance factor is the ratio of the amount of light transmitted through a surface.
- For a point source of light:

$$E = \frac{I \cos \theta}{D^2}$$

- Light emitted by a source:

$$\text{Total lumens} = \text{MSCP} \times 12.57$$

- The intensity distribution curve displays the pattern of light emitted from a luminaire.
- The point-by-point method using the inverse square and cosine laws is suitable for outdoor lighting calculations for point sources of light.

QUESTIONS

1. Explain the difference between the terms quantity and quality with regard to lighting.
2. Explain the difference between accommodation and adaptation with regard to the functioning of the eye.
3. What four factors affect the seeing process?
4. How does the eye respond to color?
5. What is light?
6. What is infrared energy?
7. What is ultraviolet energy?
8. What is the lighting quantity associated with the ability of the source to produce light in a given direction?
9. Why is the unit lumen the same in both the English and SI systems of measurement?
10. What does the quantity of illuminance indicate?
11. What is the relationship between the units footcandle and lux?
12. Explain the difference between luminous exitance and luminance (brightness).
13. What does the reflectance factor represent?
14. What does the transmittance factor represent?
15. What is the relationship between the mean spherical candlepower and the total lumens emitted by a light source?
16. What is an intensity distribution curve?
17. What does the efficiency of a luminaire indicate?
18. Why is the point-by-point method suitable for the calculations for outdoor lighting?

PROBLEMS

1. A room is 10 m by 16 m and there is a total of 120,000 lm falling on the workplane. Calculate the average illuminance in SI units.
2. A room is 15 ft by 30 ft and has an average illuminance of 50 fc at the workplane. Calculate the total lumens falling on the workplane.
3. The luminous exitance from a surface with a reflectance factor of 80% is 100 lm/ft^2. Calculate the illuminance of the surface.
4. A piece of white diffusing glass has a transmittance factor of 75%. The side opposite the light source has a luminous exitance of 30 lm/ft^2. Calculate the footcandles measured on the side nearest the light source.
5. A surface is at an angle of 20° to the normal and is 6 ft from a light source with an intensity of 3000 cd. Calculate the illuminance on the surface in both (a) English and (b) SI units.
6. The illuminance of a surface normal to and 5 m away from a light source is 360 lx. Calculate the illuminance of the surface if the light source is moved 5 m farther away.
7. An opaque surface has a reflectance factor of 80%. The surface is normal to the light source, which has an intensity of 8000 cd and is 8 ft away. Calculate the luminous exitance of the surface.
8. A light has an intensity of 10,000 cd in the direction of a point that is 12 ft below and 8 ft horizontally from the vertical axis of the light. Calculate the illuminance at this point on a surface that is (a) horizontal and (b) vertical.
9. The illuminance on the horizontal plane at a point 10 ft below and 5 ft from the vertical axis of a light is 10 fc. Calculate the intensity of the light source in the direction of the point.
10. A 500 W lamp is rated at 10,000 lm. Determine the mean spherical candlepower of the lamp.

4 Light Sources

OBJECTIVES

After studying this chapter, you will be able to:

- Recognize the different types of light sources.
- Explain how each type functions.
- Identify the characteristics and ratings of each type.
- Identify the advantages of each type.
- Identify the disadvantages of each type.
- List the general applications for each type.

INTRODUCTION

The primary purpose of the electric light source is to convert electrical energy into light energy. The measure of how well the source performs this function is its *luminous efficacy* expressed in *lumens emitted per watt of power consumed.* If the energy in a light source could be converted without loss into yellow-green light, the efficacy of the source would be 683 lumens per watt. The theoretical maximum efficacy of a practical source that produces some light across all sections of the visible spectrum would be less than 683 lumens per watt.

No light source presently being manufactured comes close to its theoretical maximum efficacy. As an introduction to light sources, the following list gives the approximate efficacies of some of the light sources:

Type	Lumens/watt
Original incandescent lamp (1879)	1.4
200 Watt incandescent lamp (1981)	20
400 Watt mercury lamp	50[a]
40 Watt fluorescent lamp	70[a]
400 Watt metal halide lamp	75[a]
400 Watt high-pressure sodium lamp	110[a]

[a] Assuming an average ballast loss.

The first thing to notice is the tremendous improvement that has been made in the performance of the incandescent lamp since its inception. However, with all this improvement, it is still less than 10% efficient. Even the most efficient source, the high-pressure sodium lamp, converts only some 35% of the input energy to light, the rest of the energy being given off as ultraviolet or infrared (heat energy).

The following is a list of the various types of sources with regard to method of operation:

—Incandescent (passage of an electric current through a filament)
—Electric discharge (passage of an electric current through a vapor)
    Low intensity: (1) fluorescent (mercury vapor) and (2) sodium vapor
    High intensity: (1) mercury vapor, (2) metal halide (multivapor), and (3) sodium vapor

As with any technology, continuous research is being carried on to improve existing light sources and to develop new ones. In the last 10 years, many new lighting products have been brought to market. However, since the purpose of this text is to introduce you to lighting, the scope of the discussions in this chapter is limited primarily to those sources that, by their usage up to the present, have been accepted as standards in the industry. Only brief mention can be made of new developments.

4.1 INCANDESCENT LAMPS

The *incandescent lamp* produces light *by the passage of an electric current through a filament, which heats it to incandescence,* that is, to the point where some of the energy is emitted in the visible region. However, the percentage of input energy emitted as light is relatively low, and the majority of the energy is emitted as heat. In spite of this major disadvantage, the incandescent lamp is still widely used because of inherent advantages, which will be discussed later.

4.1.1 Principal Parts of the Incandescent Lamp

The construction of a general-purpose incandescent lamp is shown in Figure 4.1. The bulb, the base, and the filament are described next.

Bulb. The enclosed glass envelope that seals in the filament is the bulb. The filament, once it reaches incandescence, would rapidly oxidize if it were not sealed in either a vacuum or an atmosphere of inert gas. The various shapes that the bulb can have are shown in

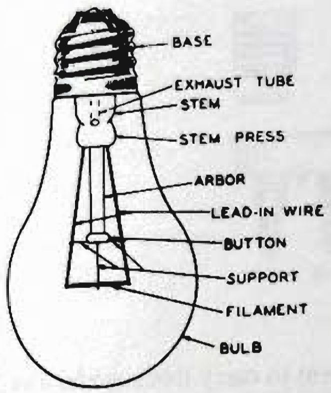


FIGURE 4.1

General-purpose incandescent lamp

Figure 4.2. Some shapes are for practical reasons, such as the R type, which is shaped like a parabola in order to beam the light; others are for decorative purposes, such as the F type. The overall diameter of the bulb is designated by a number given in eighths of an inch. Thus the designation *R40* indicates the R shape with a diameter of 40/8 or 5 inches.

Lamps with clear glass bulbs are used when a point source of light is required for good optical control. However, these types of lamps are extremely bright and require good shielding if they are not to be annoying. For most applications, lamps with the bulb treated to diffuse the light are used. This considerably reduces the brightness. The inside surface of the bulb is either etched with acid (inside frosted) or coated with white silica. Bulbs can also be treated to produce colored lamps for decorative lighting.

Bases. The base provides both the means of making the electrical connections to the filament and the means of supporting the lamp in the socket. The different types used are shown in Figure 4.3. The two most common types for general-purpose lighting are the *medium* base, used on lamps up to 300 watts, and the *mogul* base, used on lamps 300 watts and over.

Filament. The filament is the most critical part of the lamp and must be designed to give the maximum light output at its rated voltage and wattage, and yet still provide a satisfactory life (that is, hours to burn-out). Tungsten, which has the properties of high melting point and low rate of evaporation, is used almost exclusively to make the filaments. The majority of lamps have coiled filaments so that the heat can be concentrated in a smaller space. The larger lamps have double-coiled filaments to increase efficiency and reduce their size.

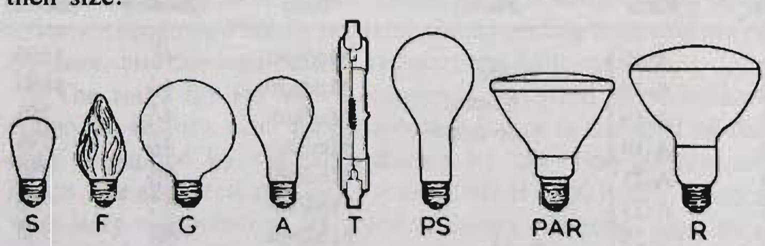


FIGURE 4.2

Bulb shapes for incandescent lamps

4.1.2 Efficacy of Lamps versus Wattage and Voltage

The rated wattage of a lamp is equal to its rated voltage times the current that flows through the filament. For lamps designed to operate on a specific voltage (for example, rated for 120 volts), the higher the wattage rating is the higher the current drawn by the lamp. This

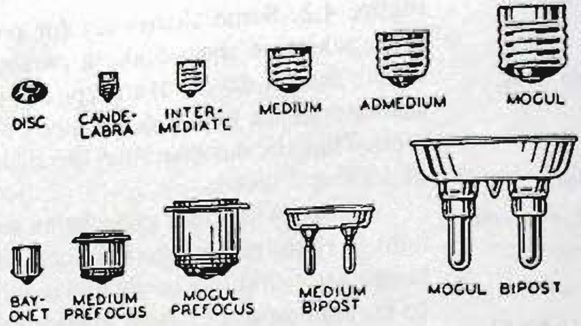


FIGURE 4.3

Bases for incandescent lamps

in turn requires a larger-diameter filament to carry this current. The heavier filament can be operated at a higher temperature without having excessive evaporation, thus maintaining its rated life. This higher temperature results in a greater portion of the energy being emitted as light and less as heat, and therefore the efficacy of the lamp increases. Refer to Table 4.1 and note that the values in the column headed *lumens per watt* increase as the rated wattage increases. This is important to remember when designing a lighting layout using incandescent lamps. The wattage of the lamps selected should be as high as possible, consistent with satisfying all other design criteria. Refer to Example 5.12.

Next consider lamps that have the same rated wattage but are

TABLE 4.1 General-Service Incandescent Lamps for 120 Volts

Watts	Bulb	Finish	Base	Length (inches)	Rated Life (hours)	Initial Lumens	Lumens per Watt	LLD[a] (%)
40	A-19	Inside frosted or white	Medium	$4\frac{1}{4}$	1500	455	11.4	87.5
60	A-19		Medium	$4\frac{7}{16}$	1000	860	14.3	93
75	A-19		Medium	$4\frac{7}{16}$	750	1,180	15.7	92
100	A-19		Medium	$4\frac{7}{16}$	750	1,740	17.4	90.5
150	A-23	Inside frosted or clear	Medium	$6\frac{3}{16}$	750	2,780	18.5	89
200	A-23		Medium	$6\frac{5}{16}$	750	4,000	20.0	89.5
300	PS-25		Medium	$6\frac{15}{16}$	750	6,360	21.2	87.5
300	PS-30		Mogul	$8\frac{5}{8}$	1000	5,960	19.8	89
500	PS-35		Mogul	$9\frac{3}{8}$	1000	10,600	21.2	89
750	PS-52		Mogul	$13\frac{1}{16}$	1000	17,000	22.6	89
1000	PS-52		Mogul	$13\frac{1}{16}$	1000	23,600	23.6	89
1500	PS-52		Mogul	$13\frac{1}{16}$	1000	34,000	22.6	78

[a] Lamp lumen depreciation: percent of initial light output at 70% of rated life.

This table is only a partial listing of general-service lamps. Refer to the *IES Lighting Handbook*, 1984 Reference Volume, for a complete listing.

designed to operate on different voltages. As the rated voltage of the lamp decreases, the current drawn by the lamp increases, since the wattage is the same. This again requires a larger-diameter filament, allowing the lamp to operate with increased efficacy. To take advantage of this increase in efficacy, a line of 6 and 12 volt reflectorized lamps has been developed that incorporate their own step-down transformers to allow operation from the standard 120 volt circuit.

The converse of the foregoing, however, means that the higher the rated voltage of an incandescent lamp is the lower its efficacy. This then becomes a disadvantage for the use of incandescent lamps for general lighting in buildings. To keep the sizes of feeders within the building to a minimum, the system voltages should be as high as possible (for example, many large buildings have 480Y/277 volt systems). This is incompatible with the incandescent lamp. The highest rating for general-service lamps is 230 volts, but 120 volt lamps are normally selected as a compromise because of the higher efficacy. The electric discharge type of light sources can easily be designed to operate from the higher system voltages and therefore do not have this disadvantage.

4.1.3 Rated Life of Incandescent Lamps

As previously discussed, the light output of an incandescent lamp can be increased by raising the operating temperature of the filament. However, this higher temperature results in an increased rate of evaporation of the tungsten, which shortens the life of the lamp. The normal end of life is reached when the filament wire breaks or burns through at its thinnest point. Thus the light output and the life of a lamp are very interdependent. For a specific wattage and voltage rating, a lamp can be designed for a higher light output, but only at the expense of its rated life. Conversely, a lamp can be designed to have a long rated life by reducing the operating temperature of the filament, but this significantly reduces the light output.

The rated life for which a lamp is designed must balance all economic factors. One very important factor is the cost of the energy consumed by the lamp during its life. For general-service lamps, the accepted standard for rated life is 1000 hours. Thus a 100 watt lamp will consume 100 kilowatt-hours of energy over its rated life, which, at a cost of $0.05 per kilowatt-hour, amounts to $5.00. The cost of the lamp is only approximately 15% of that amount. To increase life at the expense of light output means that, to provide the same level of lighting, more lamps consuming more energy would be required. This would not be economically justified.

The preceding does not take into account the cost of the labor to replace a burned out lamp. For those cases where the lamp is very difficult to replace (with resulting higher labor charges) and where the lighting level is not critical, long-life lamps (for example, 5000 hours) may be the better selection.

The meaning of the published data on rated lamp life must be understood. The data refer to the average or mean life of a group from a specific type and rating of lamp. This group of lamps is operated under a controlled set of test conditions, and the rated life is determined by the elapsed time to the point when 50% of the total number are still burning (that is, 50% have burned out). The rated life is not intended as a guarantee of the performance of any individual lamp.

4.1.4 Operating Characteristics of Incandescent Lamps

The effects of voltage variations and lamp lumen depreciation are the chief operating characteristics of concern.

Effects of Voltage Variations. The rated values for the lamps as previously discussed are based on operating the lamp exactly at its proper voltage; that is, the actual operating voltage at the lamp socket must be the same as the rated voltage of the lamp. In most electrical systems, the actual voltage will vary from the rated value because of voltage drops within the system and variations in the voltages supplied by the electric utility. Small deviations from the rated lamp voltage cause approximately 3% decrease in lumen output for each 1% decrease in voltage. However, there is an improvement in the expected life of the lamp; a 5% decrease in voltage doubles the life. It is important that correct voltage levels be maintained at the lamps if rated light output is to be obtained. On the other hand, where it is desired that lighting levels be adjustable, incandescent lamps can very easily be dimmed by reducing the applied voltage. This makes them ideal for such applications as stage lighting.

Lamp Lumen Depreciation. As the operating hours of a lamp increase, the filament gradually deteriorates due to the evaporation of the tungsten. (Actually, the tungsten sublimes, as it goes directly from the solid to the vapor state.) The tungsten is then deposited on the inner surface of the bulb, causing a noticeable blackening of the lamp, especially near the base if the lamp is operated in the base up (normal) position. Thus the light output of the lamp decreases with usage, first because of the deterioration of the filament, and second because of the absorption of some of the light by the black tungsten deposits. This loss of light must be taken into account when designing a lighting system. The *lamp lumen depreciation* factor is used in lighting calculations, as discussed in Section 5.3. Typical values of lamp lumen depreciation (LLD) for incandescent lamps are shown in Table 4.1.

4.1.5 Types of Incandescent Lamps

The types of lamps we will discuss are those most often used for general lighting applications in buildings.

General-Service Lamps. This is the most familiar type, as they are used extensively in our homes. They have either the type A or PS shape bulb (Figure 4.2), with inside frosted, white silica, or clear finishes, and screw bases. Wattage ratings range from 10 to 1500 watts. See Table 4.1 for a partial listing of general-service lamps.

Reflectorized Lamps. These lamps combine in one unit the light source and a very efficient sealed-in reflector. There are two types designated PAR and R, as shown in Figure 4.2. The PAR (parabolic aluminized reflector) lamp has a molded reflector to which a separate lens is then attached. The R lamp uses a less expensive, one-piece blown-glass bulb, which can result in a less accurate beam pattern than for the molded type.

Both types can have either spot (narrow) or flood (wide) beams. For outdoor use, the smaller wattage PAR lamps up to 150 watts may be used directly exposed to the elements without breakage, but the larger wattages must be mounted in a protective enclosure. The total lumen output of these lamps is lower than for general-purpose lamps of the same wattage because light is lost in controlling the beam. Nevertheless, they are widely used where compact lighting units with precise beam control are necessary. Wattages for the type R range from 30 to 1000 watts, and for the type PAR they range from 75 to 1000 watts. See Table 4.2 for a partial listing of 120 volt reflectorized lamps.

The type ER lamps are a recent development. They use an elliptical-shaped reflector that focuses the light beam 2 inches in front of the lamp. When type ER lamps are used in deep-recessed downlights, less light is trapped by the baffles in the luminaire, and therefore more light is projected downward to the workplane, making the overall system more efficient. Wattages for the type ER range from 44 to 135 watts.

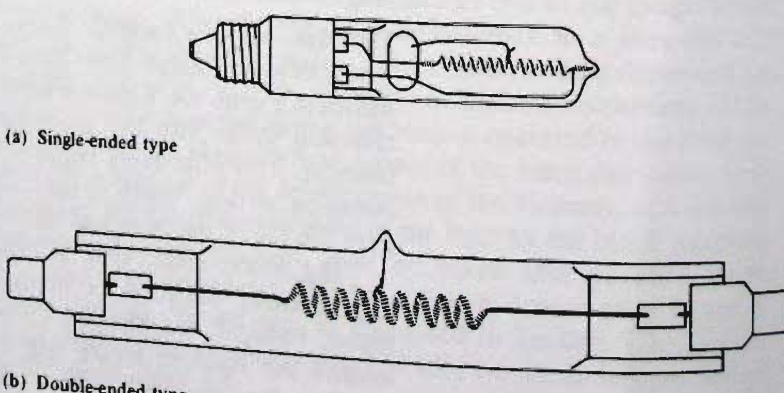
Tungsten–halogen Lamps. These lamps are often referred to as quartz or iodine lamps. They have a long tubular quartz envelope, as shown in Figure 4.4. Iodine is added inside the envelope to create a chemical cycle with the tungsten that has evaporated from the filament. This effectively reduces the deposits of tungsten on the envelope surface, which in turn increases the maintenance of light over the life of the lamp and allows for a rated life of 2000 hours.

The double-ended type of lamp also has the advantage that it can be easily designed for operation at higher voltages. For the higher voltages, the filament diameter can remain the same, and instead the filament length can be increased (a longer tube) to provide the required higher filament resistance. Thus the

TABLE 4.2 Reflectorized Lamps for 120 Volts

Watts	Bulb	Base	Beam Pattern	Beam Spread (degrees)	Length (inches)	Rated Life (hours)	Total Initial Lumens
50	R-20	Medium	Flood	90	$3\frac{15}{16}$	2000	435
75	R-30	Medium	Spot	50	$5\frac{3}{8}$	2000	850
75	R-30	Medium	Flood	130	$5\frac{3}{8}$	2000	850
150	R-40	Medium	Spot	37	$6\frac{1}{2}$	2000	1,825
150	R-40	Medium	Flood	110	$6\frac{1}{2}$	2000	1,825
300	R-40	Medium	Spot	35	$6\frac{1}{2}$	2000	3,600
300	R-40	Medium	Flood	115	$6\frac{1}{2}$	2000	3,600
500	R-40	Mogul	Spot	60	$7\frac{1}{4}$	2000	6,500
500	R-40	Mogul	Flood	120	$7\frac{1}{4}$	2000	6,500
1000	R-60	Mogul	Spot	32	$10\frac{1}{8}$	3000	18,300
1000	R-60	Mogul	Flood	110	$10\frac{1}{8}$	3000	18,300
75	PAR-38	Medium	Spot	30 × 30	$5\frac{5}{16}$	2000	750
75	PAR-38	Medium	Flood	60 × 60	$5\frac{5}{16}$	2000	750
100	PAR-38	Medium	Spot	30 × 30	$5\frac{5}{16}$	2000	1,250
100	PAR-38	Medium	Flood	60 × 60	$5\frac{5}{16}$	2000	1,250
150	PAR-38	Medium	Spot	30 × 30	$5\frac{5}{16}$	2000	1,735
150	PAR-38	Medium	Flood	60 × 60	$5\frac{5}{16}$	2000	1,735
300	PAR-56	Mogul end prong	Narrow	15 × 20	5	2000	3,750
300	PAR-56	Mogul end prong	Medium flood	20 × 35	5	2000	3,750
300	PAR-56	Mogul end prong	Wide flood	30 × 60	5	2000	3,750
500	PAR-56	Mogul end prong	Narrow	15 × 32	5	4000	7,650
500	PAR-56	Mogul end prong	Medium flood	20 × 42	5	4000	7,650
500	PAR-56	Mogul end prong	Wide flood	34 × 66	5	4000	7,650

This table is only a partial listing of reflectorized lamps. Refer to the *IES Lighting Handbook*, 1984 Reference Volume, for a complete listing.



(a) Single-ended type

(b) Double-ended type

FIGURE 4.4

Tungsten–halogen lamps

higher-voltage lamps (available up to 277 volts) have almost the same efficacy as the 120 volt lamps.

The tungsten–halogen lamps are very compact, but they operate with very high socket temperatures and have to be mounted in well-constructed enclosures. A major application for these lamps is floodlighting. For the double-ended type, wattages range from 200 to 1500 watts, and for the single-ended type, they range from 75 to 1000 watts. For a partial listing of tungsten–halogen lamps, see Table 4.3.

PAR and R tungsten–halogen lamps are another recent development. These lamps have a very compact, small-wattage, low-voltage tungsten–halogen source mounted and sealed within a PAR or R bulb. Each unit is complete with a built-in step-down transformer for operation from 120 volts. These lamps combine the higher efficacy and longer life of the low-voltage tungsten–halogen source with the beam control afforded by the PAR and R reflectors. They are being widely used for special accent lighting for display purposes in stores and art galleries.

TABLE 4.3 Tungsten–Halogen Lamps: Clear Bulb Type

Watts	Volts	Bulb	Type	Length (inches)	Rated Life (hours)	Initial Lumens	Lumens per Watt	LLD[a] (%)
200	120	T-3	Double ended	$3\frac{1}{8}$	1500	3,460	17.3	96
300	120	T-3		$4\frac{11}{16}$	2000	5,950	19.8	96
400	120	T-4		$3\frac{1}{8}$	2000	7,750	19.4	96
500	120	T-3		$4\frac{11}{16}$	2000	10,950	21.9	96
1000	120	T-6		$5\frac{5}{8}$	2000	23,400	23.4	96
1000	240	T-3		$10\frac{1}{16}$	2000	21,400	21.4	96
1250	208	T-3		$10\frac{1}{16}$	2000	28,000	22.4	96
1500	208	T-3		$10\frac{1}{16}$	2000	35,800	23.9	96
1500	240	T-3		$10\frac{1}{16}$	2000	35,800	23.9	96
1500	277	T-3		$10\frac{1}{16}$	2000	33,700	22.5	96
100	120	T-4	Single ended	$2\frac{3}{4}$	1000	1,800	18.0	—
150	120	T-4		$2\frac{3}{4}$	1500	2,900	19.3	—
250	120	T-4		$3\frac{1}{8}$	2000	4,850	19.4	96
400	120	T-4		$3\frac{5}{8}$	2000	8,800	22.0	96
500	120	T-4		$3\frac{3}{4}$	2000	11,500	23.0	—
1000	120	T-24		$9\frac{1}{2}$	3000	22,400	22.44	93

[a] Lamp lumen depreciation: percent of initial light output at 70% of rated life.

This table is only a partial listing of tungsten–halogen lamps. Refer to the *IES Lighting Handbook*, 1984 Reference Volume, for a complete listing.

4.2 ELECTRIC DISCHARGE LIGHT SOURCES

The *electric discharge* type of source produces light by *the passage of an electric current through a vapor or gas*. When an electrical potential is applied between the electrodes at each end of the lamp tube, the gas is ionized and current (that is, electrons) flows between the electrodes. The electrons travel at tremendous speeds, and when they collide with the atoms of the vapor, they temporarily alter the atomic structure. Energy is given off in the visible and/or ultraviolet region as the disturbed atoms return to their normal state. The electrodes at the ends of the tube are generally made of tungsten and are coated with some form of emission material that, when heated, gives off electrons.

The various types of electric discharge lamps differ mainly in the size of the lamp tube, the operating pressure within the tube, and the metal used for the vapor.

4.2.1 Ballasts

A fundamental characteristic of the electric current through the vapor, called an *arc*, is that it has a negative volt–ampere relationship; as the current increases, the resistance of the arc decreases. If a constant voltage were to be applied to the ends of the lamp, once the arc was struck (that is, electrons started to flow), the lamp current would very quickly increase to a destructive value. Therefore, the lamp circuit must have a device that can limit the current to a constant value that is safely handled by the lamp. This device is referred to as a *ballast*. A ballast can be as simple as a high-inductance coil in series with the lamp.

Most types of electric discharge lamps cannot be started using the standard 120 volts. Either because of the length of the tube or the pressure within the tube, this voltage (even though it peaks at 170 volts) is not high enough to initially ionize the gas in the tube. An autotransformer is required to raise the voltage to a value that will ionize the gas and strike the arc. Thus the lamp circuit is not as simple as it is for the incandescent lamp. With the requirement of inductance coils and transformers, the current drawn by the lamp will lag the voltage, creating lagging power factor problems in the system. To prevent this, a capacitor may be added to the lamp circuit for power factor correction. (See Section 1.4.4 for a discussion of power factor.) The autotransformer, the coil, and, if used, the capacitor are all mounted in one enclosure that constitutes the final form of the ballast.

The input or primary winding of the autotransformer in a ballast can easily be designed for voltages other than 120 volts. This is a considerable advantage over the incandescent lamp. The electric discharge type of lamp through its ballast can be operated directly from higher-voltage systems (up to 600 volts), which permits considerable savings in the distribution system (Examples 11.11 and 11.14).

The conventional ballast has a magnetic core and windings, and losses are associated with its operation. These losses reduce the overall efficiency of converting the electrical energy to light energy. Ballast losses can amount to 15% of the total power input to the system. A recent development is the introduction of electronic ballasts using solid-state technology (Section 4.3.5). One advantage of this new type is the reduction of ballast losses. As the cost of these units comes down and as their reliability improves, they no doubt will start to replace the conventional magnetic-core ballasts.

4.2.2 Lamp Flicker and Stroboscopic Effect

One problem with any light source operating on alternating current systems is lamp flicker. This is caused by the fact that the current passes through zero twice in each cycle (see Section 1.3.1). For the incandescent lamp, this does not cause much of a problem with the 60 hertz systems because the filament does not have time to cool down enough to noticeably affect light output. However, with the electric discharge type of source, the arc current is extinguished at each current zero and it must be restruck. This causes a 120 cycle per second flicker, which fortunately is too fast for the eye to notice because of the persistence of our vision. However, where rotating objects are observed under electric discharge type of lighting, problems can occur. If the frequency of the lamp flicker approaches the speed of rotation, then an object appears to be rotating at a very slow speed. If the frequency and speed exactly match, then the object appears to be stationary. This is referred to as the *stroboscopic effect*. In fact, this is the means by which strobe lights are used to measure the speed of rotating machinery. The stroboscopic effect can create a very dangerous situation with regard to rotating equipment.

There are several ways by which the problem can be minimized. For the fluorescent lamp, which uses phosphors as discussed in Section 4.3, the type of phosphor is selected partly on the basis of its persistence, that is, its ability to continue to fluoresce over the current zero periods. When it is practical to mount lamps in pairs, another method is to operate one lamp with a lagging lamp current and the other with a leading lamp current. The flickers of the lamps are then out of phase with each other, reducing the stroboscopic effect of the complete luminaire. This method is very common with fluorescent lamps, as discussed in Section 4.3.2. When it is not practical to operate lamps in pairs, such as with large-wattage, high-intensity sources, adjacent lamps can be operated from alternate phases of the three-phase system. This makes the flicker of the adjacent lamps 120° out of phase with each other, again reducing the overall stroboscopic effect.

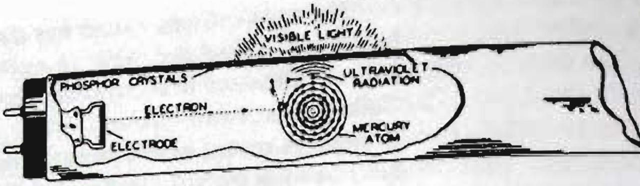


FIGURE 4.5

Operation of the fluorescent lamp

4.3 FLUORESCENT LAMPS

The fluorescent lamp is a low-intensity type of electric discharge lamp using mercury vapor. See Figure 4.5 for the details of the lamp. As discussed in Section 4.2, electrons are propelled at extremely high speeds between the electrodes at each end of the lamp. The energy resulting from the collisions between the electrons and the mercury atoms, because of the very low vapor pressure, is emitted mainly in the ultraviolet region. To convert the ultraviolet into visible energy, the inside of the lamp tube is coated with phosphors. The ultraviolet radiation activates the phosphors, causing them to give off light, or to *fluoresce*; hence the name of the lamp. Approximately 90% of the total light output of the lamp is produced by fluorescence; the remaining 10% is produced directly by the visible lines in the mercury spectrum. A small amount of an inert gas, usually argon, is added to the arc tube to facilitate starting the lamp.

The standard fluorescent lamp has a tubular bulb that varies in diameter from $\frac{5}{8}$ to $2\frac{1}{8}$ inches and in length from 6 to 96 inches. Similar to the incandescent bulb, the overall diameter of the tube is designated by a number that indicates eighths of an inch. The most common size is the nominal 40 watt lamp, which is designated T-12 (tube shape, $1\frac{1}{2}$ inches in diameter) and has a length of 48 inches. There are also special lamps with circular tubes and U-shaped tubes.

The types and shapes of the bases at each end of the lamp are shown in Figure 4.6. As is shown in the circuit diagrams of the lamps in Section 4.3.1, the preheat and rapid-start lamps require bipin bases for the connection of the electrode circuits, whereas the instant-start lamps designated as slimline require only a single pin. The medium and highly loaded lamps, as discussed in Section 4.3.3, require the more rugged, recessed, double-contact bases.

Fluorescent lamps are classified by (1) method of starting, (2) operating currents, and (3) color output. Each characteristic is discussed in the following sections.

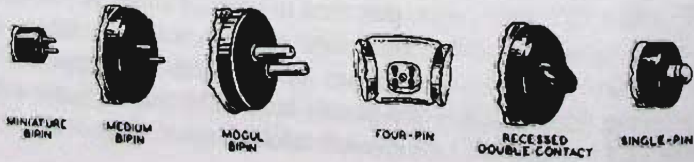


FIGURE 4.6

Bases for fluorescent lamps

4.3.1 Methods of Starting Fluorescent Lamps

The methods of starting fluorescent lamps are presented in the order in which they were developed and used. The preheat method was introduced with the original fluorescent lamp in 1938, followed by the instant-start method introduced in 1944. However, because of the disadvantages listed for these methods, the vast majority of fluorescent lighting installed at the present uses the third method, introduced in 1952, which is the rapid start.

Preheat Method of Starting. Refer to Figure 4.7(a) for the circuit diagram, which shows the connections for the operation of a single lamp. For a source of 120 volts and the standard 48 inch lamp, an

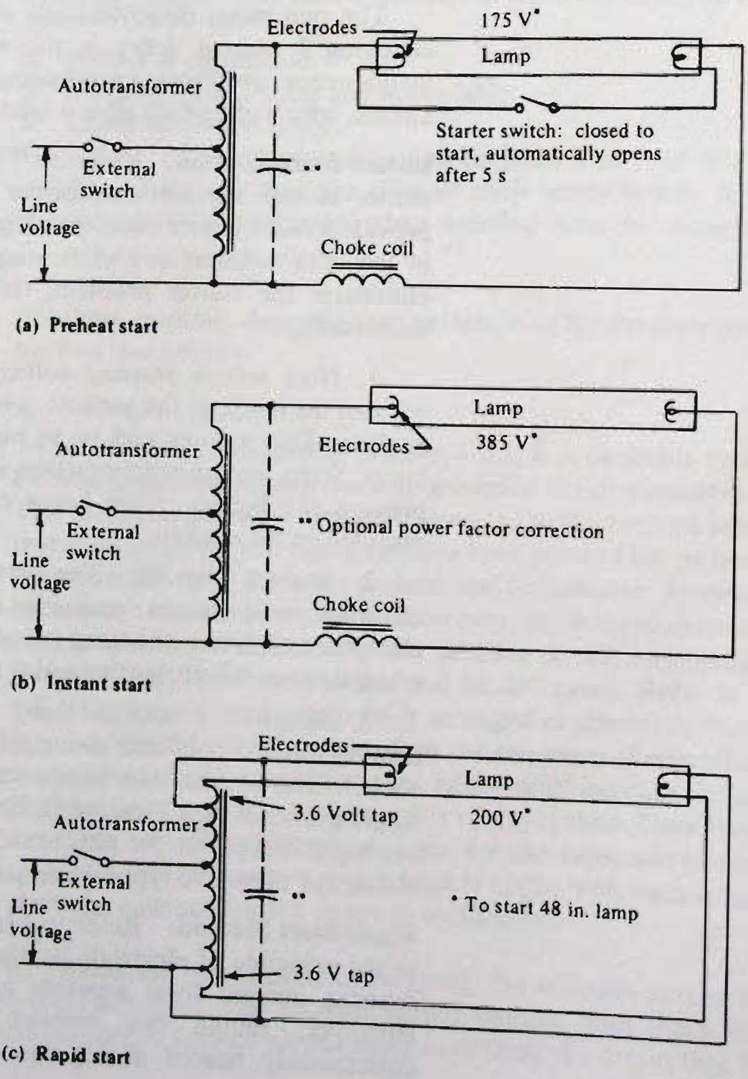


FIGURE 4.7

Methods of starting fluorescent lamps

autotransformer is required to step up the voltage applied across the ends of the lamp in order to strike the arc (that is, start the lamp). To keep this starting voltage as low as possible, the electrodes are preheated for a period of 5 seconds after the external operating switch is first turned on. At the end of 5 seconds, the starting switch automatically opens, applying the full output voltage from the autotransformer across the lamp and striking the arc. The path of the current is then through the lamp. A high-inductance (choke) coil is required to stabilize this current, as previously discussed in Section 4.2.1. The capacitor for power factor correction is optional. Without the capacitor, the ballast is labeled low power factor, and with it, high power factor.

The two major disadvantages with the preheat system are the annoying 5 second delay in the starting of the lamps and the maintenance problems encountered with the automatic starting switch, which often fails after a relatively short period of operation.

Instant-Start Method. Refer to Figure 4.7(b). To eliminate the starter switch, the autotransformer for this method is designed to provide a much higher starting voltage, which directly strikes the arc in the lamp without any preheating of the electrodes. While this eliminates the starter problem, this method results in additional disadvantages:

1. *High unsafe starting voltages* If the power is turned on without the lamps in the sockets, a hazardous voltage exists at these sockets. This voltage can be as high as 565 volts for the 96 inch lamp. Some instant-start systems incorporate a special system to prevent the ballasts from being energized unless the lamps are installed in the sockets.

2. *Shorter lamp life* The severe starting conditions with the electrode cold causes emission material to be torn from the electrodes each time the lamp is started. The end of lamp life comes when there is insufficient material to allow the lamp to start.

3. *Requires a special lamp* Since there is no electrode heating circuit, only one electrical connection is required at each socket. The instant-start lamps referred to as *slimline* have only single-pin bases (see Figure 4.6). The smaller instant-start lamps still use bipin bases, but the pins are shorted together inside the lamp. Neither of these two types is compatible with the other two systems.

Rapid-Start Method. Refer to Figure 4.7(c). This method returns to the principle of electrode heating. The electrodes are heated by drawing current from separate low-voltage taps on the ballast. However, unlike the preheat system, the electrodes are continuously heated during the operation of the lamp by this separate current. Also, to minimize starting time, the starting voltage is slightly higher than for the preheat system, but nowhere near that for the instant start. The delay in starting is only about 1 second, which is acceptable.

The continuous heating of the electrodes causes a small power drain, but this is more than offset by the more efficient operation of the electrodes. Hot spots on the electrodes are eliminated. With the previous two methods, the heating of the electrodes, once the lamp is operating, is provided only by the electron stream bombarding the electrodes. This causes very localized heating or hot spots. Continuous electrode heating with the rapid-start system leads to longer life because the deterioration of the electrode is uniform over its entire length. Thus the advantages of this system are as follows:

1. Starter is eliminated.
2. Starting time is short and acceptable.
3. Lamp life is increased.
4. Lamps are interchangeable with preheat. This is of less importance today, but at the time of their introduction, it was of considerable advantage when existing systems using preheat lamps were expanded.

For these reasons, the rapid-start system is by far the most prevalent method used today.

4.3.2 Two-Lamp, Rapid-Start Operation

As previously mentioned in Section 4.2.2, it is desirable to operate electric discharge lamps in pairs to minimize the stroboscopic effect. This arrangement is particularly suited to the fluorescent lamp, and therefore most fluorescent luminaires have pairs of lamps housed in the one enclosure. Both the preheat and instant-start systems have ballasts for two-lamp operation. However, since these systems have largely been superceded, only the detailed circuit arrangement for the two-lamp, rapid-start ballast will be discussed. Refer to Figure 4.8. This type of circuit diagram is arranged in schematic form; that is, it is arranged in a manner to allow the sequence of operation to be easily understood, and it does not necessarily indicate the relative physical location of the various parts of the system. Note that there are three sets of individual windings for the electrode heating circuits and that the lamps are operated in series with each other. The starting sequence for the lamps is as follows:

1. When the ballast is first energized, the voltages across $C1$ and $C2$ are zero, and the full output voltage from the autotransformer is applied across lamp 1, striking the arc in that lamp.

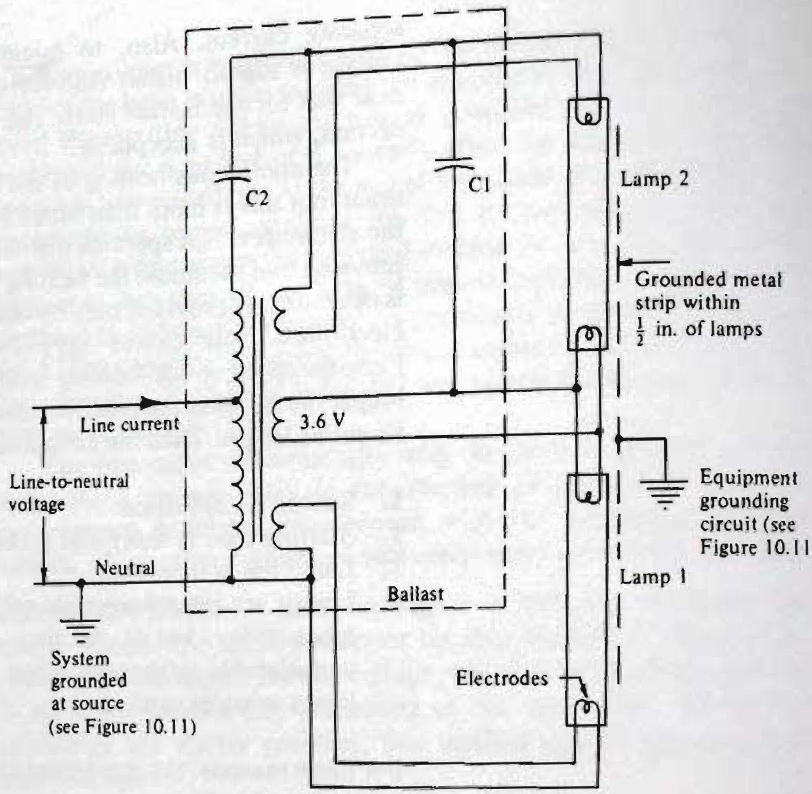


FIGURE 4.8

Diagram for two-lamp, rapid-start operation

2. This lamp current then flows in series through starting capacitor $C1$. This causes the voltage to rapidly build up across this capacitor, which, being in parallel with lamp 2, causes the arc to strike in that lamp.
3. The two lamps now operate in series, and the lamp current increases until stable hot cathode operation at rated current is established.

As discussed in Section 4.2.1, since the arcs in the lamps have negative volt–ampere characteristics, there must be a means of stabilizing their current. This is accomplished by having capacitor $C2$ in series with the lamps and by having the autotransformer designed with a high inductive reactance. Capacitors $C1$ and $C2$ provide power factor correction so that the ballast operates very close to unity (100%) power factor.

Capacitor $C1$ is also required so that the individual lamp currents are out of phase with each other in order to minimize the stroboscopic effect. Since capacitor $C1$ is in parallel with lamp 2, the voltage across this lamp leads the voltage across lamp 1. Therefore, the current through lamp 2 also leads the current through lamp 1.

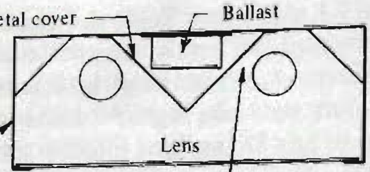


FIGURE 4.9

Cross section of typical fluorescent luminaire

Finally, to ensure reliable starting, there must be a grounded metal strip located within ½ inch of each lamp and running the full length of the lamp. For most luminaires, this is not a problem since the metal housing can serve for this purpose, as shown in Figure 4.9. The ballast must also be operated from a grounded electrical system, that is, one with the neutral grounded. The ballast is then connected to the line-to-neutral voltage. Grounded electrical systems are discussed in Section 10.2.

Refer again to Figure 4.8. There is a maintenance problem with the operation of the lamps in series. If lamp 1 burns out, no lamp current can flow and both lamps are out. This could result in both lamps being replaced when only one is faulty. On the other hand, if lamp 2 burns out, lamp 1 can continue to operate with the current flow through capacitor $C1$, although at a reduced light output.

4.3.3 Operating Currents of Fluorescent Lamps

Fluorescent lamps are further classified by the magnitude of their operating current. Do not confuse this with the line current drawn by the ballast. The classifications of the lamps by currents are as follows:

1. **Lightly loaded lamps.** These lamps operate with a nominal current of 430 milliamperes (mA). An example is the 40 W, T-12, 48 in. lamp with 3150 lm, which is extensively used for office and classroom lighting.
2. **Medium loaded lamps.** These lamps operate with a nominal current of 800 mA. They are referred to as high-output (HO) lamps. An example is the 63 W, T-12, 48 in. lamp with 4300 lm.
3. **Highly loaded lamps.** These lamps operate with a nominal current of 1500 mA. They are variously referred to as very high output (VHO) or power groove (PG). This latter name comes from the construction of the lamp tube, which has a larger than normal diameter (T-17) and has grooves in the glass envelope alternating along the length of the tube. This forces the arc through a longer path. An example of the VHO type is the 116 W, T-12, 48 in. lamp with 6900 lm.

Table 4.4 shows some of the more commonly used rapid-start lamps. The 430 milliampere lamps come in 36 and 48 inch lengths, but the 48 inch lamp is by far the most common, mainly because of its higher lumens per watt rating. The HO and VHO lamps come in various lengths up to 96 inches. However, the standard lengths of

TABLE 4.4 Rapid-Start Fluorescent Lamps

Lamp Current	Bulb Size and Length	Lamp (watts)	Color[a]	Initial Lumens per Lamp	Rated Life (hours)	LLD[b] (%)	Two-lamp Circuit: Input Watts to Ballast	Two-lamp Circuit: Lumens per Watt
Standard Lamps								
Lightly loaded, 430 mA	T-12, 48 in. (1200 mm)	40	CW	3,150	20,000	84	95	66.3
			WW	3,175				66.8
			CWX	2,200				46.3
			WWX	2,165				45.6
Medium loaded, 800 mA (HO)	T-12, 48 in. (1200 mm)	63	CW	4,300	12,000	82	146	58.9
			WW	4,300			146	58.9
	T-12, 96 in. (2400 mm)	113	CW	9,150			252	72.6
			WW	9,200			252	73.0
Highly loaded, 1500 mA (VHO)	T-12, 48 in. (1200 mm)	116	CW	6,900	9,000	69	252	54.8
			WW	6,700		69	252	53.2
	T-12, 96 in. (2400 mm)	215	CW	15,250		72	450	67.8
			WW	14,650		72	450	65.1
Energy-Saving Lamps								
Lightly loaded, 450 mA	T-12, 48 in. (1200 mm)	34	CW	2,770	20,000	84	74[c]	74.9
			WW	2,820				76.2
			CWX	1,925				52.0
			WWX	1,925				52.0
			SSII	3,050				82.4
Medium loaded, 810 mA	T-12, 96 in. (2400 mm)	95	CW	8,500	12,000	82	207[c]	82.1
			WW	8,458				81.7

[a] CW: cool white, WW: warm white; X: deluxe lamp; SSII: super saver II

[b] Lamp lumen depreciation: percent of initial light output at 70% of rated life

[c] Using energy-saving ballast

This table is only a partial listing of rapid-start fluorescent lamps. Refer to the *IES Lighting Handbook*, 1984 Reference Volume, for a complete listing of all fluorescent lamps.

luminaires is either 48 or 96 inches. Table 4.4 lists only the lamps for these two common lengths. Note the following with regard to the cool-white lamps operating in the two-lamp circuit: (1) HO lamps of 48 and 96 inches have lumen per watt ratings of 58.9 and 72.6, respectively, and (2) VHO lamps of 48 and 96 inches have lumen per watt ratings of 54.8 and 67.8, respectively. Therefore, the 96 inch lamps with the higher efficacies should be used wherever possible, unless the length of lamp causes installation problems. In the layout examples shown in Chapter 5, the 96 inch lamps are used when considering the HO and VHO lamps.

When selecting the type of lamp with regard to the lamp operating current for a particular lighting layout, the following should be considered:

1. **Luminance (brightness) of the lamps.** The higher-current lamps, because they produce more light per unit of length, will have a higher luminance. The luminance of the HO lamp is approximately one and one-half times and the VHO lamp is approximately two and one-half times that of the standard 430 mA lamp. Therefore, the HO and VHO lamps could cause problems with glare.
2. **Spacing ratios of luminaires.** The increased light output from the HO and VHO lamps results in fewer lamps and luminaires being required for a given lighting level. This may result in the luminaires being spaced too far apart, creating uneven lighting levels. The spacing ratio of luminaires is fully discussed in Section 5.5.1.
3. **Noise of ballasts.** The HO and VHO lamps, since they have higher wattage ratings, require much larger ballasts. The power input to the ballast for two 96 in. VHO lamps is 450 W. The iron core required for this much power creates considerable hum because of the ac supply, especially when magnified by the metal body of the luminaire.

For these reasons, the HO and VHO lamps are not normally used in low-ceiling areas such as offices or classrooms. The 430 milliampere, 48 inch lamps are generally the choice for these types of areas. The HO and VHO lamps are much more suitable for the higher-ceiling areas of factories and warehouses.

4.3.4 Color Output of Fluorescent Lamps

Fluorescent lamps are also classified as to color output. They are offered in a wide variety of colors. However, the discussion here will be concerned only with lamps producing the so-called *white* light. In this case, the color output of the lamp refers to the type of atmosphere created by the light. A *cool* atmosphere has a connotation of efficiency and neatness, and a *warm* atmosphere that of friendliness or coziness. These lamps then are referred to as cool white or warm white.

From its introduction in 1938, the fluorescent lamp has naturally been compared to the incandescent lamp with which people are familiar. The incandescent lamp inherently creates a warm and friendly atmosphere because of its higher output at the red end of the spectrum (refer to Figure 3.2). This output is also flattering to skin tones. The early fluorescent lamps, because of the mercury spectrum, were high in output at the blue end of the spectrum, which is not flattering to skin tones. This created an unfavorable reaction to these lamps. Extensive research with the phosphors has since created lamps with much more acceptable color outputs.

The spectral distribution curves for the *cool white* and *warm white* lamps are shown on the left in Figure 4.10. They show that the warm white lamp has more output in the yellow-red area and therefore an output that creates a warmer atmosphere. If these two types of lamps are viewed side by side, the difference is quite apparent.

However, these lamps are still relatively low in energy output at the red end of the spectrum. The deluxe lamps were developed for use where a high degree of color rendering is required. Color rendering is a general expression for the effect of a light source on the color of an object. The spectral distribution curves for the *cool white deluxe* and the *warm white deluxe* lamps are shown on the right in Figure 4.10. The warm white deluxe lamp has the highest output at the red end of the spectrum. This is the type that should be used, for

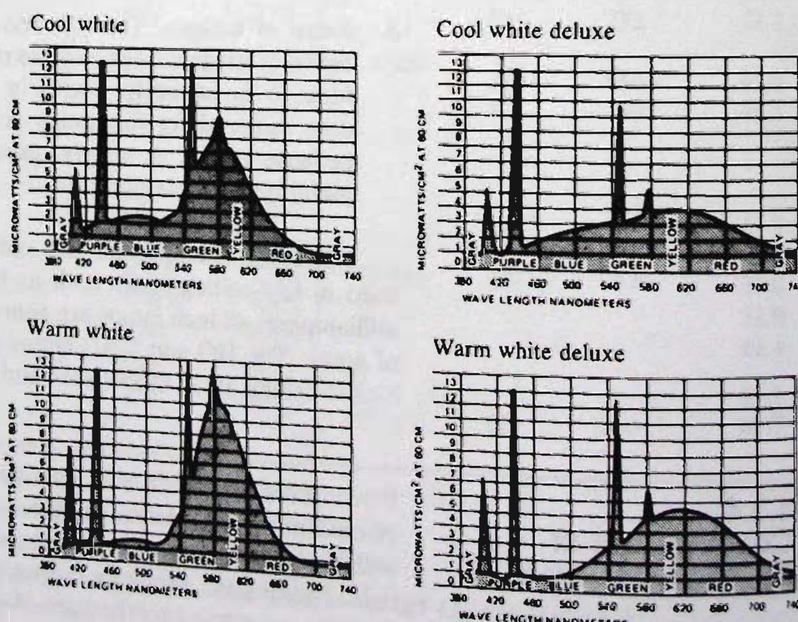


FIGURE 4.10

Spectral distribution curves for fluorescent lamps example, in residential lighting, because it comes the closest to matching the color output of the incandescent lamp. Unfortunately, this improvement in color output is at the expense of total light output. As shown in Table 4.4, the initial lumen rating of the deluxe lamps is only some 70% of the standard cool white lamp.

Additional advances have recently been made in the development of phosphors that improve both the efficacy and color output of fluorescent lamps. Unfortunately, the new variations of lamps being offered by manufacturers are too numerous to list here. Lamp manufacturers should be consulted for the latest data on their lamps.

4.3.5 Energy-Saving Fluorescent Lamps and Ballasts

As a result of the energy shortage caused by the oil embargo in the early 1970s, much emphasis has been put on saving energy. One area that has received a lot of attention is the lighting of offices and factories.

The first step was the development of lower-wattage lamps that could be used in place of the standard fluorescent lamps. As an example, a new type of lamp with a rating of only 34 watts was produced as a replacement for the standard 40 watt, 430 milliampere, 48 inch lamp. The first versions of this lamp, however, had correspondingly lower lumen outputs. Since then improvements have been made so that there are now types of energy-saving lamps that nearly equal the light output of the standard lamps and therefore have improved lumen per watt ratings.

Some energy-saving lamps are listed in Table 4.4. These lamps are generally more expensive than standard lamps, but their use can be justified on the basis of savings in the cost of the electrical energy to operate the lighting system. Refer to Example 5.17, which shows a good rate of return on investment for relamping with energy-saving lamps for a typical fluorescent lighting layout. In all probability, the new energy-saving lamps will be the standard of the future.

Parallel with these new trends in lamps has been the development of energy-saving ballasts. Table 4.4 shows power inputs to the new energy-saving ballasts when used with the energy-saving lamps. A comparison with the standard cool white 40 watt, 430 milliampere, 48 inch lamps operated on the conventional two-lamp ballast shows the following:

— Conventional lamps and ballasts: 66.3 lm/W
— Energy-saving SSII lamps and ballasts: 82.4 lm/W

With very nearly a 25% increase in efficacy, the energy-saving systems should be given a great deal of consideration, notwithstanding their higher initial cost.

Advancements in solid-state technology have resulted in the recent development of electronic ballasts. This system reduces the ballast losses by substituting integrated circuits and a high-frequency transformer for the conventional magnetic core transformer. In addition, tests have shown that the efficacy of fluorescent lamps is increased on the order of 10% when operated on higher frequencies up to 22,000 hertz. With conventional ballasts, the frequency applied to the lamps can only be the same as that of the power supply (60 hertz). With an electronic ballast, the 60 hertz input can be converted to the higher frequency necessary for optimum operation of the lamps. Also, the ability to dim the fluorescent lamps can easily be incorporated into the solid-state circuitry, resulting in further benefits (see Section 4.3.9).

Unfortunately, some earlier models of electronic ballasts did not live up to expectations, resulting in poor lamp operation and early component failures. However, these problems are gradually being overcome, and electronic ballasts are now gaining a small but increasing share of the market, notwithstanding their higher costs, because of their many potential advantages. To date, no standards have been developed for electronic ballasts. Therefore, there are no criteria against which the performance of a particular manufacturer's ballast can be judged.

4.3.6 Compact Fluorescent Lamps

Recent advances in phosphor technology have led to the development of much smaller single-ended fluorescent lamps. These compact lamps were first introduced as a replacement for incandescent lamps so that the much higher efficacy of the fluorescent lamp could be utilized, and therefore they had to be comparable in physical size. The reduction in size from the standard fluorescent lamp was accomplished by adopting a much smaller diameter tube [T-4 (10 mm) or T-5 (15 mm)] and by using parallel tubes (twin tube or quad tube). The T-4 twin-tube lamps range from 5 to 13 watts, and the T-4 quad-tube lamps range from 10 to 26 watts. Figure 4.11 shows the comparison in size between the 13 watt, T-4, quad-tube, compact fluorescent lamp and a standard 60 watt incandescent lamp, both of which have comparable light outputs. Even when the ballast losses are included, the compact fluorescent lamp has four times the efficacy (lumens per watt rating) as compared to the incandescent lamp. The new lamps also have a rated life of 10,000 hours, compared to the 1000 hours for the standard incandescent lamp.

FIGURE 4.11

Comparison of size between the 13 watt compact quad-tube fluorescent lamp and a standard 60 watt incandescent lamp

For compact fluorescent lamps to be a direct replacement for incandescent lamps, some models are available with built-in ballasts and are mounted on a medium screw base that fits the standard light socket. However, these compact lamps are not a point source of light and therefore cannot provide the optical control of light pattern that is possible with incandescent lamps.

A second generation of longer, twin-tube, compact lamps is now available that has light outputs comparable to the standard T-12, single-tube fluorescent lamps. As an example, the 36 watt, T-5, twin-tube, compact lamp has a rated light output of 3000 lumens and yet is only 16.5 inches long. The standard 40 watt, T-12, 48 inch long lamp has a rated output of 3150 lumens. The compact lamp provides 163 lumens per cubic inch of volume, whereas the standard lamp provides only 35 lumens per cubic inch; a ratio of almost 5 to 1. The T-5, twin-tube lamps range from 18 to 55 watts. The compact size of these new lamps means that the luminaires in turn can be much smaller, allowing for a greater degree of flexibility in the luminaire ceiling arrangement. As the technology of compact fluorescent lamps progresses, and as the necessary ballasts and luminaires to go along with them are developed, these new lamps will have a significant impact on the design of lighting systems.

4.3.7 Rated Life of Fluorescent Lamps

As discussed in Section 4.1.3 with regard to incandescent lamps, the rated life means the average or mean life of a group of lamps. The normal end of life for a fluorescent lamp comes when there is insufficient electron emission material remaining on the electrodes to allow the arc to strike. Some emission material is continuously consumed as the lamp burns, but a considerable amount is removed by the impact of the arc each time the lamp is started. Therefore, the life of the lamp is affected by the number of starts. The standard is to rate fluorescent lamps on the basis of a minimum of 3 hours burning per start. Refer to Table 4.4 for the rated life of the lamps listed. Note that the rated life is many times that for incandescent lamps. For example, the standard 40 watt, rapid-start lamp has a rated life of 20,000 hours, 20 times that of the standard incandescent lamp.

4.3.8 Operating Characteristics of Fluorescent Lamps

The chief operating characteristics of concern are the effects of voltage variation, lamp lumen depreciation, and the effects of ambient temperature.

The Effects of Voltage Variation. A fluorescent lamp is not nearly so sensitive to voltage changes as the incandescent lamp. A 1% variation in line voltage changes the lumen output also by about 1%. However, low voltage will not extend the life of the fluorescent lamp, as is the case with the incandescent lamp, but will instead shorten it. Low voltage can cause starting problems, which can seriously deteriorate the electrodes. Operating voltages above normal cause excessive lamp operating currents, which can cause premature lamp failure and overheating of the ballasts. For these reasons, the supply voltage should be maintained within a small tolerance, generally plus or minus 5% of the rated voltage of the ballast.

A serious voltage dip on the system, even for a few cycles, will cause the fluorescent lamp to go out. For the rapid-start ballasts, if the voltage drops below 80% of rated, the arc becomes unstable and is extinguished. Fortunately, the lamp will restrike almost immediately upon restoration of full voltage. However, this creates a serious problem for the dimming of fluorescent lamps (see Section 4.3.9).

Lamp Lumen Depreciation. As with the incandescent lamp, the light output of a fluorescent lamp depreciates as it burns. This is caused by the deterioration of the phosphor powders and by the blackening of the inside of the tube from deposits of electrode material. Typical lamp lumen (LLD) factors are shown in Table 4.4. These factors are used in the lighting calculations discussed in Section 5.3.

The Effects of Ambient Temperature. The performance of fluorescent lamps is seriously affected by the ambient temperature (the temperature of the air that surrounds the lamp). The temperature of the tube wall controls the amount of ultraviolet energy generated by the arc, which in turn affects the amount of light produced by fluorescence. Because the area of the tube wall is relatively large, the temperature of the air can easily affect the temperature of the tube wall. The rated initial lumens of fluorescent lamps are based on measurements made with the lamp in still air at an ambient temperature of 25°C (77°F). The effects of higher and lower ambient temperatures are shown in Figure 4.12. Note that light output also falls off with temperatures that are too high. This

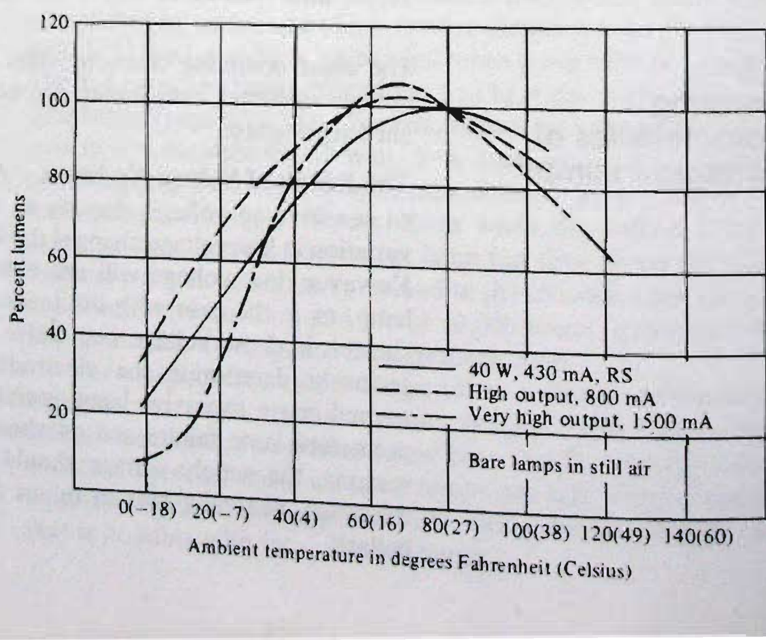


FIGURE 4.12

Effect of ambient temperature on fluorescent lamps requires that luminaires must be well designed so that the lamps are properly ventilated even when used in a normal environment.

The most serious problem, however, is the use of fluorescent lamps outdoors or in unheated areas in those parts of the country that experience any degree of cold weather. With reference to Figure 4.12, if the ambient temperature falls to −7°C (20°F), the light output of the standard 40 watt lamp is only 50% of the rated output. If the lamps are exposed to any wind, the output is even lower. An equally serious problem is the fact that the starting of the lamps is extremely unreliable. Standard rapid-start ballasts provide reliable starting down to only 10°C (50°F). Special ballasts that provide higher starting voltages are available for cold weather starting down to −29°C (−20°F), but they are more expensive.

The use of fluorescent lighting in areas that can experience low ambient temperatures is therefore not normally recommended. Also, care must be taken in the location of fluorescent lamps for indoor lighting with respect to air-conditioning outlets. If cool air is allowed to blow over the lamps, the light output can be decreased and the color of the light can be noticeably affected.

4.3.9 Dimming of Fluorescent Lamps

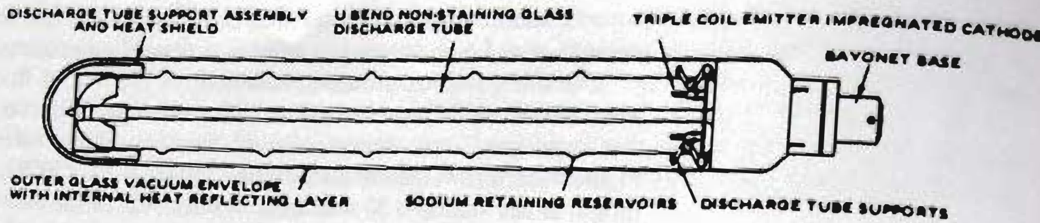
The dimming of fluorescent lamps is not nearly as simple as the dimming of incandescent lamps. The voltage to the ballast cannot just be reduced to dim the lamps. As mentioned in Section 4.3.8, if the voltage across a rapid-start lamp decreases below 80% of normal, the arc becomes unstable and the lamp can suddenly turn off. To have a steady controlled decrease of light output, it is required that:

1. Constant voltage be maintained on the electrode heating circuits so that the electrodes remain at their proper temperature.
2. A high-voltage pulse of very short duration be generated after each current zero to restrike the arc for the next half-cycle as the voltage across the ends of the lamp is decreased.

These requirements call for a much more complicated and costly ballast than the conventional one using magnetic cores and coils. However, with the development of the electronic type of ballast discussed in Section 4.3.5, the dimming requirements can be incorporated more readily, and therefore the dimming of fluorescent lamps can be more easily justified on a cost basis. For applications of dimming, see Section 5.9.

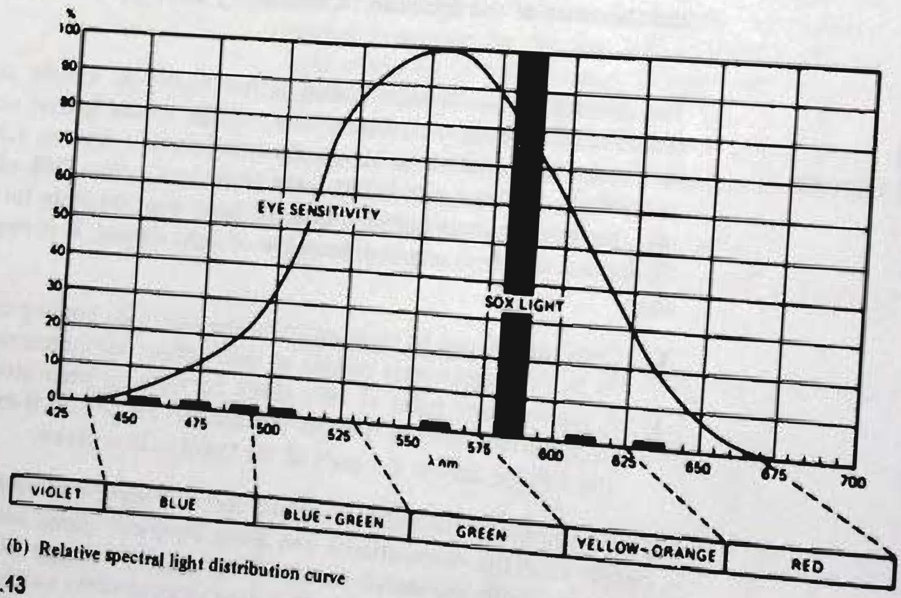
4.4 LOW-PRESSURE SODIUM LAMPS

The low-pressure sodium lamp (also referred to as the low-*intensity* sodium lamp) is similar to the fluorescent lamp in that it has a long narrow tube and operates at a very low vapor pressure. Otherwise,



Lamp Wattage	Lamp Lumens	Rated Life Hours	Overall Length (in.)	Maximum Diameter (in.)
18	1,800	12,000	8.50	2.13
35	4,800	18,000	12.19	2.13
55	8,000	18,000	16.75	2.13
90	13,500	18,000	20.79	2.68
135	22,500	18,000	30.50	2.68
180	33,000	18,000	44.13	2.68

(a) Lamp construction and performance data



(b) Relative spectral light distribution curve

FIGURE 4.13

Low-pressure sodium lamp

it is very different. The metal used for the vapor is sodium instead of mercury. The arc tube is a U-shape that is enclosed in a separate outer glass envelope, as shown in Figure 4.13(a). Both electrodes are located at the same end of the lamp and there is just one base. The arc then travels twice the length of the lamp.

The collision of the electron stream with the atoms of sodium creates energy directly in the visible region. Unfortunately, over 98% of this energy lies in a very narrow band in the yellow-orange area, and negligible amounts are created in the other color areas, as shown in the relative spectral light distribution curve of Figure 4.13(b). This is the major disadvantage of this type of lamp. The color distortion of objects viewed under this source can be extreme. Why then is it used? As compared to other sources, it has the highest efficacy rating, approximately 165 lumens per watt (assuming a 10% loss in the ballast). Also, the light output is near the peak of the eye sensitivity curve.

Other advantages are long life, good lumen maintenance throughout its life, reliable cold weather starting, and prompt reignition after a temporary power interruption. Another disadvantage is the relatively long warm-up time. The available wattages of lamps with their rated lumen output are listed in Figure 4.13(a).

This type of lamp is used for such outdoor applications as the lighting of roadways and intersections, the lighting of yard areas for factories, railways, and docks, and floodlighting. For these types of applications, the severe color distortion can be overlooked in favor of the efficient operation of the lamp. The long warm-up time is of little consequence if the lighting is turned on as darkness begins to fall.

4.5 HIGH-INTENSITY MERCURY VAPOR LAMPS

The high-intensity mercury vapor lamp is most often referred to as simply the *mercury lamp*. It was the first high-intensity discharge (HID) lamp to be developed. The characteristics that most differentiate the HID sources from the low-intensity type (that is, the fluorescent) are that the arc tubes are much smaller and they operate at much higher vapor pressures, up to 10 atmospheres in extreme cases. The exact spectral distribution of an electric discharge lamp varies greatly with the vapor pressure at which the arc operates.

The basic operation of the electric discharge type of source is discussed in Section 4.2. In the case of the mercury lamp, the higher vapor pressure results in a much larger percentage of the energy from the electron activity being produced directly in the visible region, with only a small percentage being in the ultraviolet region.

The construction of the typical mercury lamp is shown in Figure 4.14. Note that there are two bulbs. The inner bulb is the arc tube and is made of quartz. Because of the intense energy developed in this small arc tube, it must be shielded by an outer bulb. The space between the two is filled with an inert gas. The outer glass envelope also filters out unwanted and harmful ultraviolet energy.

The original mercury lamps had clear glass envelopes. The spectral energy distribution curve for the clear mercury lamp is shown in

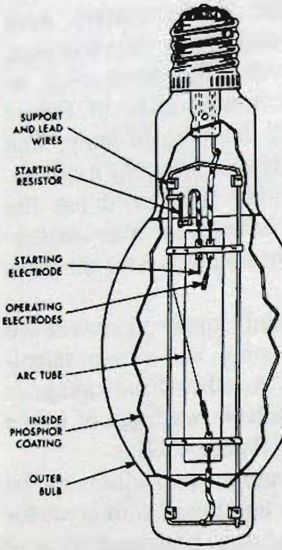


FIGURE 4.14

Construction of the mercury lamp

Figure 4.17(a). Note that relatively large amounts of energy are produced in the blue and green-yellow regions. Hence these lamps are characterized by a very noticeable bluish color of their light. They have the disadvantage of color distortion, especially for the red colors. In spite of this disadvantage, the mercury lamp gained acceptance for such applications as roadway and parking lot lighting and high-bay industrial area lighting. Its efficacy is approximately 250% that of the incandescent lamp, yet it is still essentially a point source of light, which permits good control of the distribution pattern of the luminaire. Also, mercury lamps have a much longer life than the incandescent lamp.

The next development was the introduction of the color-improved mercury lamp. In this type, the inside of the outer bulb is coated with a white phosphor that converts most of the ultraviolet energy radiated by the arc into visible energy. This not only increases the efficacy of the lamp but improves its color output. For example, the 400 watt clear lamp has an initial output of 21,000 lumens, whereas the 400 watt deluxe white lamp has 23,125. However, this higher initial output is partly offset by a higher rate of lumen depreciation. There are various degrees of color improvement: deluxe white, warm deluxe white, and so on. The spectral energy distribution curve for the deluxe white lamp is shown in Figure 4.17(b). Note that there is less output in the blue and yellow-green regions and considerably more output in the red region as compared to the clear lamp. However, in spite of these improvements, the metal halide lamp, which is a further development of the mercury lamp, is now beginning to supercede the mercury lamp (see Section 4.6).

The mercury lamp can continue to operate for many hours in the event that the outer glass bulb is accidentally broken, allowing the harmful ultraviolet energy to escape from the lamp. To prevent this, the lamp can be provided with an internal switch that extinguishes the arc if the outer glass envelope is broken or removed. This is especially important for lamps mounted in open luminaires that are subject to acts of vandalism. Self-extinguishing lamps are mandatory in many jurisdictions.

Lamp wattages for the mercury lamp range from 40 to 1000 watts. For a partial listing of mercury lamps, refer to Table 4.5. Mercury lamps can have a great many variations of characteristics. For instance, a lamp of the same wattage can have different operating voltages and currents. These lamps would not be interchangeable. The American National Standards Institute (ANSI) has established the following nomenclature system for the designation of lamps. As an example, the ANSI designation for one lamp shown in Table 4.5 is H33GL-400/DX. The coding indicates the following:

H identifies lamp as mercury vapor.
33 identifies the electrical characteristics.
GL identifies the physical characteristics.
400 identifies the wattage.
DX identifies the color correction (deluxe white). No designation indicates a clear lamp.

A "T" before the wattage indicates a self-extinguishing lamp.

4.5.1 Ballasts for Mercury Lamps

As discussed in Section 4.2.1, all electric discharge lamps require a ballast. The circuit diagram for a ballast operating a single mercury lamp is shown in Figure 4.15. The windings of the autotransformer are designed to have high inductive reactance, which then provides the necessary current limitation to the lamp. Power factor correction (90% or better) can be provided by a capacitor as shown.

Figure 4.16(a) shows the effect on the operation of the mercury lamp from variations in the line (primary) voltage to the ballast. Since many applications using the mercury lamp involve long runs of feeders (for example, streetlighting), the voltages at the ballast can often vary more than the allowable 5%. To help overcome this, self-regulated (or constant wattage) ballasts are available. These ballasts keep the lamp wattage and hence the light output almost constant over a range of plus or minus 10% of the rated primary volts, as shown in Figure 4.16(b).

With the use of an autotransformer type of ballast, the output (that is, the lamp circuit) cannot be electrically isolated from the power supply. Where it is necessary to be able to electrically isolate the lamp circuit from the power supply, ballasts using separate pri-

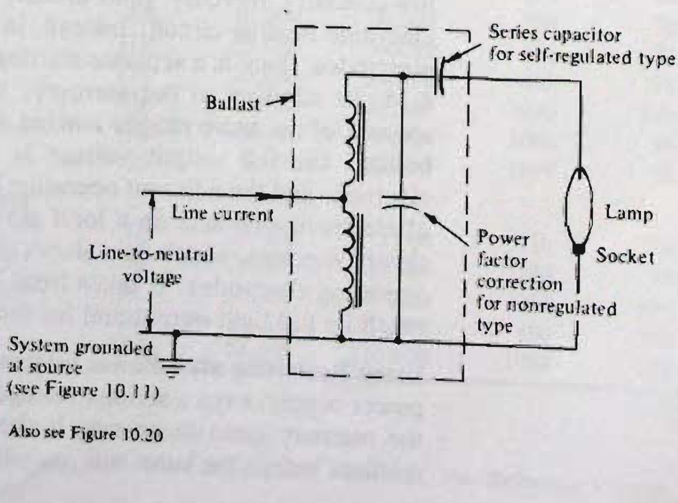
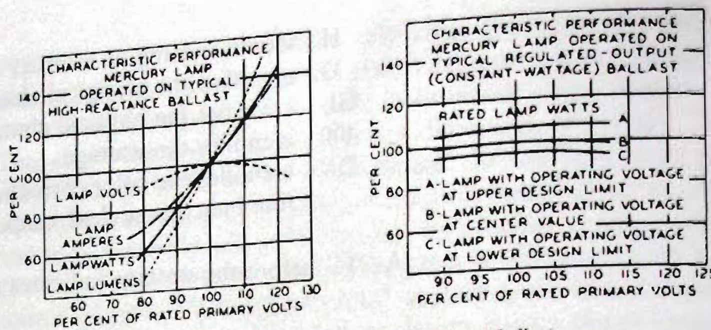


FIGURE 4.15
Autotransformer type of ballast for single mercury lamp

Also see Figure 10.20



(a) Unregulated ballast

(b) Regulated ballast

FIGURE 4.16

Characteristic operating curves for mercury lamp

mary and secondary windings are required. This is discussed further in Section 10.6 and shown in Figure 10.20.

Two-lamp ballasts are available that operate one lamp on a leading current and the other on a lagging current, as discussed in Section 4.2.2. However, the operation of two mercury lamps from one ballast is not always practical. Since uniform lighting levels are desirable, lamps should be equally spaced from one another. Therefore, two-lamp ballasts would have to be placed midway between two pairs of widely separated lamps, which would increase the cost of the wiring. The present trend is to operate each lamp from its own ballast, which is mounted as an integral part of the luminaire.

4.5.2 Operating Characteristics of Mercury Lamps

There are six major factors to consider with regard to the operation of mercury lamps.

Starting of Lamps. The method of starting the HID mercury lamp differs somewhat from the method discussed in Section 4.3.1 for the low-intensity mercury (fluorescent) lamp. There is no separate electrode heating circuit. Instead, in addition to the two operating electrodes, there is a separate starting electrode, as shown in Figure 4.14. In addition to the mercury, the arc tube contains a small amount of the more readily ionized argon gas. Upon energizing the ballast, the full output voltage is applied between the starting electrode and the adjacent operating electrode, creating an emission of electrons that sets up a local glow. This causes the mercury to slowly vaporize, which then allows the arc to strike between the two operating electrodes. It takes from 3 to 4 minutes for the lamp to reach its full light output and for the lamp current to stabilize.

Lamp Restarting after Power Interruption. Any interruption in the power supply, even a serious voltage dip for a few cycles, will cause the mercury lamp to go out. It then requires a period of up to 4 minutes before the lamp will restart. It is necessary for the lamp to cool and the vapor pressure to decrease to the point where the arc can restrike. Together with the warm-up period, this can mean up to 8 minutes before full light returns. This is a serious problem when mercury lamps are used for indoor lighting in industrial areas with moving equipment. Emergency incandescent lighting to span the blackout period may be required.

Lamp Life. In common with other electric discharge lamps, the mercury lamp has a long life of up to 24,000 hours.

Lamp Lumen Depreciation. The light output of the mercury lamp, especially the color-corrected type, can depreciate up to 50% if allowed to operate to burn-out. It is often more economical to replace the lamp after no more than 18,000 hours. Typical values for lamp lumen depreciation (LLD) are shown in Table 4.5.

TABLE 4.5 High-Intensity Discharge (HID) Lamps

Watts	Outer Bulb Finish	ANSI Designation	Length (inches)	Rated Life (hours)	Initial Lumens[a]	Input Watts to Ballast	Lumens per Watt	LLD[b] (%)
Mercury Lamps								
100	Phos.	H38JA-100/DX	$7\frac{1}{2}$	24,000	4,425	120	33.9	69
175	Phos.	H39KC-175/DX	$8\frac{5}{16}$	24,000	8,600	205	42.0	78
250	Phos.	H37KC-250/DX	$8\frac{5}{16}$	24,000	12,775	285	44.9	76
400	Clear	H33CD-400	$11\frac{1}{2}$	24,000	21,000	450	46.7	80
400	Phos.	H33GL-400/DX	$11\frac{1}{2}$	24,000	23,125	450	51.4	71
1000	Clear	H36GV-1000	$15\frac{3}{8}$	24,000	56,150	1085	51.8	80
1000	Phos.	H36GW-1000/DX	$15\frac{3}{8}$	24,000	63,000	1085	58.1	71
Metal Halide Lamps								
175	Clear	M57PE-175	$8\frac{5}{16}$	7,500	14,000	210	66.7	77
250	Clear	M58PG-250	$8\frac{5}{16}$	10,000	20,500	290	70.7	76
400	Clear	M59PJ-400	$11\frac{1}{2}$	15,000	34,000	455	74.7	70
400	Phos.	M59PK-400	$11\frac{1}{2}$	15,000	34,000	455	74.7	68
1000	Clear	M47PA-1000	$15\frac{3}{8}$	10,000	110,000	1090	100.9	73
1000	Phos.	M47PB-1000	$15\frac{3}{8}$	10,000	105,000	1090	96.4	70
1500	Clear	M48PC-1500	$15\frac{3}{8}$	3,000	155,000	1610	96.3	—
High-Pressure Sodium (HPS) Lamps								
100	Clear	S54SB-100	$7\frac{3}{4}$	24,000	9,500	130	73.1	—
150	Clear	S55SC-150	$7\frac{3}{4}$	24,000	16,000	180	88.9	88
250	Clear	S50VA-250/S	$9\frac{3}{4}$	24,000	30,000	295	101.7	88
400	Clear	S51WA-400	$9\frac{3}{4}$	24,000	50,000	460	108.7	88
1000	Clear	S52XB-1000	$15\frac{1}{16}$	24,000	140,000	1085	129.0	90

[a] Lamps burning in the vertical position.

[b] Lamp lumen depreciation: percent of initial light output at 70% of rated life.

This table is only a partial listing of HID lamps. Refer to the *IES Lighting Handbook*, 1984 Reference Volume, for a complete listing of all HID sources.

Effects of Ambient Temperature. Because of the double-bulb construction, mercury lamps are not significantly affected by the ambient temperature once they are operating at full output. However, the starting of the lamp can be a problem. Since they are often used outdoors, ballasts are normally designed to provide sufficient starting voltage to give reliable starting down to −29°C (−20°F).

Circuit Protection. The starting of some mercury lamps can cause a problem with the overcurrent protection of the circuits feeding the lamps. The unregulated autotransformer type of ballast draws a line current during the starting period that is higher than the normal operating current. This higher current, which lasts for most of the 4 minute warm-up time, may be sufficient to operate the circuit overcurrent protection and shut the lamps off, unless allowance is made for it in the design of the circuit. The self-regulated type of ballast does not cause this type of problem. It draws less than the normal current when starting.

4.6 METAL HALIDE LAMPS

The metal halide lamp is basically a high-intensity mercury lamp with traces of metal halides added to the arc tube. Various combinations of scandium, thallium, indium, dysprosium, and sodium iodides are used. The addition of these trace elements improves the efficacy of the lamp. The efficacies for metal halide lamps average 75 lumens per watt against 50 lumens per watt for mercury lamps,

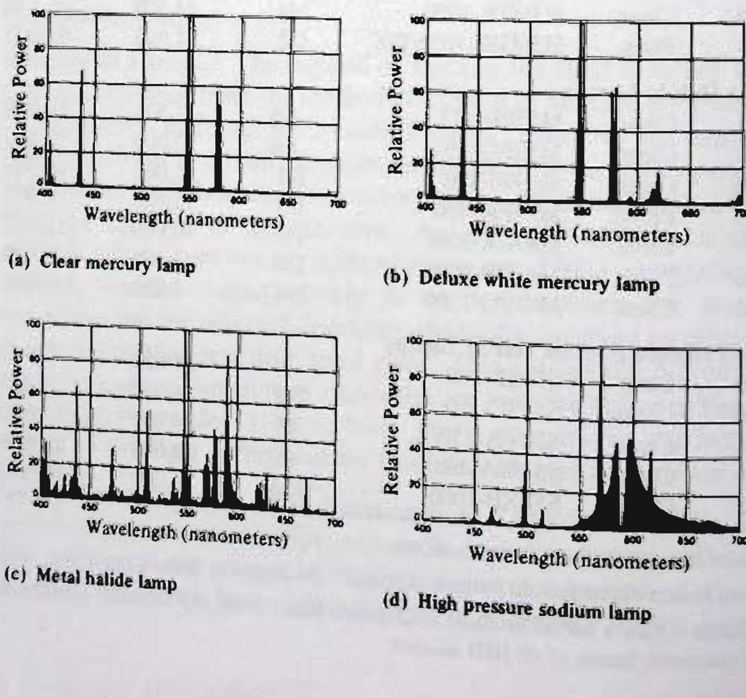


FIGURE 4.17

Spectral energy distribution curves for HID lamps assuming average ballast losses. There is also considerable improvement in the color output. Refer to Figure 4.17(c) and compare the spectral energy distribution curve for the metal halide lamp with that for the clear mercury lamp. Note that the distribution of the outputs across the color spectrum is improved, especially at the red end. Similarly to the mercury lamp, the metal halide lamp is available with a clear outer bulb or it can have the inside of the outer bulb coated with phosphor for additional color improvement. More recently, very compact, low-wattage, metal halide lamps have been developed. These new types now allow for the use of the much more efficient metal halide lamps in low-ceiling interior applications in place of inefficient incandescent lamps.

The metal halide lamp has some disadvantages when compared to the mercury lamp. The rated life is shorter, typically 15,000 hours, and the rate at which the lamp lumens depreciate is somewhat higher. Also, the warm-up and restrike times are even longer, up to 10 minutes. Notwithstanding these disadvantages, the metal halide lamp has largely replaced the mercury lamp, especially on new lighting installations, because of its higher efficacy and better color output.

Ballasts for the metal halide lamp are similar in principle to those for the mercury lamp. However, metal halide lamps, even of the same wattage, are not interchangeable with mercury lamps as they have different operating voltages and currents. The coding of the ANSI lamp designations is similar to that outlined for the mercury lamp in Section 4.5, with the exception that the first letter is an M to designate the metal halide type. Lamp wattages range from 75 to 3500 watts. Refer to Table 4.5 for a partial listing of metal halide lamps.

4.7 HIGH-PRESSURE SODIUM LAMPS

The high-pressure sodium (HPS) lamp, introduced in 1964, is the latest development of the high-intensity discharge (HID) sources. As the name implies, it uses sodium as the main metal in the arc tube. It is the most efficient of all of the light sources which have acceptable color outputs, averaging 110 lumens per watt (assuming normal ballast losses).

To obtain good color output, it is necessary that the arc pass through the sodium vapor at a pressure higher than normal for the other HID sources. The arc tube is constructed from a new type of ceramic material, translucent aluminum oxide, that was developed in the late 1950s. This material can withstand the much higher pressures and temperatures of the arc, and is also resistant to the extremely corrosive effects of the hot sodium and can transmit over 90% of the visible energy generated by the arc.

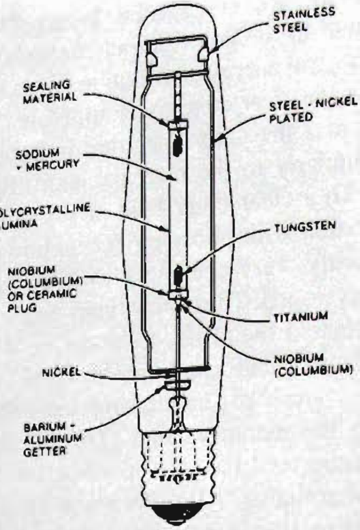


FIGURE 4.18

Construction of the high-pressure sodium lamp

The construction of the lamp is shown in Figure 4.18. It is an extremely compact lamp, considering the amount of light that it produces. In addition to the sodium, the arc tube contains a small amount of xenon as a starting gas. The small diameter of the arc tube does not permit the installation of a separate starting electrode as is used for the mercury lamp. Instead, the ballast contains a special starting circuit that creates a high pulse of voltage each half-cycle, peaking at 2500 volts and lasting 1 microsecond. These high-voltage pulses ionize the xenon gas, allowing the arc to strike between the electrodes. Once the arc has struck, the starting pulses cease.

Similarly to the mercury lamp, the HPS lamp takes 3 to 4 minutes to warm up and reach its full light output and final color. However, unlike the other HID sources, the restrike time of the HPS lamp is short, usually less than 1 minute. This is the result of the high starting pulses that the ballast produces when there is no lamp current.

The spectral energy distribution curve of the HPS lamp is shown in Figure 4.17(d). The output is high in the yellow-orange region, giving the lamp a very distinctive golden color. However, there is some output in all regions across the color spectrum, making the light source acceptable for many general-purpose lighting applications. It is now widely used for outdoor lighting and for indoor, high-bay, industrial lighting because of its high efficacy. Further research has very recently produced an HPS lamp with an enhanced color output that makes it much more acceptable for lighting areas where color rendition is important. This new lamp has a lower efficacy and shorter rated life than the standard HPS lamp, but no doubt further research will improve on these deficiencies. Therefore, in the future the use of the high-efficacy HPS lamp will no doubt increase even further. In addition to its wide use in industrial and outside lighting, its use will extend into the lighting of commercial and merchandising areas.

Lamp wattages range from 35 to 1000 watts. Refer to Table 4.5 for a partial listing of HPS lamps. The rated life of the HPS lamp is very good, up to 24,000 hours. The lumen maintenance over the life of the lamp is excellent. Typical lamp lumen depreciation (LLD) factors as shown in Table 4.5 approach 90%. The coding of the ANSI lamp designations is similar to that outlined for the mercury lamp in Section 4.5, with the exception that the first letter is an S to designate the HPS lamp.

Ballasts for HPS lamps are similar in type to those outlined for the mercury lamp in Section 4.5, with the exception of the addition of the special starting circuit as previously mentioned. HPS lamps, even those with the same wattage, are not interchangeable with mercury lamps because of different voltage and current characteristics.

SUMMARY

The following is a summary of the advantages and disadvantages of the main types of light sources covered in this chapter, together with typical applications.

- Incandescent lamps
  - Advantages
    - Point source of light, easy to control light distribution pattern
    - Low initial cost
    - Simple; no ballasts required, no ballast noise
    - Light output not affected by ambient temperature
    - Small size, compact luminaires
    - Very simple to dim
    - Favorable color output for humans
    - No delay on starting or restarting
    - No stroboscopic problems on 60 hertz
  - Disadvantages
    - Very low efficacy
    - Very high operating temperature
    - High infrared component
    - Seriously affected by voltage variations
    - Extremely bright source
    - Short life
    - Restricted to operating on lower voltages

— Applications

Incandescent lamps, because of their low efficacies and short lives, are not normally a good choice for large-area commercial, industrial, and outdoor lighting. They are a good choice for social areas where good color rendering and a warm, pleasant, low-key effect is desired, for accent and display lighting where good light control is necessary, for localized or supplementary lighting, and for decorative lighting.

- Standard fluorescent lamps
  - Advantages
    - Good efficacy
    - Very long life
    - Low brightness
    - Low operating temperature
    - Low infrared output
    - Good color rendition
    - Can be operated on higher system voltages
    - Only minor delay on starting and restarting
  - Disadvantages
    - Not a point source of light, light distribution more difficult to control.
    - Require ballast; extra weight; noise
    - Higher initial cost
    - Seriously affected by ambient temperature
    - Large size; require bulky luminaires
    - Require special ballasts to dim
  - Applications

    Fluorescent lamps are widely used for large-area general lighting in offices and industrial plants. They provide approximately 70% of all light generated in North America.
- High-intensity discharge lamps (mercury, metal halide, and HPS)
  - Advantages
    - Very good efficacies
    - Very long life
    - High output in compact size
    - Essentially a point source of light
    - Negligible infrared component
    - Light output not affected by ambient temperature
    - Can be operated on higher system voltages

— Disadvantages

Can cause color-rendition problems

High initial cost

Requires ballast; extra weight; noise

Very bright source

Very difficult and expensive to dim

Long warm-up and restrike times

Stroboscopic effect can be a problem

Cold weather starting problems

— Applications

HID lamps are widely used for high-bay interior industrial applications and many outdoor applications, such as street, parking lot, and security lighting. With the development of the better color-rendering metal halide lamps, they are being used with increasing frequency for indoor commercial applications.

QUESTIONS

1. What is the luminous efficacy of a perfect light source that could convert all the energy into yellow-green light without any losses?
2. List the following lamp types in order of their luminous efficacies from the lowest to the highest: (a) 400 W mercury, (b) 400 W metal halide, (c) 200 W incandescent, (d) 400 W high-pressure sodium, and (e) 40 W fluorescent.
3. State what the designation PS-25 for an incandescent lamp indicates.
4. For a given rated voltage and lamp life, are large-wattage incandescent lamps more or less efficient than small-wattage lamps? Explain your answer.
5. For a given rated wattage and lamp life, are high-voltage incandescent lamps more or less efficient than low-voltage lamps? Explain your answer.
6. Explain what is meant by the rated life of a lamp.
7. If the voltage applied to an incandescent lamp is 5% below rated voltage, approximately how much does its lumen output decrease?
8. List the two causes of lamp lumen depreciation in an incandescent lamp?
9. Where are reflectorized incandescent lamps used?
10. Describe the tungsten–halogen lamp and list its advantages.
11. State the two major reasons why ballasts are required for electric discharge lamps.
12. State the means of minimizing the stroboscopic effect of electric discharge lamps.
13. What are the main differences between the major types of electric discharge lamps?
14. Describe the basic operation of the fluorescent lamp (that is, how electric energy is converted to light).
15. State the three completely separate ways by which fluorescent lamps are classified.
16. State the difference between the preheat and rapid-start methods for fluorescent lamps.
17. State the disadvantages of the instant-start method.
18. What is the lamp operating current of the medium loaded fluorescent lamp and how is the lamp designated?
19. What is the lamp operating current of the highly loaded fluorescent lamp and how is the lamp designated?
20. List the four common types of white fluorescent lamps with regard to color output and indicate which type has the highest output at the red end of the spectrum.

21. Besides the hours of burning, what else affects the life of a fluorescent lamp?
22. State the problems with operating fluorescent lamps in low ambient temperatures.
23. State the problems that must be considered in the application of HO and VHO fluorescent lamps to lighting indoor areas.
24. State the major advantage and disadvantage of the low-pressure sodium lamp.
25. An HID lamp is coded H38JA-100/DX. State the characteristic that each of the numbers or letters designates.
26. Indicate the starting sequence of the mercury lamp.
27. State the effects of low ambient temperature on the operation of the standard mercury lamp.
28. Describe the metal halide lamp.
29. Describe the HPS lamp.
30. Explain why the HPS lamp has a relatively short restrike time.
31. List the advantages and disadvantages of the incandescent lamp.
32. List the advantages and disadvantages of the fluorescent lamp.
33. List the advantages and disadvantages of HID lamps.
34. List four good applications for incandescent lamps.
35. List typical applications for HID lamps.

5 Lighting System Layouts for Interior Spaces

OBJECTIVES

After studying this chapter, you will be able to:

- Determine the lighting level recommended for a specific task.
- Calculate the required number of luminaires.
- Prepare a plan of the actual arrangement of luminaires.
- Do an economic comparison between lighting systems.
- Discuss the factors involved in the quality of light.

INTRODUCTION

The design of a lighting system for an interior space involves many variable factors. These factors include the size and shape of the space; the types of finishes on the ceilings, walls, and floors; the details of the construction; the economic considerations of both the initial and the operating costs; the compatibility of the lighting system with the architectural design; and the type of activities that will be carried out in the space.

As discussed in the introduction to Chapter 3, there are two differing criteria in the design of a lighting system: *quantity* and *quality*. This chapter concentrates on the means by which the quantity of light is determined (that is, how many luminaires are required to properly light the space). The quality of light (the comfort of the seeing environment) is only discussed very briefly, not because it is not important, but only because of the size constraints of this textbook.

The methods outlined in this chapter for designing lighting layouts are based on the recommended procedures of the Illuminating Engineering Society of North America (IES). The examples presented are only meant to be a general overview of these procedures. The reader is referred to the *IES Lighting Handbook (Reference Volume* and *Application Volume)* for all aspects of the design of lighting systems.

5.1 ILLUMINANCE SELECTION

The lighting levels required to efficiently perform specific tasks can vary widely. Many factors involved in the seeing process were discussed in Section 3.1. It has not been easy to establish recommendations for lighting levels. Many research studies have been carried out. On the basis of these studies, the IES has published recommended illuminance values. Until 1979, a single value was recommended for each specific task. However, in that year the IES adopted a more flexible approach that recommends a range of illuminance values for each specific task accompanied by a weighting factor guidance system. These weighting factors take into account

TABLE 5.1 Illuminance Categories: Commercial, Institutional, Residential, and Public Assembly Interiors

Area/Activity	Illuminance Category
Auditoriums	
Assembly	C
Social activity	B
Drafting	
Tracing paper: high contrast	E
low contrast	F
Educational facilities	
Science laboratories	E
Lecture rooms: audience	(see Reading)
demonstration	F
Offices	
General and private offices	(see Reading)
Lobbies, lounges, and reception areas	C
Off-set Printing and Duplicating Areas	D
Reading	
Copied tasks: photocopies	D
Handwritten tasks: carbon copies	E
Residences	
General lighting: conversation, relaxation, and entertainment	B
Reading: books, magazines, and newspapers	D
Service areas	
Stairways and corridors	C
Toilets and washrooms	C

Source: Adapted from *IES Lighting Handbook, 1987 Application Volume* (New York: Illuminating Engineering Society of North America, 1987). Refer to the *1987 Application Volume* for a complete listing of areas and activities.

the object being viewed (the visual display), the age of the observer, the importance of speed and accuracy for visual performance, and the reflectance of the task background against which the details are seen.

Nine illuminance categories designated A through I have been established. Each letter has been assigned a range of illuminance values. Categories A, B, and C range from 20 to 200 lux. At these low levels, it is considered that all the lighting in the area will be provided by general overall lighting and that no specific task or task locations are involved. Such areas include lobbies and hallways. Categories D, E, and F, which range from 200 to 2000 lux, are for the lighting of specific tasks at fixed locations. The lighting may be provided by a combination of general overall lighting and local lighting at the task or by general overall lighting alone. Categories G, H, and I, which range from 2000 to 20,000 lux, are for the lighting of extremely difficult visual tasks requiring high levels of lighting. For practical and economic reasons, lighting systems for these levels should definitely be a combination of general overall lighting and specific lighting at the task area.

Tables 5.1 and 5.2 show the letter categories for a few specific areas and activities. Table 5.3 is a partial listing of the recommended ranges of illuminances for categories E and F. The criteria for the final single-value illuminance selection involves the workers' ages, the demand for speed and/or accuracy, and the task background reflectance. To use these tables, the first step is to determine the type of activity involved. After selecting the letter category from either Table 5.1 or 5.2, next refer to Table 5.3 for the single-value recommendation.

■ EXAMPLE 5.1

An office area is to be lighted. The task is reading handwritten carbon copies with a background (paper) reflectance of 70%. The average age of the workers is 35. Speed and accuracy are important but not critical. Select the recommended illuminance.

Solution

STEP 1 From Table 5.1, for general offices under *Reading, handwritten carbon copies*, category E is listed.

STEP 2 From Table 5.3, for category E, average of workers' ages under 40, demand for speed and/or accuracy important, task background reflectance 30% to 70%, the recommended illuminance is 750 lx.

The recommended values in Table 5.3 are in lux. For the equivalent values in footcandles, it is accepted that the values in the table

TABLE 5.2 Illuminance Categories: Industrial Group Interiors

Area/Activity	Illuminance Category
Assembly	
Simple	D
Moderately difficult	E
Difficult	F
Garages	
Repairs	E
Active traffic areas	C
Inspection	
Simple	D
Difficult	F
Exacting	H
Locker rooms	C
Machine shops	
Rough bench or machine work	D
Medium bench or machine work	E
Fine bench or machine work	G
Service spaces	
Stairways and corridors	B
Toilets and washrooms	C
Storage rooms or warehouses	
Inactive	B
Active: rough bulky items	C
Active: small items	D
Woodworking	
Rough sawing and bench work	D
Fine bench work	E

Source: Adapted from *IES Lighting Handbook, 1987 Application Volume* (New York: Illuminating Engineering Society of North America, 1987). Refer to the *1987 Application Volume* for a complete listing of areas and activities.

be divided by 10 (refer to Table 3.1; 1.0 footcandle equals 10.76 lux). In Example 5.1, the recommended level is 75 footcandles.

The use of selected illuminance values may be influenced by work areas involving many tasks. If general overall lighting only is to be provided, then the selection should be based on the task of prime importance. With general overall lighting, the recommended illuminance values are the average of the lighting levels over the entire area. For good lighting, the individual values should be as uniform as possible.

TABLE 5.3 Recommended Illuminance Values Maintained in Lux for Illuminance on Task for Categories E and F

Weighting Factors				
Average of Workers' Ages	Demand for Speed and/or Accuracy[a]	Task Background Reflectance (%)	Categories[b] E	F
Under 40	NI	Over 70	500	1000
		30 to 70	500	1000
		Under 30	750	1500
	I	Over 70	500	1000
		30 to 70	750	1500
		Under 30	750	1500
	C	Over 70	750	1500
		30 to 70	750	1500
		Under 30	750	1500

[a] NI, not important; I, important; C, critical.

[b] For footcandles, divide by 10.

Source: Adapted from the *IES Lighting Handbook, 1987 Application Volume* (New York: Illuminating Engineering Society of North America, 1987). Refer to the *IES Lighting Handbook, 1987 Application Volume,* for the complete table on recommended illuminance values for categories A through I and for the full range of ages.

5.2 LUMEN METHOD

The lumen method is used to design the general overall lighting of a room. This method calculates the illuminance that represents the average of the values at all points over the entire workplane of the room. The workplane is an imaginary horizontal plane at the height at which the task will be performed. For example, in an office the workplane is assumed to be 2.5 feet above the floor, as this is the standard height of desk tops. The lumen method is based on the definition of illuminance as covered in Section 3.3 and Table 3.1:

$$\text{Illuminance} = \frac{\text{luminous flux } (\phi)}{\text{area}}$$

Since the illuminance level applies to the workplane, and the workplane for general lighting covers the whole room:

$$E = \frac{\text{total luminous flux falling on the workplane}}{\text{area of room}}$$

Now consider a room in which the lighting has already been installed. By noting the number of luminaires in the room and the number and type of lamps installed in each luminaire, the total lumens generated by the lamps can easily be calculated:

$$\text{TILL} = \text{total lamps} \times \text{initial lumens per lamp}$$

where TILL is the total initial lamp lumens. However, not all these lamp lumens reach the workplane as some are trapped within the luminaire and some are absorbed by the room surfaces. Before the illuminance at the workplane can be calculated, it is necessary to establish a factor that represents the ratio between the lumens reaching the workplane and the total lamp lumens. This factor is known as the *coefficient of utilization* (CU). Thus,

$$\text{CU} = \frac{\text{total lumens falling on the workplane}}{\text{total initial lamp lumens}}$$

Combining the previous relationships gives

$$E = \frac{\text{TILL} \times \text{CU}}{\text{area}} \qquad \textbf{(5.1)}$$

where E is the average illuminance at the workplane. To complete this calculation, it is necessary to be able to determine the coefficient of utilization for the particular lighting system.

5.2.1 Coefficient of Utilization

The coefficient of utilization represents the efficiency of the whole lighting system, including the luminaires and the space (room) in which they are installed. [It does not include the efficiency (efficacy) of the light source itself.] The coefficient of utilization depends on a number of factors.

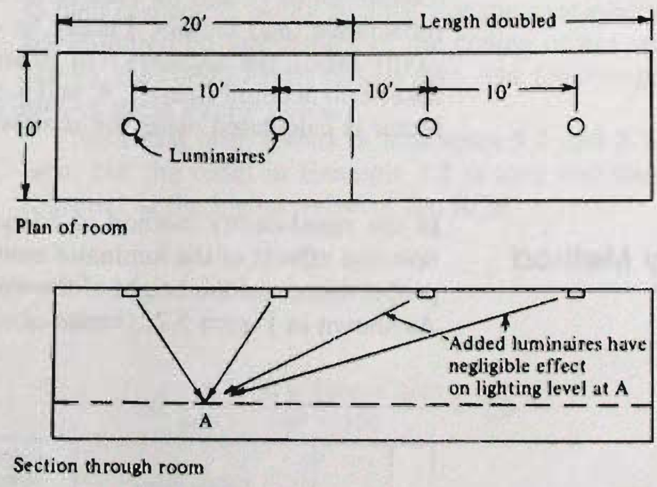
1. *Type of luminaire* Its efficiency and distribution pattern (see Section 3.7).

2. *Reflectance of the room surfaces* The higher the reflectance factors of ceilings, walls, and floors, the greater the percentage of the lamp lumens that will be redirected to the workplane. Also, their effect will vary with the type of distribution pattern of the luminaire. For example, compare the case where the luminaire has an upward light component and is suspended from the ceiling with the case where the luminaire has only a downward light component and is recessed in the ceiling. In the first case, the amount of light reaching the workplane is very dependent on the reflected light from the ceiling. In the latter case, most of the light reaching the workplane comes directly from the luminaire, and the ceiling reflectance has far less effect.

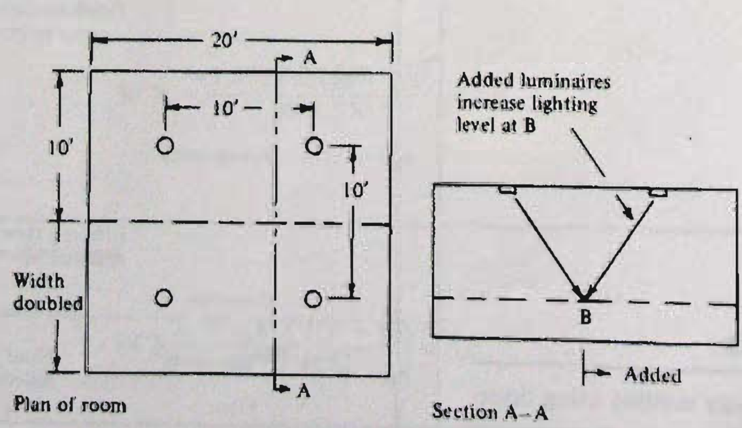
3. *Mounting height of the luminaire* The greater the height, the greater the area of the wall surfaces is, which in turn absorbs more of the lamp lumens.

4. *Area of the room* The larger the room is, the greater the number of luminaires required. The light distributed from each luminaire overlaps one another, helping to increase the overall lighting level. Also, there is less wall surface per unit of area to absorb the light.

5. *Proportions of the room* A room may be long and narrow or square. Figure 5.1 shows the effect of doubling the size of the room, first by increasing its length, and second by increasing its width. In part (a), the additional two lamps have very little effect on the lighting level in the original area, and vice versa. However, in part (b),



(a) Doubling room area by increasing length



(b) Doubling room area by increasing width

FIGURE 5.1

Effect of room proportions on lighting levels the additional two lamps do increase the overall lighting level, even though each luminaire still covers an area of 10 feet by 10 feet as before. Also, compare the amount of wall surface enclosing the 10 × 40 foot room with that enclosing the 20 × 20 foot room, both of which have the same floor area. The greater wall surface area of the former will absorb more light. As a result, a square room has a higher coefficient of utilization than a long and narrow room, all other factors being the same.

To take all of the preceding factors into account, tables of coefficient of utilization (CU) factors are required. Refer to Table 5.5. There is a separate set of CU values shown for each type of luminaire. The type is identified by a sketch, together with its distribution pattern and the type of light source used. Across the top of the table, effective ceiling cavity reflectance (ρ_{CC}) factors are listed, (columns 4 to 9), and for each of these there are three different wall reflectance (ρ_W) factors. Finally, in column 3, headed RCR (room cavity ratio), the numbers 0 to 10 are listed. The room cavity ratio takes into account items 3, 4, and 5, which affect the CU. The RCR factor is calculated using the *zonal-cavity* method.

5.2.2 Zonal-Cavity Method

In the zonal-cavity method of computing the coefficient of utilization, the effects of the luminaire mounting height, the room size and proportions, and the height of the workplane are taken into account. As shown in Figure 5.2, the cross section of a room is divided into

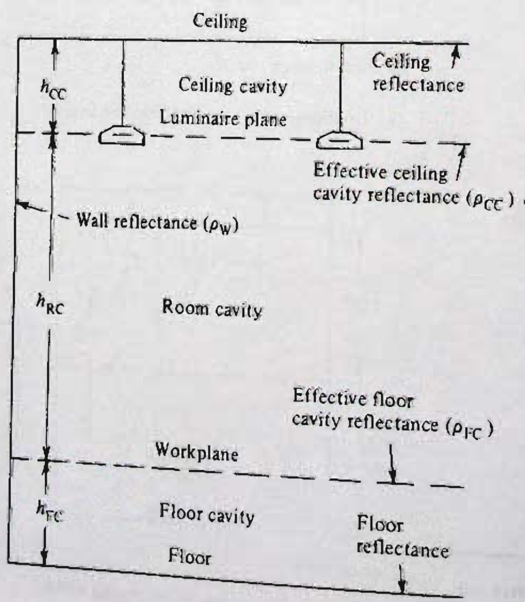


FIGURE 5.2

Zonal-cavity method using three cavities three separate cavities. The space between the ceiling and the luminaire plane is the ceiling cavity, the space between the luminaire plane and the workplane is the room cavity, and the space between the workplane and the floor is the floor cavity. The cavity ratios (CR) for these three cavities are determined by using the following formula:

$$\mathrm{CR} = \frac{5h \times (\text{room width} + \text{room length})}{\text{room width} \times \text{room length}} \tag{5.2}$$

where $h = h_{CC}$ for the ceiling cavity ratio (CCR)
$= h_{RC}$ for the room cavity ratio (RCR)
$= h_{FC}$ for the floor cavity ratio (FCR)

Note that for a given room the cavity ratios are in direct proportion to their respective cavity heights. For the case where the luminaires are mounted on the surface of the ceiling or are recessed into the ceiling, the ceiling cavity ratio is zero. The following are three examples of room cavity ratios.

Note that both rooms in Examples 5.2 and 5.3 have the same area, but the room in Example 5.3 is long and narrow and this is reflected in the higher value of the RCR.

EXAMPLE 5.2

A room is 100 ft by 100 ft (10,000 ft^2 in area). The luminaire is mounted 20 ft above the workplane.

Solution

$$\mathrm{RCR} = \frac{5 \times 20 \times (100 + 100)}{100 \times 100} = 2.0$$

EXAMPLE 5.3

A room is 40 ft by 250 ft (10,000 ft^2 in area). The luminaire is mounted 20 ft above the workplane.

Solution

$$\mathrm{RCR} = \frac{5 \times 20 \times (40 + 250)}{40 \times 250} = 2.9$$

EXAMPLE 5.4

A room is 12 ft by 12 ft (144 ft^2 in area). The luminaire is mounted 6 ft above the workplane.

Solution

$$\mathrm{RCR} = \frac{5 \times 6 \times (12 + 12)}{12 \times 12} = 5.0$$

Note that the rooms in Examples 5.2 and 5.4 are both square, but the room in Example 5.4 is much smaller. This is reflected in a much higher value of RCR. Note also that the room cavity ratio is directly proportional to the height of the room cavity (h_{RC}), which is also the mounting height of the luminaire above the workplane. The greater the mounting height is, the greater the value of the RCR factor (for the same width and length).

Refer to Table 5.5. Note that for any of the luminaires, as the RCR factor increases from 0 toward 10, the coefficient of utilization factor decreases (for the same reflectance factors). This substantiates the points made in Section 5.2.1, items 3, 4, and 5. Note also that the cavity ratios are dimensionless and that the calculated values would be the same if the dimensions were in meters.

Since the coefficient of utilization is based on the room cavity ratio, it is necessary to treat this cavity as if there were a ceiling surface at the luminaire plane and a floor surface at the workplane level as shown in Figure 5.2. Therefore, it is necessary to convert the actual ceiling reflectance into an *effective ceiling cavity reflectance* (ρ_{CC}). Similarly, the actual floor reflectance must be con-

TABLE 5.4 Effective Cavity Reflectances

Base Refl. %	90						
Wall Refl. %	90	80	70	50	30	10	0
Cavity Ratio 0.2	89	88	88	86	85	84	82
0.4	88	87	86	84	81	79	76
0.6	87	86	84	80	77	74	73
0.8	87	85	82	77	73	69	67
1.0	86	83	80	75	69	64	62
1.5	85	80	76	68	61	55	51
2.0	83	77	72	62	53	47	43
2.5	82	75	68	57	47	40	36
3.0	80	72	64	52	42	34	30
3.5	79	70	61	48	37	31	26
4.0	77	69	58	44	33	25	22
5.0	75	59	53	38	28	20	16
6.0	73	61	49	34	24	16	11
8.0	68	55	42	27	18	12	06
10.0	65	51	36	22	15	09	04

Base Refl. %	80						
Wall Refl. %	90	80	70	50	30	10	0
Cavity Ratio 0.2	79	78	78	77	76	74	72
0.4	79	77	76	74	72	70	68
0.6	78	76	75	71	68	65	63
0.8	78	75	73	69	65	61	57
1.0	77	74	72	67	62	57	55
1.5	75	72	68	61	54	49	46
2.0	74	69	64	56	48	41	38
2.5	73	67	61	51	42	35	32
3.0	72	65	58	47	37	30	27
3.5	71	63	55	43	33	26	24
4.0	70	61	53	40	30	22	20
5.0	68	58	48	35	25	18	14
6.0	66	55	44	31	22	15	10
8.0	62	50	38	25	17	11	05
10.0	59	46	33	21	14	08	03

Base Refl. %	70						
Wall Refl. %	90	80	70	50	30	10	0
Cavity Ratio 0.2	70	69	68	67	66	65	64
0.4	69	68	67	65	63	61	58
0.6	69	67	65	63	59	57	54
0.8	68	66	64	60	56	53	50
1.0	68	65	62	58	53	50	47
1.5	67	62	59	54	46	42	40
2.0	66	60	56	49	40	36	33
2.5	65	60	54	45	36	31	29
3.0	64	58	52	42	32	27	24
3.5	63	57	50	38	29	23	21
4.0	63	55	48	36	26	20	17
5.0	61	52	44	31	22	16	12
6.0	60	51	41	28	19	13	09
8.0	57	46	35	23	15	10	05
10.0	55	43	31	19	12	08	03

Base Refl. %	60						
Wall Refl. %	90	80	70	50	30	10	0
Cavity Ratio 0.2	60	59	59	58	56	55	53
0.4	60	59	59	57	54	52	50
0.6	60	58	57	55	51	50	46
0.8	59	57	56	54	48	46	43
1.0	59	57	55	51	45	43	41
1.5	59	55	52	46	40	37	34
2.0	58	54	50	43	35	31	29
2.5	58	53	47	39	30	25	23
3.0	57	52	46	37	28	23	20
3.5	57	50	44	35	25	20	17
4.0	57	49	42	32	23	18	14
5.0	56	48	40	28	20	14	11
6.0	55	45	37	25	17	11	07
8.0	53	42	33	22	14	08	04
10.0	51	39	29	18	11	07	02

Base Refl. %	50						
Wall Refl. %	90	80	70	50	30	10	0
Cavity Ratio 0.2	50	50	49	48	47	46	44
0.4	50	49	48	47	45	44	42
0.6	50	48	47	45	43	41	38
0.8	50	48	47	44	40	38	36
1.0	50	48	46	43	38	36	34
1.5	50	47	45	40	34	31	26
2.0	50	46	43	37	30	26	24
2.5	50	46	41	35	27	22	21
3.0	50	45	40	32	24	19	17
3.5	50	44	39	30	22	17	15
4.0	50	44	38	28	20	15	12
5.0	50	42	35	25	17	12	09
6.0	50	42	34	23	15	10	06
8.0	49	40	30	19	12	07	03
10.0	47	37	27	17	10	06	02

Base Refl. %	40						
Wall Refl. %	90	80	70	50	30	10	0
Cavity Ratio 0.2	40	40	39	39	38	36	36
0.4	41	40	39	38	36	34	34
0.6	41	40	39	37	34	32	31
0.8	41	40	38	36	33	31	29
1.0	42	30	38	34	32	29	27
1.5	42	39	37	32	28	24	22
2.0	42	39	36	31	25	21	19
2.5	43	39	35	29	23	18	15
3.0	43	39	35	27	21	16	13
3.5	44	39	34	26	20	14	12
4.0	44	38	33	25	18	12	10
5.0	45	38	31	22	15	10	07
6.0	44	37	30	20	13	08	05
8.0	44	35	28	18	11	06	03
10.0	43	34	25	15	08	05	02

Base Refl. %	30						
Wall Refl. %	90	80	70	50	30	10	0
Cavity Ratio 0.2	31	31	30	29	29	28	27
0.4	31	31	30	29	28	26	25
0.6	32	31	30	28	26	25	23
0.8	32	31	30	28	25	23	22
1.0	33	32	30	27	24	22	20
1.5	34	33	30	25	22	18	17
2.0	35	33	29	24	20	16	14
2.5	36	32	29	24	18	14	12
3.0	37	33	29	22	17	12	10
3.5	38	33	29	21	15	10	09
4.0	38	33	28	21	14	09	07
5.0	39	33	28	19	13	08	05
6.0	39	33	27	18	11	06	04
8.0	40	33	26	16	09	04	02
10.0	40	32	24	14	08	03	01

Base Refl. %	20						
Wall Refl. %	90	80	70	50	30	10	0
Cavity Ratio 0.2	21	20	20	20	19	19	17
0.4	22	21	20	20	19	18	16
0.6	23	21	21	19	18	17	15
0.8	24	22	21	19	18	16	14
1.0	25	23	22	19	17	15	13
1.5	26	24	22	18	16	13	11
2.0	28	25	23	18	15	11	09
2.5	29	26	23	18	14	10	08
3.0	30	27	23	17	13	09	07
3.5	32	27	23	17	12	08	05
4.0	33	28	23	17	11	07	07
5.0	35	29	24	16	10	06	04
6.0	36	30	24	16	10	05	02
8.0	37	30	23	15	08	03	01
10.0	37	29	22	13	07	03	01

Base Refl. %	10						
Wall Refl. %	90	80	70	50	30	10	0
Cavity Ratio 0.2	11	11	11	10	10	09	09
0.4	12	11	11	11	10	09	08
0.6	13	13	12	11	10	08	08
0.8	15	14	13	11	10	08	07
1.0	16	14	13	12	10	08	07
1.5	18	16	15	12	10	07	06
2.0	20	18	16	13	09	06	05
2.5	22	20	17	13	09	05	04
3.0	24	21	18	13	09	05	03
3.5	26	22	19	13	09	05	03
4.0	27	23	20	14	09	04	02
5.0	30	25	20	14	08	04	02
6.0	31	26	21	14	08	03	01
8.0	33	27	21	13	07	03	01
10.0	34	28	21	12	07	02	01

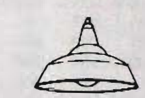
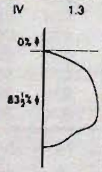
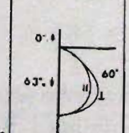
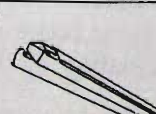
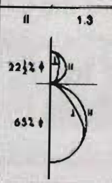
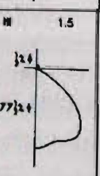
Base Refl. %	0						
Wall Refl. %	90	80	70	50	30	10	0
Cavity Ratio 0.2	02	02	02	01	01	00	0
0.4	04	03	03	02	01	00	0
0.6	05	05	04	03	02	01	0
0.8	07	06	05	04	02	01	0
1.0	08	07	06	04	02	01	0
1.5	11	10	08	06	03	01	0
2.0	14	12	10	07	04	01	0
2.5	16	14	12	08	05	02	0
3.0	18	16	13	09	05	02	0
3.5	20	17	15	10	05	02	0
4.0	22	18	15	10	05	02	0
5.0	25	21	17	11	06	02	0
6.0	27	23	18	12	06	02	0
8.0	30	25	20	12	06	02	0
10.0	31	25	20	12	06	02	0

Source: Adapted from the *IES Lighting Handbook, 1984 Reference Volume* (New York: Illuminating Engineering Society of North America, 1984). Refer to the *1984 Reference Volume* for the complete table on effective cavity reflectances.

verted to an *effective floor cavity reflectance* (ρ_{FC}). Refer to Table 5.5 and note that it is the effective values of reflectances that are used to obtain the coefficient of utilization.

The values for the effective reflectances are obtained from Table 5.4. The term *base reflectance* refers to the actual reflectance of the cavity surface. For instance, when obtaining the effective reflectance for the ceiling cavity, the base reflectance is the actual reflectance of the ceiling. Similarly, when obtaining the effective reflectance for the floor cavity, the base reflectance is the actual reflectance of the floor. Note that the coefficient of utilization factors in

TABLE 5.5 Coefficients of Utilization

Typical Luminaire	Typical Intensity Distribution and Per Cent Lamp Lumens		ρ_{CC} →	80			70			50			30			10			0
			ρ_W →	50	30	10	50	30	10	50	30	10	50	30	10	50	30	10	0
	Maint. Cat.	SC	RCR ↓	Coefficients of Utilization for 20 Per Cent Effective Floor Cavity Reflectance (ρ_{FC} = 20)															
1	IV	1.3	0	.99	.99	.99	.97	.97	.97	.93	.93	.93	.89	.89	.89	.85	.85	.85	.83
			1	.87	.84	.81	.85	.82	.79	.82	.79	.77	.79	.76	.74	.78	.74	.72	.71
			2	.76	.70	.65	.74	.69	.65	.71	.67	.63	.69	.65	.62	.66	.63	.60	.59
			3	.66	.59	.54	.65	.59	.53	.62	.57	.53	.60	.56	.52	.58	.54	.51	.49
			4	.58	.51	.45	.57	.50	.45	.55	.49	.44	.53	.48	.44	.51	.47	.43	.41
			5	.52	.44	.39	.51	.44	.38	.49	.43	.38	.47	.42	.37	.46	.41	.37	.35
			6	.46	.39	.33	.46	.38	.33	.44	.38	.33	.43	.37	.33	.41	.36	.32	.31
			7	.42	.34	.29	.41	.34	.29	.40	.33	.29	.39	.33	.29	.38	.32	.28	.27
			8	.38	.31	.26	.37	.31	.26	.36	.30	.26	.35	.30	.25	.34	.29	.25	.24
Porcelain-enameled ventilated standard			9	.35	.28	.23	.34	.28	.23	.33	.27	.23	.32	.27	.23	.32	.26	.23	.21
dome with incandescent lamp			10	.32	.25	.21	.32	.25	.21	.31	.25	.21	.30	.24	.21	.29	.24	.20	.19
2	V	1.4/1.2	0	.75	.75	.75	.73	.73	.73	.70	.70	.70	.67	.67	.67	.64	.64	.64	.63
			1	.67	.64	.62	.65	.63	.61	.63	.61	.59	.60	.59	.58	.58	.57	.56	.56
			2	.59	.56	.52	.58	.55	.52	.56	.53	.51	.54	.52	.49	.52	.50	.48	.47
			3	.53	.48	.45	.52	.48	.44	.50	.46	.43	.48	.45	.43	.47	.44	.42	.41
			4	.47	.42	.38	.46	.42	.38	.45	.41	.38	.44	.40	.37	.42	.39	.37	.35
			5	.43	.37	.34	.42	.37	.33	.41	.36	.33	.39	.38	.33	.38	.35	.32	.31
			6	.39	.33	.30	.38	.33	.29	.37	.32	.29	.36	.32	.29	.35	.31	.29	.27
			7	.35	.30	.26	.35	.30	.26	.34	.29	.26	.33	.29	.26	.32	.28	.26	.24
			8	.32	.27	.24	.32	.27	.23	.31	.26	.23	.30	.26	.23	.29	.26	.23	.22
Fluorescent unit with flat prismatic lens,			9	.30	.25	.21	.29	.24	.21	.28	.24	.21	.28	.24	.21	.27	.24	.21	.20
4-lamp 610 mm (2') wide—see note			10	.27	.22	.19	.27	.22	.19	.26	.22	.19	.26	.22	.19	.25	.22	.19	.18
3	II	1.3	0	.99	.99	.99	.94	.94	.94	.85	.85	.85	.77	.77	.77	.69	.69	.69	.65
			1	.87	.84	.81	.83	.80	.77	.75	.73	.71	.68	.66	.65	.62	.60	.59	.56
			2	.77	.71	.67	.73	.68	.64	.67	.63	.60	.60	.58	.55	.55	.53	.51	.48
			3	.68	.62	.56	.65	.59	.54	.59	.55	.51	.54	.50	.47	.49	.46	.44	.41
			4	.61	.54	.48	.58	.52	.47	.53	.48	.44	.48	.44	.41	.44	.41	.38	.35
			5	.54	.47	.42	.52	.46	.41	.48	.42	.38	.44	.39	.36	.40	.36	.33	.31
			6	.49	.42	.37	.47	.40	.36	.43	.38	.34	.40	.35	.32	.36	.33	.30	.27
			7	.45	.37	.32	.43	.36	.32	.39	.34	.30	.36	.32	.28	.33	.29	.26	.24
			8	.41	.34	.29	.39	.33	.28	.36	.31	.27	.33	.29	.25	.31	.27	.24	.22
Porcelain-enameled reflector with			9	.37	.31	.26	.36	.30	.25	.33	.28	.24	.31	.26	.23	.28	.24	.22	.20
35°CW shielding			10	.34	.28	.24	.33	.27	.23	.31	.25	.22	.28	.24	.21	.26	.22	.20	.18
4	III	1.5	0	.93	.93	.93	.91	.91	.91	.87	.87	.87	.83	.83	.83	.79	.79	.79	.78
			1	.84	.81	.79	.82	.80	.78	.79	.77	.75	.76	.74	.73	.73	.72	.70	.69
			2	.75	.71	.67	.74	.70	.66	.71	.68	.65	.68	.66	.63	.66	.64	.62	.60
			3	.67	.62	.57	.66	.61	.57	.64	.59	.56	.61	.58	.55	.59	.56	.54	.52
			4	.60	.54	.50	.59	.54	.49	.57	.52	.48	.55	.51	.48	.54	.50	.47	.46
			5	.54	.48	.43	.53	.47	.43	.52	.46	.42	.50	.45	.42	.49	.45	.41	.40
			6	.49	.42	.38	.48	.42	.38	.47	.41	.37	.45	.41	.37	.44	.40	.37	.35
			7	.44	.38	.34	.44	.38	.33	.42	.37	.33	.41	.36	.33	.40	.36	.33	.31
			8	.40	.34	.30	.40	.34	.30	.39	.33	.30	.38	.33	.29	.37	.32	.29	.28
"High bay" wide distribution ventilated			9	.37	.31	.27	.37	.31	.27	.36	.30	.27	.35	.30	.28	.34	.29	.26	.25
reflector with clear HID lamp			10	.34	.28	.24	.34	.28	.24	.33	.28	.24	.32	.27	.24	.31	.27	.24	.22

For a luminaire similar to No. 2 except 1 ft (300 mm) wide using two lamps, multiply CU values by 0.9.

Source: Adapted from the *IES Lighting Handbook, 1984 Reference Volume* (New York: Illuminating Engineering Society of North America, 1984). Refer to the *1984 Reference Volume* for a more complete listing of luminaires.

TABLE 5.6 Multiplying Factors for Other Than 20% Effective Floor Cavity Reflectances

% Effective Ceiling Cavity Reflectance, ρ_{CC}	80				70				50			30			10		
% Wall Reflectance, ρ_W	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10
For 30 Per Cent Effective Floor Cavity Reflectance (20 Per Cent = 1.00)																	
Room Cavity Ratio																	
1	1.092	1.082	1.075	1.068	1.077	1.070	1.064	1.059	1.049	1.044	1.040	1.028	1.026	1.023	1.012	1.010	1.008
2	1.079	1.066	1.055	1.047	1.068	1.057	1.048	1.039	1.041	1.033	1.027	1.026	1.021	1.017	1.013	1.010	1.006
3	1.070	1.054	1.042	1.033	1.061	1.048	1.037	1.028	1.034	1.027	1.020	1.024	1.017	1.012	1.014	1.009	1.005
4	1.062	1.045	1.033	1.024	1.055	1.040	1.029	1.021	1.030	1.022	1.015	1.022	1.015	1.010	1.014	1.009	1.004
5	1.056	1.038	1.026	1.018	1.050	1.034	1.024	1.015	1.027	1.018	1.012	1.020	1.013	1.008	1.014	1.009	1.004
6	1.052	1.033	1.021	1.014	1.047	1.030	1.020	1.012	1.024	1.015	1.009	1.019	1.012	1.006	1.014	1.008	1.003
7	1.047	1.029	1.018	1.011	1.043	1.026	1.017	1.009	1.022	1.013	1.007	1.018	1.010	1.005	1.014	1.008	1.003
8	1.044	1.026	1.015	1.009	1.040	1.024	1.015	1.007	1.020	1.012	1.006	1.017	1.009	1.004	1.013	1.007	1.003
9	1.040	1.024	1.014	1.007	1.037	1.022	1.014	1.006	1.019	1.011	1.005	1.016	1.009	1.004	1.013	1.007	1.002
10	1.037	1.022	1.012	1.006	1.034	1.020	1.012	1.005	1.017	1.010	1.004	1.015	1.009	1.003	1.013	1.007	1.002
For 10 Per Cent Effective Floor Cavity Reflectance (20 Per Cent = 1.00)																	
Room Cavity Ratio																	
1	.923	.929	.935	.940	.933	.939	.943	.948	.956	.960	.963	.973	.976	.979	.989	.991	.993
2	.931	.942	.950	.958	.940	.949	.957	.963	.962	.968	.974	.976	.980	.985	.988	.991	.995
3	.939	.951	.961	.969	.945	.957	.966	.973	.967	.975	.981	.978	.983	.988	.988	.992	.996
4	.944	.958	.969	.978	.950	.963	.973	.980	.972	.980	.986	.980	.986	.991	.987	.992	.996
5	.949	.964	.976	.983	.954	.968	.978	.985	.975	.983	.989	.981	.988	.993	.987	.992	.997
6	.953	.969	.980	.986	.958	.972	.982	.989	.977	.985	.992	.982	.989	.995	.987	.993	.997
7	.957	.973	.983	.991	.961	.975	.985	.991	.979	.987	.994	.983	.990	.996	.987	.993	.998
8	.960	.976	.986	.993	.963	.977	.987	.993	.981	.988	.995	.984	.991	.997	.987	.994	.998
9	.963	.978	.987	.994	.965	.979	.989	.994	.983	.990	.996	.985	.992	.998	.988	.994	.999
10	.965	.980	.989	.995	.967	.981	.990	.995	.984	.991	.997	.986	.993	.998	.988	.994	.999

Source: Adapted from the *IES Lighting Handbook, 1984 Reference Volume* (New York: Illuminating Engineering Society of North America, 1984). Refer to the *1984 Reference Volume* for the complete table.

Table 5.5 are based on an effective floor cavity reflectance (ρ_{FC}) of 20% as indicated at the top of the table. For values other than 20%, the value of the CU obtained from Table 5.5 is corrected by applying the appropriate multiplying factor obtained from Table 5.6. See Example 5.5 for the calculation of the coefficient of utilization for a typical lighting layout.

■ EXAMPLE 5.5

A room is 60 ft by 120 ft in area with a 24 ft high ceiling. The luminaire 1 in Table 5.5 is used, and it is suspended 5 ft below the ceiling. The reflectance factors are ceiling 60%, walls 30%, and floor 10%. The workplane is 3 ft above the floor. Calculate the coefficient of utilization.

Solution

STEP 1 Draw the cross section through the room and determine the cavity heights (see Figure 5.3).

STEP 2 Calculate the cavity ratios using Equation 5.2:

$$\text{CCR} = \frac{5 \times 5 \times (60 + 120)}{60 \times 120} = 0.625 \approx 0.6$$

$$\text{RCR} = \frac{5 \times 16 \times (60 + 120)}{60 \times 120} = 2.0$$

$$\text{FCR} = \frac{5 \times 3 \times (60 + 120)}{60 \times 120} = 0.375 \approx 0.4$$

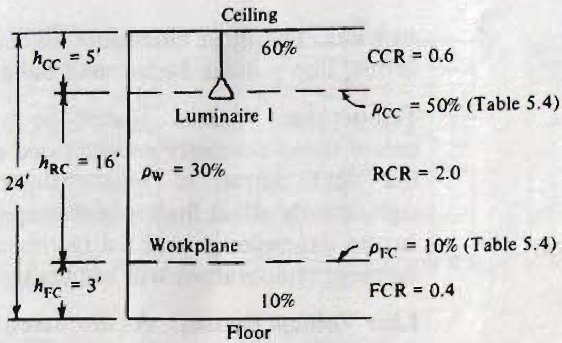


FIGURE 5.3

Cross section diagram for Example 5.5

STEP 3 Determine the effective ceiling cavity reflectance from Table 5.4. For a base reflectance of 60%, wall reflectance of 30%, and cavity ratio of 0.6, ρ_{CC} = 51 (use 50%).

STEP 4 Determine the effective floor cavity reflectance from Table 5.4. For a base reflectance of 10%, wall reflectance of 30%, and cavity ratio of 0.4, ρ_{FC} = 10% (no change).

STEP 5 Determine the coefficient of utilization (CU) from Table 5.5. For luminaire 1, ρ_{CC} = 50%, ρ_W = 30%, and RCR = 2. CU = 0.67 (for 20% floor reflectance).

STEP 6 Determine the correction for 10% floor reflectance from Table 5.6. For ρ_{CC} = 50%, ρ_W = 30%, and RCR = 2, the multiplying factor is 0.968. b/c Table 5.5 is for 20% = ρ_{FC}

Final CU = 0.67 × 0.968 = 0.648 = 0.65

CU

(Two-figure accuracy is acceptable.)

5.3 LIGHT LOSS FACTOR

From the time that a new lighting system is first energized, the lighting level gradually decreases because of aging. The recommended lighting levels as discussed in Section 5.1 are based on minimum values that should be maintained over the operating life of the system. Therefore, it is necessary to provide higher initial illuminance levels to compensate for the loss of light with time. The light loss factor is the ratio of the illuminance when it reaches its lower level just before corrective action is taken as compared to the initial level. The light loss factor is the product of all the individual factors that contribute to the loss of light. These factors are divided into two categories, unrecoverable and recoverable. The unrecoverable factors are those attributed to equipment and site conditions that cannot be changed with normal maintenance. Recoverable factors are those that can be changed by regular scheduled maintenance, such as cleaning and relamping luminaires and cleaning and painting room surfaces. The three chief unrecoverable factors are the temperature factor, line voltage factor, and ballast factor.

Temperature Factor. Variations in ambient temperature above or below those normally encountered in interiors have little effect on the light output of incandescent and HID lamps, but they significantly affect fluorescent lamps (refer to Section 4.3.8, item 3). In the examples presented in this chapter, it is assumed that the ambient temperature will not create a problem.

Line Voltage Factor. As discussed for each light source in Chapter 4, its light output is affected by variations in the supply voltage. In the examples presented in this chapter, it is assumed that voltages will be kept at the proper level to maintain full light output from the lamps.

Ballast Factor. The published initial lumen ratings for fluorescent and HID lamps are based on the use of test quality ballasts. The commercially available ballasts actually installed with the luminaires may not operate the lamps with the same efficacy. The ballast factor (BF) is the ratio of the lamp lumens generated on commercial ballasts to those generated on the test quality ballasts. The ballast factor for good quality fluorescent ballasts is nominally 0.95. There is no published standard for HID source ballasts and therefore a factor of 1.0 is assumed in the examples.

Other unrecoverable factors are the equipment operating factor, the lamp positioning factor, and the luminaire surface depreciating factor. For the sake of simplifying the examples, these factors are not considered.

The recoverable factors that must be considered in calculating the light loss factor are lamp lumen depreciation, luminaire dirt depreciation, and room surface dirt depreciation.

Lamp Lumen Depreciation. This item is discussed in Chapter 4 for each type of light source. The lamp lumen depreciation (LLD) factors are listed in the appropriate tables in that chapter.

Luminaire Dirt Depreciation. With the passage of time, dirt accumulates on the lamps and on the surfaces of the luminaires. This dirt absorbs some of the light. The resulting loss of light is accounted for by the luminaire dirt depreciation (LDD) factor, which is determined by referring to Figure 5.4. Depending on the type of construction, luminaires are divided into six maintenance categories. Each luminaire listed in Table 5.5 has an assigned maintenance category that indicates which of the graphs in Figure 5.4 to use. Also, there are five degrees of operating atmosphere, ranging from very clean to very dirty. In the examples presented in

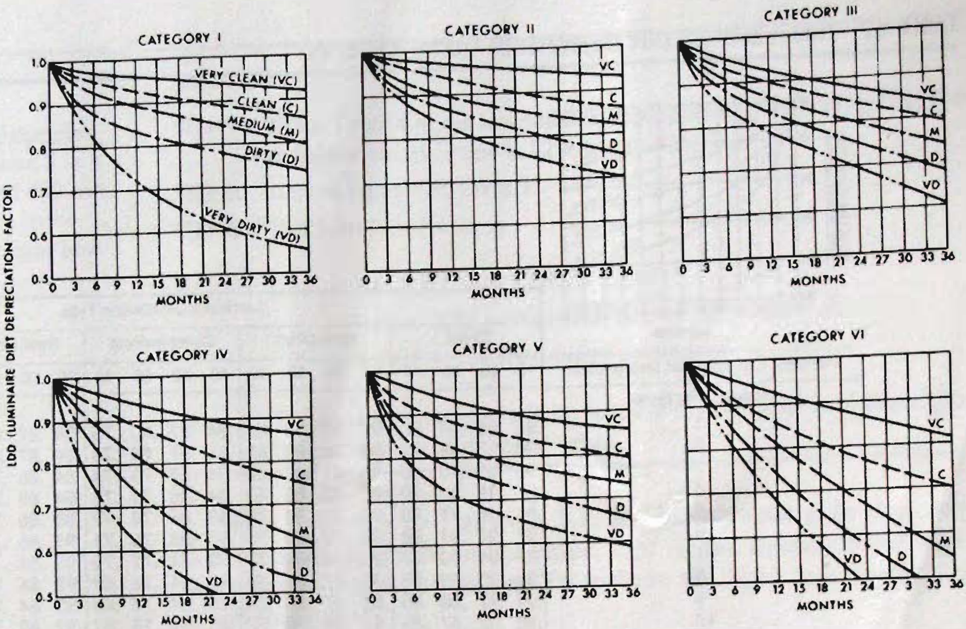


FIGURE 5.4

Luminaire dirt depreciation (LDD) factors

this chapter, the degree of operating atmosphere is given. For information on how to determine the specific degree of an operating atmosphere, consult the *IES Lighting Handbook, 1984 Reference Volume*.

■ EXAMPLE 5.6

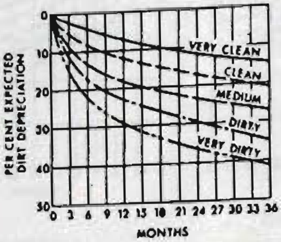
Luminaire 3 in Table 5.5 is used for a lighting layout. The atmosphere will be clean and the period between cleanings will be 24 months. Determine the LDD factor.

Solution

From Table 5.5, the assigned maintenance category for luminaire 3 is II. From Figure 5.4, category II graph, for clean atmosphere at 24 months, the LDD factor is 0.89.

Room Surface Dirt Depreciation. With the passage of time, the accumulation of dirt on the surfaces of the room further reduces the amount of light that reaches the workplane. The exact effect of dirt on light loss varies according to the size and proportions of the room (that is, the room cavity ratio), the type of operating atmosphere, and the luminaire distribution type. The resulting loss of light is accounted for by the room surface dirt depreciation (RSDD) factor, which is determined by referring to Table 5.7. First, select th

TABLE 5.7 Room Surface Dirt Depreciation (RSDD) Factors



	Luminaire Distribution Type																			
	Direct				Semi-Direct				Direct-Indirect				Semi-Indirect				Indirect			
Per Cent Expected Dirt Depreciation	10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40
Room Cavity Ratio																				
1	.98	.96	.94	.92	.97	.92	.89	.84	.94	.87	.80	.76	.94	.87	.80	.73	.90	.80	.70	.60
2	.98	.96	.94	.92	.96	.92	.88	.83	.94	.87	.80	.75	.94	.87	.79	.72	.90	.80	.69	.59
3	.98	.95	.93	.90	.96	.91	.87	.82	.94	.86	.79	.74	.94	.86	.78	.71	.90	.79	.68	.58
4	.97	.95	.92	.90	.95	.90	.85	.80	.94	.86	.79	.73	.94	.86	.78	.70	.89	.78	.67	.56
5	.97	.94	.91	.89	.94	.90	.84	.79	.93	.86	.78	.72	.93	.86	.77	.69	.89	.78	.66	.55
6	.97	.94	.91	.88	.94	.89	.83	.78	.93	.85	.78	.71	.93	.85	.76	.68	.89	.77	.66	.54
7	.97	.94	.90	.87	.93	.88	.82	.77	.93	.84	.77	.70	.93	.84	.76	.68	.89	.76	.65	.53
8	.96	.93	.89	.86	.93	.87	.81	.75	.93	.84	.76	.69	.93	.84	.76	.68	.88	.76	.64	.52
9	.96	.92	.88	.85	.93	.87	.80	.74	.93	.84	.76	.68	.93	.84	.75	.67	.88	.75	.63	.51
10	.96	.92	.87	.83	.93	.86	.79	.72	.93	.84	.75	.67	.92	.83	.75	.67	.88	.75	.62	.50

Source: Adapted from the *IES Lighting Handbook, 1984 Reference Volume.*

percent of expected dirt depreciation from the graph accompanying Table 5.7, using the appropriate atmosphere curve and the time interval in months between cleaning. Then refer to the table and, depending on the room cavity ratio and the luminaire distribution type, select the RSDD factor. Refer to Section 5.4 and Figure 5.5 for the luminaire distribution types.

■ EXAMPLE 5.7

Luminaire 3 is to be used, the atmosphere will be clean, and the period between cleanings will be 24 months (all the same as in Example 5.6). The room cavity ratio has been calculated to be 2.0. Determine the RSDD factor.

Solution

STEP 1 From Table 5.5, luminaire 3 has a ratio of 22.5% to 65% for upward and downward light components, which translates to 26% upward and 74% downward.

STEP 2 From Figure 5.5, the luminaire is a semidirect type.

STEP 3 From the graph in Table 5.7, for a clean atmosphere at 24 months, the percent of expected dirt depreciation is 17.5%.

STEP 4 From Table 5.7 for a semidirect luminaire and a room cavity ratio of 2, the room surface dirt depreciation (RSDD) factor is 0.93 (interpolate between 0.96 for 10% and 0.92 for 20% expected dirt depreciation).

The light loss factor is then the product of all the individual factors discussed.

■ EXAMPLE 5.8

Continue on from Examples 5.6 and 5.7. Luminaire 3 is a fluorescent type, and 800 mA rapid-start lamps are to be used. Calculate the light loss factor.

Solution

STEP 1 From Table 4.4, the lamp lumen depreciation (LLD) factor for 800 mA fluorescent lamps is 82% (use 0.82).

STEP 2 Ballast factor (BF) is 0.95.

STEP 3 The light loss factor is

$$\begin{aligned} \text{LLF} &= \text{BF} \times \text{LLD} \times \text{LDD} \times \text{RSDD} \\ &= 0.95 \times 0.82 \times 0.89 \text{ (Ex. 5.6)} \times 0.93 \text{ (Ex. 5.7)} \\ &= 0.6448 \approx .64 \text{ (two-figure accuracy)} \end{aligned}$$

Thus the lighting level will be reduced to 64% of its initial level just before corrective action is taken.

With reference to Equation 5.1, the illuminance E in that relationship represents the initial value, that is, the lighting level when the system is first turned on. To include the light loss factor, the equation expands to

$$E = \frac{\text{TILL} \times \text{CU} \times \text{LLF}}{\text{area}} \tag{5.3}$$

where E is the minimum average illuminance at the workplane just before corrective action is taken.

5.4 LUMINAIRE DISTRIBUTION TYPES

Luminaires are classified on the basis of their distribution pattern, that is, on the relative amounts of light projected upward and/or downward from the luminaire (see Section 3.7). There are six categories, each of which is assigned a percentage range for the upward and downward components, as shown in Figure 5.5. These percentages are based on the total lumens emitted from the luminaire.

Note that the general-diffuse and the direct–indirect types have the same percentage ranges. However, the general-diffuse type has a fairly uniform light output around the full 360 degrees, such as a suspended type of incandescent luminaire with an enclosing glass globe. In contrast, the direct–indirect type has very little light output in the few degrees above and below the horizontal. Typical of this type is a suspended type of fluorescent luminaire with open top and bottom but with very dense side panels.

Lighting systems using the direct type of luminaire are generally the most efficient since the majority of the light is projected directly down onto the workplane. However, this efficiency can be at the

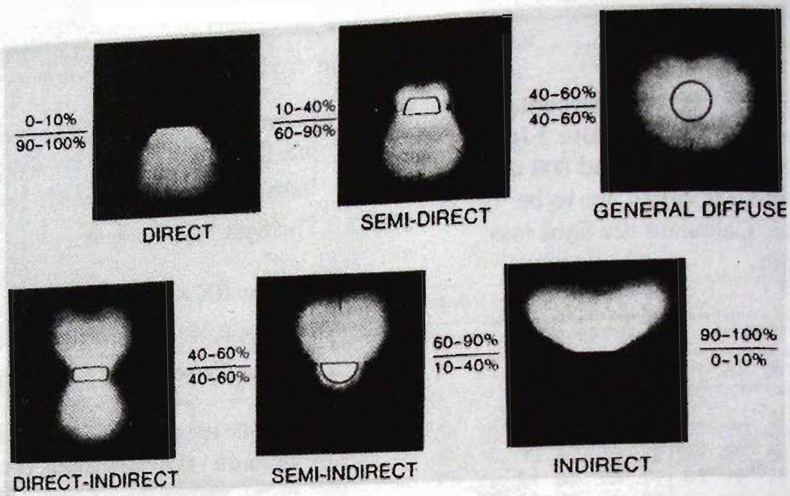


FIGURE 5.5

Luminaire distribution types

expense of the quality of the lighting environment because of possible problems with direct and reflected glare. Lighting systems using the indirect type of luminaire are generally the least efficient, since the majority of the light has to be reflected back down from the ceiling to the workplane. However, this type of system can be the most comfortable, as the lighting is very diffuse with far less glare and annoying shadows. Very often the semidirect type of luminaire is chosen as a compromise.

Any luminaire with an upward component of light must, of course, be suspended from the ceiling. This requires a higher ceiling level to keep the luminaire at an acceptable height above the floor. Many types of building construction preclude high ceilings, and therefore the direct type of luminaire recessed into the ceiling is the only possible choice.

See Section 5.8 for further discussion on the quality of lighting systems.

5.5 CALCULATION OF NUMBER OF LUMINAIRES

In Section 5.2, the assumption made is that the lighting system already exists and Equations 5.1 and 5.3 therefore will give the illuminance level for that lighting system. However, this is not the situation for most lighting layout problems. What is required is a method of calculating the number of luminaires that will be required to provide the recommended minimum levels of illuminance as determined according to Section 5.1.

The relationship of Equation 5.3 can be rearranged as follows:

$$\text{TILL} = \frac{E \times \text{area}}{\text{CU} \times \text{LLF}} \tag{5.4}$$

where TILL = the total initial lamp lumens required
E = recommended minimum illuminance

The number of luminaires can then be calculated:

$$\text{No. of luminaires} = \frac{\text{TILL}}{\begin{pmatrix}\text{no. of lamps}\\ \text{per luminaire}\end{pmatrix} \times \begin{pmatrix}\text{initial lumens}\\ \text{per lamp}\end{pmatrix}} \qquad \textbf{(5.5)}$$

The value of E used in Equation 5.4 can only be a target value. The number of luminaires calculated using Equations 5.4 and 5.5 can therefore only be considered as the theoretical number required, as a practical layout may dictate an adjustment to this number. Example 5.9 shows a sample calculation of the theoretical number of luminaires required for a lighting layout.

■ EXAMPLE 5.9

Refer to Example 5.5. Continue with the same room, for which a CU of 0.65 has been calculated using luminaire 1. A 300 W, mogul base, 1000 hr incandescent lamp is to be installed in the luminaire. The room is to be lighted to an illuminance level of 20 fc. The atmosphere will be clean and the luminaires and room surfaces will be cleaned every 18 months. Calculate the number of luminaires required.

Solution

STEP 1 Determine the lamp lumen depreciation factor. From Table 4.1, LLD is 89% (use 0.89).

STEP 2 Determine the luminaire dirt depreciation factor.
— From Table 5.5, luminaire 1 is category IV.
— From Figure 5.4, for clean and 18 months, LDD is 0.84.

STEP 3 Determine the room surface dirt depreciation factor.
— From the graph in Table 5.7, for clean and 18 months, the percent of expected dirt depreciation is 15%.
— From Table 5.5, for luminaire 1, the light output is all down (direct distribution; see Figure 5.5).
— From Table 5.7, for direct and RCR 2, interpolate between 0.98 for 10% and 0.96 for 20%; RSDD is 0.97.

STEP 4 Calculate the light loss factor:

$$\text{LLF} = 0.89 \times 0.84 \times 0.97 = 0.73 \quad \text{(two-figure accuracy)}$$

STEP 5 Calculate the total initial lamp lumens (Equation 5.4):

$$\text{TILL} = \frac{20 \times (60 \times 120)}{0.65 \times 0.73} = 303{,}500$$

STEP 6 Calculate the required number of luminaires (Equation 5.5). From Table 4.1, for a 300 W, mogul base, 1000 hr lamp, the initial lamp lumens are 5960.

$$\text{No. of luminaires} = \frac{303{,}500}{1 \times 5960} = 50.9$$

See Example 5.10 for the actual number selected.

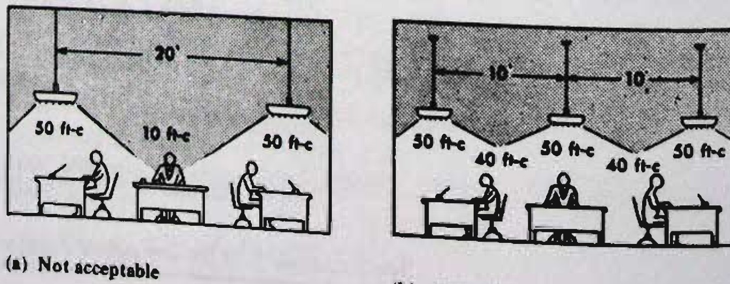
5.5.1 Practical Layout of Luminaires

An arrangement of luminaires that provides a reasonably uniform lighting level on the workplane over an entire area is known as general lighting. Equations 5.4 and 5.5 were developed from the lumen method and, as such, give the number of luminaires required to provide the recommended average level of illuminance for general lighting. However, if the luminaires are not spaced properly, the actual point-by-point levels throughout the room may not be uniform, and there will be noticeable variations in the levels.

Uniform lighting requires that the spacing between adjacent luminaires must not exceed defined limits. Refer to Figure 5.6. The diagram on the left shows a spacing arrangement that does not give uniform lighting. The diagram on the right shows that with reduced spacing the lighting levels are reasonably uniform.

Spacing limitations between luminaires are a function of their intensity distribution patterns (see Section 3.7) and their mounting heights. The luminaire *spacing criterion* (SC) is a classification relating to its distribution pattern. This classification is done numerically. Refer to Table 5.5. In column 3 under the heading SC, a number is shown for each luminaire. For example, luminaire 1 has a value of 1.3 for SC. This means that the spacing between adjacent luminaires of this type cannot exceed 1.3 times their mounting height above the workplane if reasonably acceptable uniformity of horizontal illuminance is to be obtained.

For luminaires using essentially point sources of light, such as incandescent or HID lamps, the maximum spacing applies equally to both directions in the room. Luminaires using fluorescent lamps, because of their length, do not necessarily fit this pattern. A very common and desirable arrangement is continuous rows of fluorescent luminaires in one direction in the room, usually lengthwise, as shown in Figure 5.7(a). The maximum spacing then applies only between the center lines of each row. Where rows of fluorescent luminaires are not continuous, the maximum spacing along the rows applies as shown in Figure 5.7(b). For 4 foot long luminaires, the maximum spacing is from center line to center line (the same as for



(a) Not acceptable

(b) Acceptable

FIGURE 5.6

Spacing requirements for reasonably uniform lighting

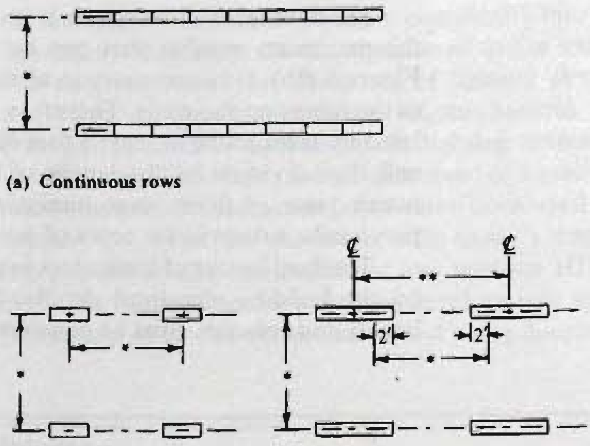


FIGURE 5.7

Maximum spacing dimensions (in feet) for fluorescent luminaires

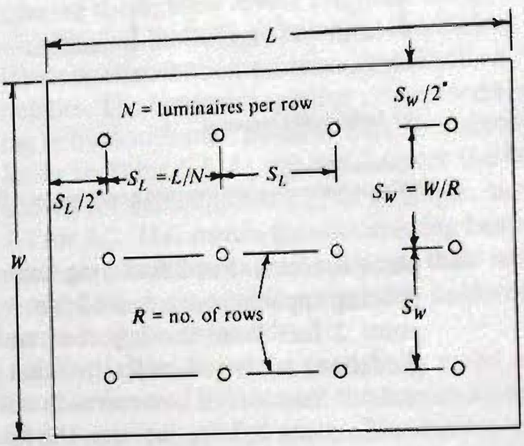
point sources). For 8 foot long luminaires, the maximum lengthwise spacing applies from a point 2 feet from the end of one luminaire to a point 2 feet from the adjacent end of the next luminaire. These guidelines are based on the fact that the distribution of light from the ends of fluorescent luminaires is not as good as it is from the sides.

In many lighting layouts, the final spacing is less than the maximum permitted by the spacing criterion. After the theoretical number of luminaires required for the layout has been calculated, it is necessary to adjust this number so that it can be evenly divisible by the number of rows.

For point sources of light, the ratio between the number of rows and the number of luminaires per row should be in proportion to the width-to-length ratio of the room. This is required to give symmetrical spacing in both directions in the room for uniform lighting. Refer to Figure 5.8(a). The exact spacing between rows is calculated by dividing the room width by the number of rows, and spacing between luminaires in each row by dividing the room length by the number of luminaires per row. This means that the spacing between the outer luminaires and the adjacent wall is one-half of the luminaire spacing. Refer to Figure 5.6. If the spacing from the wall to the first luminaire was to be greater than one-half, the lighting level adjacent to the wall would noticeably fall off. In fact, if it is known that desks or other work areas are to be located alongside the walls, then the wall-to-luminaire spacing should be reduced to one-third of the luminaire spacing.

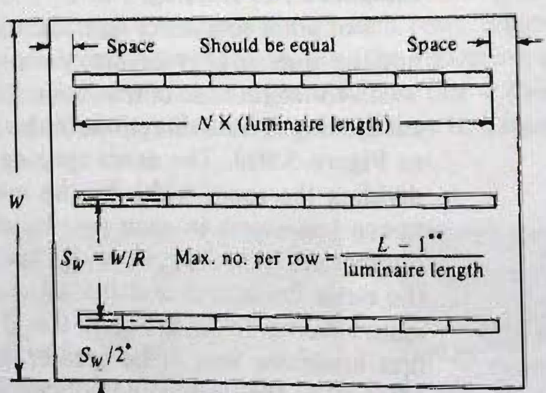
For fluorescent luminaires, it is often necessary to first establish the maximum number that can be installed in one row. Refer to Figure 5.8(b). It is necessary to allow some space between the ends of the rows and the walls. Therefore, the maximum number is calculated by subtracting at least 1 foot (0.3 meter) from the room length and then dividing by the length of the luminaire. The spacing between rows of fluorescent luminaires is determined the same as previously indicated for rows of point sources.

The final layout of luminaires in practice is very often influenced by the building structural details. Such things as the location of beams and columns must be considered in locating luminaires. Since



S_L and S_W should be approximately equal.
*Can be reduced to one-third luminaire spacing.

(a) Incandescent and HID



**Minimum 1.0 ft (0.3 m)

(b) Fluorescent, continuous rows

FIGURE 5.8

Layout arrangements for luminaires

these details introduce much more complexity into the design of the lighting system, they are not considered in the examples shown in this chapter. However, designers of lighting systems in the real world must be able to read structural, mechanical, and architectural drawings in order to coordinate the lighting systems.

Example 5.10 shows the development of a practical layout using point sources. Incandescent lamps have been used for this layout to simplify the example. However, with today's emphasis on saving energy, one of the more efficient low wattage HID sources would likely be used, even for a lighting level as low as 20 footcandles. Example 5.11 shows a practical layout using fluorescent luminaires.

EXAMPLE 5.10

Refer to Example 5.9. A total of 50.9 incandescent luminaires was calculated as being required to provide an average level of illuminance of 20 fc for a 60 by 120 ft room. Select a practical layout for the lighting in this room.

Solution

STEP 1 Draw a plan, reasonably to scale, of the outline of the room as in Figure 5.9.

STEP 2 Note the ratio between the width and length of the room, which is 60 to 120, or 1 to 2. There should be the same ratio between the number of rows and the number of luminaires per row in order to have a symmetrical arrangement.

STEP 3 Select an arrangement of 5 rows of 10 luminaires for a total of 50. *Note:* Four rows of 13 (= 52) would not give a suitable ratio.

STEP 4 Calculate the luminaire spacing as in Figure 5.8(a):

$$S_W = \frac{60}{5} = 12 \text{ ft}, \qquad S_L = \frac{120}{10} = 12 \text{ ft}$$

Thus the spacing between the luminaires and walls is 12/2, or 6 ft.

STEP 5 Check maximum spacing allowed:

- From Table 5.5 for luminaire 1, SC is 1.3.
- Maximum spacing = 1.3 × 16 = 20.8 ft (h_{RC} = 16 from Figure 5.3).
- 12 ft spacing is well within limit.

STEP 6 Draw the luminaires on a room layout (Figure 5.9) and show dimensions.

STEP 7 Calculate the actual minimum maintained lighting level: If 50.9 luminaires are required to give 20 fc (step 6 in Example 5.9), then 50 luminaires will give

$$E = \frac{50}{50.9} \times 20 = 19.6 \text{ fc}$$

This is within 2% of the desired value.

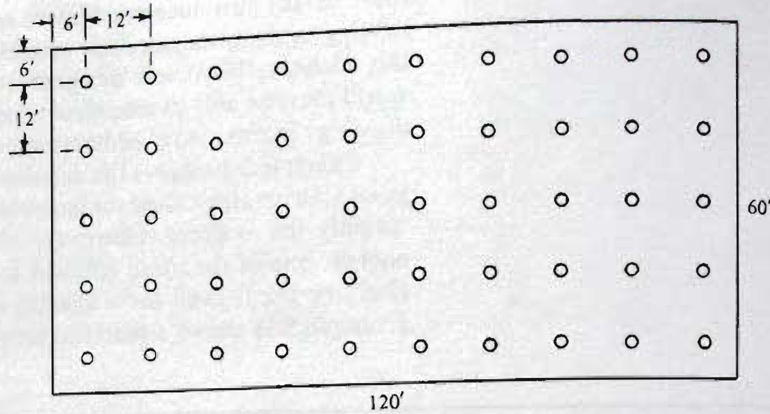


FIGURE 5.9

Plan of room showing luminaires for Example 5.10 (dimensions are in feet)

■ EXAMPLE 5.11

Refer to Example 5.5. This same 60 by 120 ft room is now to be lighted to a level of 75 fc by installing luminaire 3 (Table 5.5) suspended 5 ft from the ceiling. The luminaire will be 8 ft long and each will have two rapid-start, 800 mA, T-12, 96 in., cool white fluorescent lamps. The atmosphere and cleaning times will be the same as in Examples 5.6 and 5.7. Select a practical lighting layout.

Solution

STEP 1 Since the cross section and room surface reflectances are still the same, the cavity ratios and effective ceiling and floor reflectances as calculated in Example 5.5 still apply.

STEP 2 Determine the coefficient of utilization from Table 5.5:

— For luminaire 3, $\rho_{CC} = 50\%$, $\rho_W = 30\%$, and RCR = 2.0, a value of 0.63 is read (for 20% floor reflectance).

— The multiplying factor for 10% floor reflectance is the same as in Example 5.5.

$$\text{Final CU} = 0.63 \times 0.968 = 0.61$$

STEP 3 Calculate the light loss factor:

— Ballast factor (BF) is 0.95.

— LLD from Table 4.4 is 82% (use 0.82).

— LDD is 0.89 as in Example 5.6.

— RSDD is 0.93 as in Example 5.7.

$$\text{LLF} = 0.95 \times 0.82 \times 0.89 \times 0.93 = 0.645$$

STEP 4 Calculate the total initial lamp lumens (Equation 5.4):

$$\text{TILL} = \frac{75 \times (60 \times 120)}{0.61 \times 0.645} = 1{,}372{,}500$$

STEP 5 Calculate the required number of luminaires (Equation 5.5). From Table 4.4, for an 800 mA, 96 in., CW lamp, the initial lamp lumens are 9150 and there are two per luminaire.

$$\text{No. of luminaires} = \frac{1{,}372{,}500}{2 \times 9150} = 75.0$$

STEP 6 Select a practical layout for the luminaires:

— Assume that continuous rows will be necessary.

— Calculate the maximum number per row lengthwise in the room as in Figure 5.8(b):

$$\text{Max. no. per row} = \frac{120 - 1}{8} \approx 14$$

— Number of rows required using 14 per row = 75.0/14 ≈ 5.

— Select 5 rows of 14 = 70 (most practical arrangement):

$$E \text{ (maintained)} = \frac{70}{75.0} \times 75 = 70.0 \text{ fc}$$

This is 6.7% below the desired value, but acceptable.

STEP 7 Calculate the luminaire spacing as in Figure 5.8(b):

$$S_W = \frac{60}{5} = 12 \text{ ft}$$

$$\text{Total length of each row} = 14 \times 8 = 112 \text{ ft}$$

$$\text{Space at ends of row} = \frac{120 - 112}{2} = 4 \text{ ft}$$

STEP 8 Check the maximum spacing allowed between rows:

— From Table 5.5 for luminaire 3, SC is 1.3.

— Maximum spacing = 1.3 × 16 = 20.8 ft (h_{RC} = 16 from Figure 5.3).

— 12 ft spacing is well within the limit.

STEP 9 Draw a plan of the room and indicate the luminaires and their locations as shown in Figure 5.10.

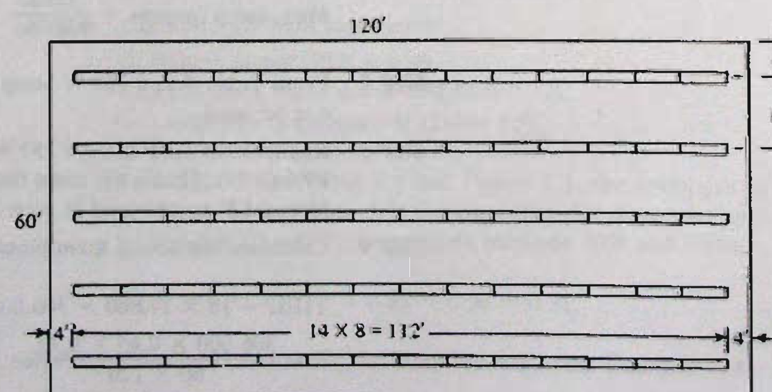


FIGURE 5.10

Plan of room showing luminaires for Example 5.11

5.5.2 Determining Maximum Wattage

When considering incandescent lamps for a lighting system, the fact that the efficacy of the lamps increases as the rated wattage of the lamps increases (Section 4.1.2) should be taken into account. When a luminaire type such as luminaire 1 in Table 5.5 can accommodate any wattage of lamp, it is advantageous to determine the maximum wattage that can be used, consistent with the spacing limitations of the luminaire. There is also the added advantage of lower installation costs with fewer luminaires. Example 5.12 shows how this calculation is done.

■ EXAMPLE 5.12

Refer to Examples 5.5 and 5.9. This same room is to be lighted to the same level (20 fc) again using luminaire 1. The lamp wattage is to be the maximum that can be used consistent with the spacing limitations.

Solution

STEP 1 The CU is 0.65, the same as calculated in Example 5.5.

STEP 2 The LLF is 0.73; assume at this point that it remains the same as calculated in Example 5.9.

STEP 3 The TILL of 303,500 lumens therefore remains the same.

STEP 4 The maximum luminaire spacing is 20.8 ft, the same as calculated in Example 5.10.

STEP 5 Calculate the minimum number of luminaires that can be installed without exceeding 20.8 ft:

$$\text{Min. no. of rows} = \frac{\text{room width}}{\text{max spacing}} = \frac{60}{20.8} \approx 3$$

$$\text{Min. no. per row} = \frac{\text{room length}}{\text{max spacing}} = \frac{120}{20.8} \approx 6$$

$$\text{Min. total} = 3 \times 6 = 18$$

STEP 6 Calculate the maximum lamp lumens that can be used:

$$\text{Max. lamp lumens} = \frac{\text{TILL}}{\text{min. no.}} = \frac{303{,}500}{18} = 16{,}900$$

STEP 7 From Table 4.1, a 750 W lamp with initial lamp lumens of 17,000 can be used.

STEP 8 Recheck the LLF using a 750 W lamp. From Table 4.1, the LLD is 89% (0.89). This is the same factor as used in Example 5.9. Therefore, LLF as assumed in step 2 is correct.

STEP 9 Calculate the actual maintained lighting level (Equation 5.3):

$$\text{TILL} = 18 \times 17{,}000 = 306{,}000 \quad \text{(for eighteen 750 W lamps)}$$

$$E = \frac{306{,}000 \times 0.65 \times 0.73}{60 \times 120} = 20.2 \text{ fc}$$

This is only 1% above target level.

We can compare layouts using 300 W (Example 5.10) and 750 W lamps:

	300 watt	750 watt
Total power (W)	50 × 300 = 15,000	18 × 750 = 13,500
Illuminance (fc)	19.6	20.2

Note that with less total power consumed the layout using the 750 W lamp gives a slightly higher lighting level. However, offsetting this advantage could be the matter of the quality of light (see Section 5.8).

5.6 COMPLETE DESIGN OF LIGHTING SYSTEM

We have now been through many examples, each showing individual steps in the design of a lighting layout. Examples 5.13 and 5.15, which follow, each present a complete design, from the selection of the recommended luminance level to the detailed layout drawing. Example 5.14 is an alternative method of lighting the same room as in Example 5.13. An economic comparison can then be made between the two systems.

EXAMPLE 5.13

An industrial area to be lighted is as follows:

Type of building: Industrial
Area/activity: Assembly, moderately difficult
Average age of workers: 35 years
Demand for speed and/or accuracy: Important
Task background reflectance: 40%
Size of room: 60 by 84 ft, 22.5 ft ceiling
Height of workplane: 3 ft
Reflectance factors: Ceiling 70%, walls 50%, and floor 20%
Luminaire type: 3, Table 5.5
Luminaire mounting: Suspended 5.5 ft
Lamps: 1500 mA, 96 in., T-12, CW, rapid-start fluorescent
Atmosphere: Medium
Interval between cleaning: 30 months

Solution

STEP 1 Determine the recommended illuminance level:
— From Table 5.2, the illuminance category is *E*.
— From Table 5.3, the recommended level is 750 lx or 75 fc.

STEP 2 Draw a cross section of the room and determine the cavity heights [see Figure 5.11(a)].

STEP 3 Calculate the cavity ratios using Equation 5.2 [see Figure 5.11(a)].

STEP 4 Determine the effective ceiling (ρ_{CC}) and floor (ρ_{FC}) cavity reflectances from Table 5.4 [see Figure 5.11(a)].

STEP 5 Determine the coefficient of utilization from Table 5.5:
— For luminaire 3, $\rho_{CC} = 60\%$, $\rho_W = 50\%$, and RCR = 2.
— CU = 0.70 (interpolate between ρ_{CC} of 70% and 50%).
— No correction required for 20% floor.

STEP 6 Calculate the light loss factor:
— Ballast factor (BF) = 0.95.
— LLD from Table 4.4 is 72% (use 0.72).
— Luminaire is category II (Table 5.5).
— LDD from Figure 5.4 is 0.83.
— RSDD: From Table 5.5 and Figure 5.5, the luminaire is semi-direct. From Table 5.7, the expected dirt depreciation is 25% and RSDD is 0.90 (interpolate between 20% and 30%).

$$\text{LLF} = 0.95 \times 0.72 \times 0.83 \times 0.90 = 0.51$$

STEP 7 Calculate the total initial lamp lumens using Equation 5.4:

$$\text{TILL} = \frac{75 \times (60 \times 84)}{0.70 \times 0.51} = 1{,}059{,}000$$

STEP 8 Calculate the required number of luminaires using Equation 5.5. From Table 4.4, initial lamp lumens are 15,250 and there are two lamps per luminaire:

$$\text{No. of luminaires} = \frac{1{,}059{,}000}{2 \times 15{,}250} = 34.7$$

STEP 9 Select a practical layout for the luminaires:

— From Table 5.5, for luminaire 3, SC is 1.3.
— Maximum spacing between rows is 1.3 × 14 = 18.2 ft.
— Minimum number of rows is 60/18.2 ≈ 4.
— Possible arrangements:

4 rows of 8 = 32 (too low)
4 rows of 9 = 36 (too high)
5 rows of 7 = 35 (select this arrangement)

STEP 10 Calculate the luminaire spacing as in Figure 5.8(a):

$$S_W = \frac{60}{5} = 12 \text{ ft}, \qquad S_L = \frac{84}{7} = 12 \text{ ft}$$

Note: There are not enough luminaires for continuous rows.

STEP 11 Draw a plan of the room and indicate the locations of luminaires [see Figure 5.11(b)].

STEP 12 Calculate the actual minimum maintained lighting level. If 34.7 luminaires will provide 75 fc (see steps 7 and 8), then 35 luminaires will provide

$$E = \frac{35}{34.7} \times 75 = 75.6 \text{ fc} \quad \text{(within 1\% of target value)}$$

STEP 13 Calculate the unit power density (UPD); see Section 5.7. From Table 4.4, the power input to the ballast for each luminaire (two 1500 mA 96 in. lamps) is 450 W.

$$\text{UPD} = \frac{\text{total power}}{\text{area}} = \frac{35 \times 450}{60 \times 84} = 3.125 \text{ W/ft}^2$$

■ EXAMPLE 5.14

The room to be lighted and the conditions are the same as outlined for Example 5.13 with the following exceptions:

Luminaire type: 4, Table 5.5
Lamp: 250 W HPS

Solution

STEP 1 The recommended illuminance level is the same (75 fc).

STEP 2 The cavity ratios and the effective ceiling and floor cavity reflectances remain the same as in Figure 5.11(a).

STEP 3 Determine the coefficient of utilization from Table 5.5:

— For luminaire 4, ρ_{CC} = 60%, ρ_W = 50%, and RCR = 2.
— CU = 0.725 (interpolate between P_{CC} of 70% and 50%).
— No correction required for 20% floor.

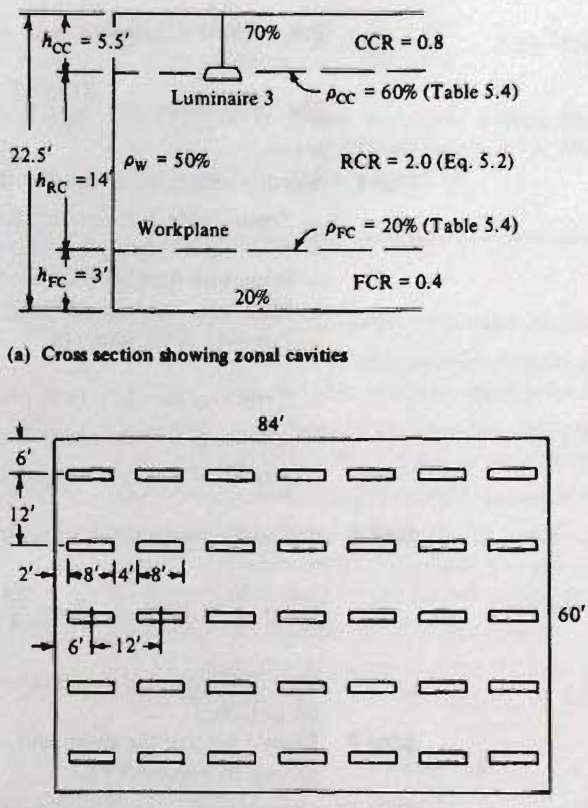


FIGURE 5.11

Diagrams for Example 5.13

STEP 4 Calculate the light loss factor:

- Ballast factor is assumed to be 1.0.
- LLD from Table 4.5 is 88% (use 0.88).
- Luminaire is category III (Table 5.5).
- LDD from Figure 5.4 is 0.77.
- RSDD: From Table 5.5 and Figure 5.5, the luminaire is direct. From Table 5.7, the expected dirt depreciation is 25% and RSDD is 0.95 (interpolate between 20% and 30%).

$$\text{LLF} = 1.0 \times 0.88 \times 0.77 \times 0.95 = 0.64$$

STEP 5 Calculate the total initial lamp lumens using Equation 5.4:

$$\text{TILL} = \frac{75 \times (60 \times 84)}{0.725 \times 0.64} = 814{,}600$$

STEP 6 Calculate the required number of luminaires using Equation 5.5.

From Table 4.5, initial lamp lumens are 30,000.

$$\text{No. of luminaires} = \frac{814{,}600}{30{,}000} = 27.2$$

STEP 7 Select a practical layout for the luminaires:

— From Table 5.5, for luminaire 4, SC is 1.5.
— Maximum spacing between rows is 1.5 × 14 = 21 ft.
— Minimum number of rows is 60/21 ≈ 3.
— Minimum number per row is 84/21 = 4.
— Possible arrangements:

3 rows of 9 = 27 (will give very unequal spacing)
4 rows of 6 = 24 (more symmetrical spacing but too few)
4 rows of 7 = 28 (select this arrangement)

STEP 8 Calculate the luminaire spacing as in Figure 5.8(a):

$$S_W = \frac{60}{4} = 15 \text{ ft}, \qquad S_L = \frac{84}{7} = 12 \text{ ft}$$

This does not give symmetrical spacing, but it is the best that can be obtained.

STEP 9 Draw a plan of the room and indicate the locations of luminaires as shown in Figure 5.12.

STEP 10 Calculate the actual minimum maintained lighting level:

$$E = \frac{28}{27.2} \times 75 = 77.2 \text{ fc} \quad \text{(slightly higher than Ex. 5.13)}$$

STEP 11 Calculate the unit power density (UPD); see Section 5.7. From Table 4.5, the power input to each ballast is 295 watts:

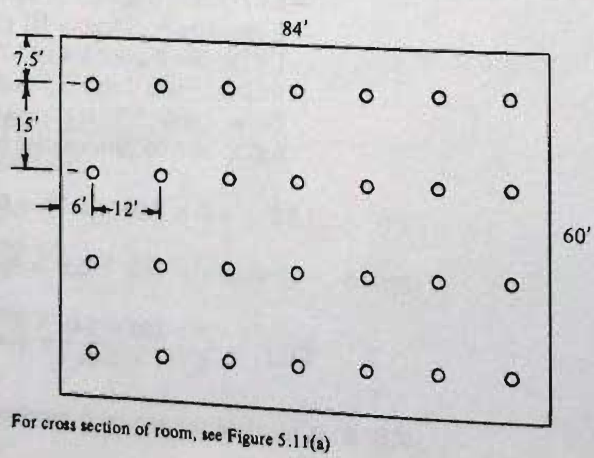


FIGURE 5.12

Plan of room showing luminaires for Example 5.14

$$\text{UPD} = \frac{\text{total power}}{\text{area}} = \frac{28 \times 295}{60 \times 84} = 1.64 \text{ W/ft}^2$$

Note the much lower watts per square foot for the unit power density as compared with Example 5.13. This is discussed further in Section 5.7 and Example 5.16.

EXAMPLE 5.15

Measurements for this example are in meters. The room to be lighted is as follows:

Type of building: Commercial
Area/activity: Drafting: tracing paper, low contrast
Average age of workers: 35 years
Demand for speed and/or accuracy: Important
Task background reflectance: 75%
Size of room: 10.0 by 13.25 m; 2.91 m ceiling
Height of workplane: 0.91 m
Reflectance factors: Ceiling 80%, walls 50%, and floor 30%
Luminaire type: 2, Table 5.5; 300 mm wide with two lamps
Luminaire mounting: Recessed in ceiling
Lamps: 430 mA, 40 W, 1200 mm, WW, RS standard fluorescent
Atmosphere: Clean
Interval between cleaning: 12 months

Solution

STEP 1 Determine the recommended illuminance level:

- From Table 5.1, the illuminance category is F.
- From Table 5.3, the recommended level is 1000 lx.

STEP 2 Draw a cross section of the room and determine the cavity heights [see Figure 5.13(a)]. Note there is no ceiling cavity.

STEP 3 Calculate the cavity ratios using Equation 5.2 [see Figure 5.13(a)].

STEP 4 Determine the effective floor cavity reflectance (ρ_{FC}) from Table 5.4 [see Figure 5.13(a)]. Note that the effective ceiling cavity reflectance is the same as the actual ceiling reflectance.

STEP 5 Determine the coefficient of utilization:

- It is necessary to interpolate for RCR = 1.75.
- For luminaire 2, ρ_{CC} = 80% and ρ_W = 50%.

RCR	Table 5.5 CU	Table 5.6 Factor for 30% Floor
1.0	0.67	1.082
1.75 (interpolate)	0.61	1.070
2.0	0.59	1.066

- Multiplying factor for effective floor of 28%:

30%	1.070 (from above)
28% (interpolate)	1.056
20%	1.00

- Multiply by factor of 0.9 as per note on Table 5.5 for luminaire 2, 300 mm wide using two lamps.

Final CU = 0.61 × 1.056 × 0.9 = 0.58 (two-figure accuracy)

STEP 6 Calculate the light loss factor:

- Ballast factor = 0.95.
- LLD from Table 4.4 is 84% (use 0.84).
- Luminaire is category V (Table 5.5).
- LDD from Figure 5.4 is 0.88.
- RSDD: From Table 5.5 and Figure 5.5, the luminaire is direct.

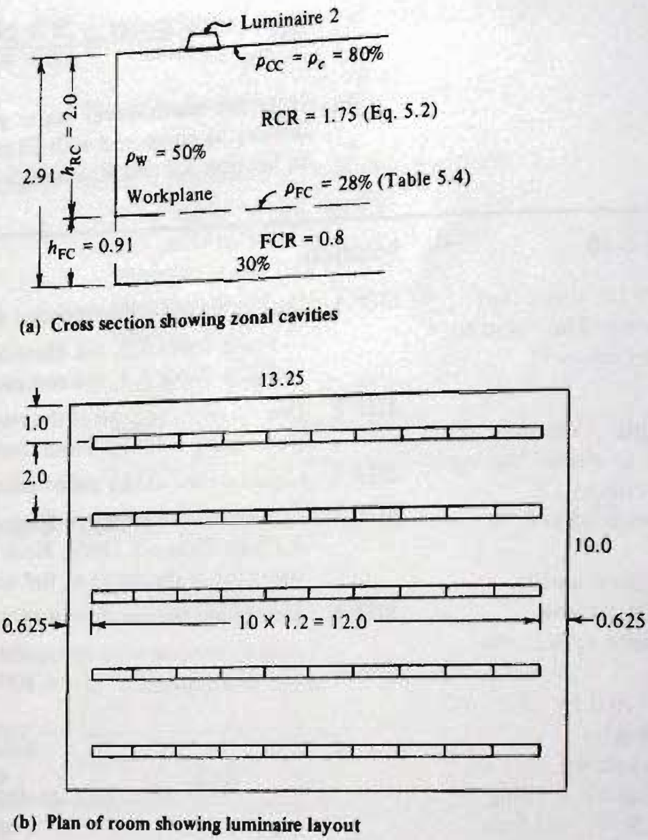


FIGURE 5.13

Diagrams for Example 5.15 (dimensions are in meters)

From Table 5.7, the expected dirt depreciation is 12% (use 10%) and RSDD is 0.98.

$$\text{LLF} = 0.95 \times 0.84 \times 0.88 \times 0.98 = 0.69$$

STEP 7 Calculate the total initial lamp lumens using Equation 5.4:

$$\text{TILL} = \frac{1000 \times (10.0 \times 13.25)}{0.58 \times 0.69} = 331{,}000$$

STEP 8 Calculate the required number of luminaires using Equation 5.5. From Table 4.4, the initial lamp lumens are 3175 and there are two lamps per luminaire.

$$\text{No. of luminaires} = \frac{331{,}000}{2 \times 3175} = 52.1$$

STEP 9 Select a practical layout for the luminaires:

— Assume continuous rows are required.
— Calculate the maximum number per row lengthwise in the room as in Figure 5.8(b) for 1.2 m long luminaires.

$$\text{Max. no. per row} = \frac{13.25 - 0.3}{1.2} \approx 10$$

— Number of rows required is 52/10 ≈ 5.
— Select 5 rows of 10 = 50.

STEP 10 Calculate the luminaire spacing as in Figure 5.8(b):

$$S_W = \frac{10.0}{5} = 2.0 \text{ m}$$

$$\text{Total length of each row} = 10 \times 1.2 = 12.0 \text{ m}$$

$$\text{Space at ends of rows} = \frac{13.25 - 12.0}{2} = 0.625 \text{ m}$$

STEP 11 Check the maximum spacing allowed between rows:
— From Table 5.5, for luminaire 2, SC is 1.4 for crosswise spacing.
— Max. spacing = $1.4 \times h_{RC} = 1.4 \times 2.0 = 2.8$ m.
— 2.0 m spacing is within the limits.

STEP 12 Draw a plan of the room and indicate the locations of luminaires (see Figure 5.13(b)].

STEP 13 Calculate the actual minimum maintained lighting level:

$$E = \frac{50}{52.1} \times 1000 = 960 \text{ lx} \quad \text{(within 4\% of target value)}$$

STEP 14 Calculate the unit power density (UPD); see Section 5.7. From Table 4.4, the power input to the ballast for each luminaire (two 430 mA, 1200 mm lamps) is 95 W.

$$\text{UPD} = \frac{\text{total power}}{\text{area}} = \frac{50 \times 95}{10.0 \times 13.25} = 35.85 \text{ W/m}^2$$

For comparison with other examples,

$35.85/10.76 = 3.33 \text{ W/ft}^2$

The unit power density of 3.33 watts per square foot in Example 5.15 is high. Before the advent of the energy shortage, this value was accepted as normal. Today's practices, however, dictate that the lighting load be kept as low as possible by using energy-saving lamps and ballasts. Example 5.17 shows the economics of using energy-saving lamps. Also, it may be necessary to redesign the layout for the drafting room as in Example 5.15 so that the 1000 lux recommended at the task is provided by a combination of general overall lighting for the room and task lighting at the individual drafting stations.

5.7 ECONOMIC ANALYSIS OF LIGHTING SYSTEMS

Economic analysis of lighting systems enables the designer to make a comparison of alternative methods of providing the required lighting for an area. This analysis should cover both the initial costs and the operating costs. The initial or capital costs cover the purchase and installation of all luminaires, together with the necessary wiring and controls. The operating costs cover the power costs, replacement of lamp and ballast costs, cleaning maintenance costs, and so on. In many instances, the system with the least initial costs may be the most expensive alternative over the life of the system because of higher operating costs.

The concept of energy management for buildings has gained importance since the early 1970s. There is a need to limit the amount of power used for lighting. The Illuminating Engineering Society of North America (IES) has established recommended lighting power limits using the *unit power density* (UPD) procedure. The unit power density is measured in watts per square meter or watts per square foot. The power must include all inputs to the lighting system, including any losses from the use of ballasts. It is beyond the scope of this textbook to present the complete UPD procedure. For information on the procedure and the recommended limitations, refer to the *IES Lighting Handbook, 1987 Application Volume*.

In Examples 5.13, 5.14, and 5.15, the unit power density values are calculated. These values give an immediate comparison between systems as to their relative power requirements. For instance, Examples 5.13 and 5.14 show the design of alternative lighting systems for the same area. The relative UPD values for the two examples are 3.125 and 1.64 watts per square foot, respectively. This shows that the system in Example 5.14 is far more efficient than the system in Example 5.13. Most of the increase in efficiency is due to the much higher efficacy of the high-pressure sodium lamp. Other factors that also contribute, but to a lesser degree, are the higher coefficient of utilization typical for a point source luminaire and the much better lumen maintenance (LLD factor) of the HPS lamp over its life.

Example 5.16, which follows, shows an economic analysis of the two systems as designed in Examples 5.13 and 5.14. This analysis shows that the latter system using the HPS lamps, while initially costing more, is the least costly over the life of the system because of the lower electrical energy costs. The assumed energy rate of \$0.05 per kilowatt-hour (kWh) used in the example is very conservative. Areas with higher rates would show an even better rate of return than that calculated in the example. This analysis shows why the use of the HPS lamp is increasing and that of the highly loaded fluorescent lamp is decreasing. However, there is still the matter of the quality of light, as discussed in Section 5.8.

EXAMPLE 5.16

Prepare an economic analysis of the alternative systems designed in Examples 5.13 and 5.14 for lighting the same area; that is, compare the initial and operating costs of the two alternative systems. Operating costs are to be based on 6000 hr of operation per year and group relamping at 80% of the rated life of the lamps. The basic costs are shown in Table 5.8 (the values shown are estimates reflecting relative costs only).

TABLE 5.8 Cost Data for Example 5.16

	Initial (Capital) Costs	
Ex. 5.13:	Luminaire 3	$135.00 each
	1500 mA, 96 in. fluorescent lamp	$8.00 each
	Installation and wiring for luminaire	$120.00 each
Ex. 5.14:	Luminaire 4	$300.00 each
	250 W HPS lamp	$60.00 each
	Installation and wiring for luminaire	$120.00 each
	Operating Costs	
Energy rate		$0.05 per kWh
Labor rates for relamping:	1500 mA, 96 in. fluorescent	$5.00 per lamp
	250 W HPS	$10.00 per lamp

Solution

The cost analysis for Example 5.16 is as follows.

Initial Costs

Ex. 5.13: Total cost per luminaire installed and wired:

$$\$135 + (2 \times \$8) + \$120 = \$271$$

Total cost of system = 35 × $271 = $9,485

Ex. 5.14: Total cost per luminaire installed and wired:

$$\$300 + \$60 + \$120 = \$480$$

Total cost of system = 28 × $480 = $13,440

Additional cost for Ex. 5.14 system $3,955

Annual Operating Costs: 6000 Hours Operation

Ex. 5.13: From Table 4.4, power input to each ballast for two 1500 mA, 96 in. lamps is 450 W:

$$\text{Total power} = 35 \times 450/1000 = 15.75 \text{ kW}$$

See Section 1.1.4 for energy calculations:

$$\text{Energy consumption} = 15.75 \times 6000 = 94{,}500 \text{ kWh}$$

Annual cost of energy = 94,500 × \$0.05 =	\$4725

Rated lamp life is 9000 hr (Table 4.4); 80% of rated life = 0.8 × 9000 = 7200 hr; and lamp replacement every 7200/6000 = 1.2 years:

Annual cost of relamping (2 lamps per luminaire at \$8.00 per lamp plus \$5.00 labor) = 35 × 2 × (\$8.00 + \$5.00)/1.2 =	\$758
Total annual operating cost for Ex. 5.13 system	\$5483

Ex. 5.14: From Table 4.5, power input to each ballast for 250 W HPS lamp is 295 W:

$$\text{Total power} = 28 \times 295/1000 = 8.26 \text{ kW}$$

$$\text{Energy consumption} = 8.26 \times 6000 = 49{,}560 \text{ kWh}$$

Annual cost of energy = 49,560 × \$0.05 =	\$2478

Rated lamp life is 24,000 hr (Table 4.5); 80% of rated life = 0.8 × 24,000 = 19,200 hr; and lamp replacement every 19,200/6,000 = 3.2 years:

Annual cost of relamping (at \$60.00 per lamp plus \$10.00 labor) = 28 × (\$60.00 + \$10.00)/3.2 =	\$613
Total annual operating cost for Ex. 5.14 system	\$3091

Operating cost saving in favor of Ex. 5.14 = \$5483 − \$3091 =	\$2392

The system as designed in Example 5.14 using HPS lamps costs \$3955 extra to install but saves \$2392 every year. Therefore, it will take only 3955/2392 = 1.65 years to recover the extra costs. The return on investment is

$$\frac{2392}{3955} \times 100 = 60.5\%$$

There are also savings that can be considered when it is time to relamp an existing lighting system. As discussed in Section 4.3.5, energy-saving lamps have been developed that offer higher efficacies than standard lamps. These new lamps can operate from the same ballasts as used for standard lamps. However, they are more expensive than standard lamps. Example 5.17 shows whether relamping a lighting system with energy-saving lamps is justified.

EXAMPLE 5.17

Refer to Example 5.15, where 50 luminaires with a total of 100 fluorescent lamps (40 W, WW standard) are required for the system. It is now time to relamp the system and a decision as to whether to relamp with energy-saving lamps should be made. The relative costs of the lamps are assumed to be:

Standard 40 W warm white: $2.37 each
Energy-saving, 34 W Super Saver II: $3.40 each

The existing standard ballasts will still be used. The power input to each ballast will be reduced from 95 to 81 W with the energy-saving lamps. Assume 4000 hours operation per year and energy costs of $0.05 per kWh.

Solution

The cost analysis is as follows.

STEP 1 The energy-saving SSII lamps have initial lamp lumens of 3050 as compared with 3175 lumens for the standard WW lamps (Table 4.4). This slight drop should not cause a noticeable problem.

STEP 2 The added cost to relamp with energy-saving lamps is

$$(\$3.40 - \$2.37) \times 2 \times 50 = \$103.00$$

STEP 3 The energy savings per year are

$$\frac{50 \times (95 - 81)}{1000} \times 4000 = 2800 \text{ kWh}$$

STEP 4 The savings in energy costs per year are 2800 × $0.05 = $140.

Therefore, the extra cost of the energy-saving lamps would be recovered in less than 1 year. The rated life of the lamps is 20,000 hours or 5 years. Relamping with energy-saving lamps would be recommended.

5.8 QUALITY OF LIGHT

The quality of light involves the comfort of the visual environment. Previous discussions and examples in this chapter have concentrated on providing a sufficient quantity of light. However, having the correct quantity of light does not necessarily mean that the quality of the lighting will be good. The main factors to consider in analyzing the quality of light are glare, luminance ratios, diffusion, and color.

Glare is any luminance (brightness) that causes discomfort, interference with vision, or eye fatigue. The major cause of glare is usually the light source itself. Point sources of light can be particularly troublesome because of their concentrated light output, which results in extremely high brightness. Fluorescent lamps are lower in brightness because their light output is spread over a larger area, but they too can cause problems because of their size. A large area of low brightness may be as uncomfortable as a smaller area of higher brightness.

The glare from the light source that can cause the most concern is that which enters the eye directly. However, a secondary problem can be caused by light reflected in the direction of the eye. Refer to Figure 5.14(a), which shows the direct and reflected glare zones.

The effect of glare is also dependent on the brightness of the area around the source of the glare. An example of this is car headlights. We have all experienced the discomfort of the glare from oncoming headlights at night on a dark road. Yet those same headlights, if left turned on in daylight, cause virtually no problem. The time that a person is exposed to the glare is a further factor. A condition that can easily be tolerated for a short time may become very uncomfortable and fatiguing to the person who must work under it for an 8 hour day.

A few of the more effective methods of reducing glare are as follows:

1. Use luminaires that shield the light source within the normal field of vision. This reduces the effect of direct glare. Figure 5.14(b) shows how luminaires and reflectors can provide shielding. Note that a fluorescent luminaire, because it is not symmetrical, has crosswise shielding and, if a louver is used, also lengthwise shielding. The two shielding angles may be different. Direct glare can also be minimized by using a lens to control the direction of the light output from the luminaire. Certain fluorescent luminaires, such as the commercial types that are for surface or suspended mounting, do not completely shield the light in the direct glare zone. Instead, they use very dense side panels, which considerably reduce the luminance on the sides of the luminaire but still provide enough light so that there is less contrast between the outside of the luminaire and its bright interior.
2. Finish the ceilings and walls with materials having light colors and high reflectance factors. This reduces the contrast between the luminaires and their background.
3. Use suspended luminaires with some upward component of light wherever the ceiling height permits. This further helps to reduce the contrast between the luminaire and its background by increasing the luminance of the ceiling.
4. Mount the luminaires above the normal field of vision wherever

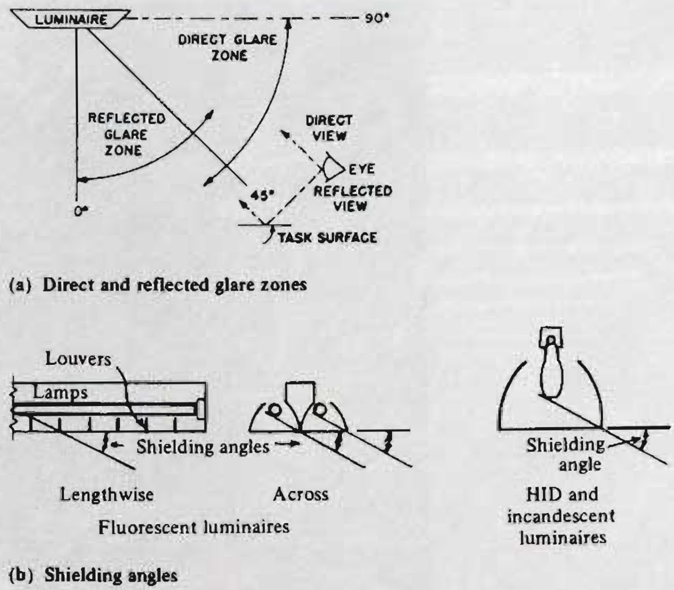


FIGURE 5.14

Glare zones and shielding angles of luminaires

possible. For example, the luminaires in high-bay industrial areas can be mounted at a considerable height. This allows the use of the very bright HID point sources. Those luminaires that fall within the normal field of vision are far enough away so that, with proper shielding, any glare problem is eliminated.

5. Avoid the use of any shiny surfaces within the normal field of vision to minimize reflected glare. As an example, desk tops should have a dull, nonglossy finish that helps to diffuse any reflected light.

Figure 5.15 shows an example of the lighting of an industrial area using high-bay HID luminaires. Note the upward component of light from the luminaire, which helps to light the ceiling. Figure 5.16 shows an example of the lighting of an office area using recessed fluorescent luminaires equipped with flat lens.

The second factor in the quality of light involves luminance ratios or brightness contrast. Consider a task that has a high brightness in contrast to its background. Eye fatigue will result since the eyes are forced to continually adjust from one brightness level to the other. On the other hand, any brightness in the peripheral field that is higher than the task brightness tends to attract the eyes away from the task. The ideal situation is to have the background brightness the same as the task brightness. However, this is difficult to achieve. The recommendations are that the ratio of the task luminance to that of its immediate background should not exceed 3 to 1 and that the

FIGURE 5.15

Example of industrial lighting using high-bay HID luminaires

ratio of task luminance to any luminance in the visual field should not exceed 10 to 1.

An example could be the desk where you study. You generally are working on white paper. If the desk top is dark, the contrast may be too high. Furthermore, if you use only a desk lamp over your work with no other lighting in the room, the contrast between the white paper and the surrounding room background may be excessive. Both condition can cause undue eye fatigue. The top of your desk should be a light color with a nonglossy finish. Also, there should be some general lighting in the room in addition to the desk lamp to brighten up the background.

The third factor in the quality of light concerns diffusion. Diffuse light is light that comes from many directions, as opposed to light that comes from only one direction. The latter creates shadows, which for most lighting applications are not desirable. Perfectly diffuse light that creates no shadows is the ideal for many critical seeing tasks, particularly in school and office areas. Fortunately, lighting layouts with a high level of illuminance require a considerable number of light sources, which in itself provides a fair degree of diffuse light. The degree of diffusion can be further in-

FIGURE 5.16

Example of office lighting using recessed fluorescent luminaires

creased by the use of suspended luminaires with some upward light output. The components of light reflected back from the ceiling increase the directions from which the light reaches the work area.

The fourth factor with regard to the quality of light is color. With equal illumination, the various "white" light sources probably have little effect on the speed of seeing. However, each type of light source, as discussed in Chapter 4, has a different spectral distribution curve. An object viewed separately under these different sources could appear to be a different color. The type of source should be carefully selected where color discrimination is important (see Section 3.2). The color output of the light source can also affect the atmosphere of the space being lighted (see Section 4.3.4). This can be important for areas in which workers remain at their jobs for long periods of time.

An example where the color output of the light source is important is the lighting of merchandising areas that display items for use in our homes. The lighting in our homes is predominantly incandescent, which has a high output in the red end of the spectrum. Therefore, the light source used in the merchandising area should also have a reasonably high output in the red end of the spectrum. If fluorescent lamps are to be used, they should be the warm white deluxe type (see Figure 4.10).

In Example 5.12, a comparison is made between using 300 watt and 750 watt incandescent lamps for the lighting of a room. It is shown that the layout using the 750 watt lamps is more efficient. However, offsetting this advantage is the fact that the larger wattage lamps could cause more glare and that, with fewer lamps, the lighting would be less diffuse and more uneven. Depending on the activities that are planned for the room, the 300 watt lamps may still be the final choice because of overriding requirements with regard to the quality of light.

In Example 5.16, the cost analysis shows that the HPS lamps have a considerable advantage over the highly loaded fluorescent lamps. However, the quality of the lighting must also be considered. The extremely high light output from the point source HPS lamps may cause glare problems. Also, with fewer luminaires, the lighting would be less diffuse and more uneven. The light output of the HPS lamp is very high in the yellow-orange area of the spectral energy distribution curve, as shown in Figure 4.17(d). This may not be compatible with planned color-matching tasks. Therefore, the fluorescent lamps may still be the final choice based on the requirements for the quality of light.

5.9 LIGHTING CONTROLS

Lighting controls can range from simple on–off devices to automatically controlled, continuous dimming systems. The simple switching of lights is discussed in Section 12.8. The basic method used in the past for dimming light sources has been to vary the voltage to the lamp with such devices as variable autotransformers. A newer method uses electronic circuitry to vary the amount of time during each cycle that the lamp current is permitted to flow. Solid-state dimming equipment has now largely taken over the field of dimming equipment because of its versatility and low power losses. Incandescent lamps are very easy to dim. Electric discharge lamps are more difficult to dim because the arc goes unstable as the voltage is decreased. See Section 4.3.9 with regard to the dimming of fluorescent lamps. Recent advances in device technology and circuit design have made it possible to have limited dimming of HID sources. However, it is very expensive.

The original use for dimming was to provide local control of the level of lighting in a particular area to suit the activities being carried out at varying times during the day. With the emphasis on energy conservation in the last few years, another use for the dimming of lighting has developed and that is to maintain constant lighting levels over the life of a system. Refer to Section 5.3 on the light loss factor. In the examples shown in this chapter on lighting layout design, the light loss factor is included in the calculations to account for the decrease in the illuminance level because of aging. Thus, with a system operating on a constant power input, the initial lighting level is much higher than required.

With dimming, however, the required lighting level can initially be set by reducing the power input to the lamps. Then, as the system operates, the power inputs can be slowly increased to compensate for lamp, luminaire, and other light losses (Section 5.3), thus keeping the lighting levels at the workplane constant with time. This type of dimming system is automatically controlled through photoelectric feedback devices that monitor the actual level of lighting. The accumulated savings in power costs can be worthwhile. For example, assume that the lighting system for an office area totaling 10,000 square feet has an average light loss of 25% over a year. Without dimming, the initial lighting level is 100/0.75 = 133.3% or 33.3% higher than required. This also means that the power input is higher by the same amount. Assume that the unit power density for the system is 3.0 watts per square foot for a total connected load of 30.0 kilowatts. With a dimming system, the initial power requirement can be reduced to 75% or 22.5 kilowatts for a saving of 7.5 kilowatts. The power input is then increased gradually with time until the full 30.0 kilowatts is required at the end of the year. Assuming the increase over the year is linear, the average power saving is one-half of the 7.5 kilowatts. If the total hours of operation for the year are 4000 and the energy rate is \$0.08 per kilowatt-hour, then the savings are

$$\frac{7.5}{2} \times 4000 \times \$0.08 = \$1200/\text{yr}$$

Further savings can be realized by incorporating a time programming that automatically adjusts the lighting levels throughout the day to suit task changes, such as from work modes to cleaning and security modes. Many new buildings are being constructed so that advantage can be taken of daylight. The costs of the automatic dimming and programming system can usually be recovered in a very few years from the accumulated savings in energy.

SUMMARY

- The quantity of light involves the generation of the necessary amount of light to provide the recommended lighting level.
- The recommended lighting level is based on the type of area or activity being performed, the average of the workers' ages, the im-

portance of speed and accuracy, and the reflectance of the task background.

- The lumen method is used to calculate the average illuminance for general lighting.
- The coefficient of utilization (CU) represents the efficiency of the lighting system.
- The CU depends on the type of luminaire, the reflectances of the room surfaces, and the size and shape of the room.
- The zonal-cavity method is used to calculate the CU.
- Cavity ratios are calculated as follows:

$$\mathrm{CR} = \frac{5h \times (\text{room width} + \text{room length})}{\text{room width} \times \text{room length}}$$

- The light loss factor (LLF) represents the degree by which the lighting level decreases up to the time corrective action is taken.
- The LLF is the product of lamp lumen depreciation (LLD), luminaire dirt depreciation (LDD), room surface dirt depreciation (RSDD), and where applicable the ballast factor.
- Luminaires are divided into six distribution types ranging from direct to indirect.
- The minimum average maintained illuminance is calculated as follows:

$$E = \frac{\mathrm{TILL} \times \mathrm{CU} \times \mathrm{LLF}}{\text{area}}$$

- The total initial lamp lumens required to provide the recommended lighting level is calculated as follows:

$$\mathrm{TILL} = \frac{E \times \text{area}}{\mathrm{CU} \times \mathrm{LLF}}$$

- The required number of luminaires is calculated as follows:

$$\text{No. of luminaires} = \frac{\mathrm{TILL}}{\begin{pmatrix}\text{no. of lamps}\\ \text{per luminaire}\end{pmatrix} \times \begin{pmatrix}\text{initial lumens}\\ \text{per lamp}\end{pmatrix}}$$

- The luminaire layout and the actual number used is based on selecting a symmetrical arrangement that suits the room proportions.
- The spacing criterion (SC) sets the maximum spacing permitted for the luminaires in order to have reasonably uniform levels for general lighting.

- The economic analysis of a lighting system must consider both the initial (capital) and operating costs.
- Systems having the lowest initial cost may not have the lowest total lifetime costs.
- The quality of light involves the comfort of the seeing environment.
- The factors to consider for quality of light are glare, luminance ratios, diffusion, and color.
- Automatic dimming and time control systems for lighting can offer lifetime economic benefits.

QUESTIONS

1. What weighting factors must be considered when selecting the IES recommended illuminance value?
2. What is the workplane?
3. What does the coefficient of utilization (CU) represent?
4. State the five factors that affect the CU.
5. What does the effective ceiling reflectance represent?
6. When are the effective and actual ceiling reflectances the same?
7. Why is it necessary to include the light loss factor in the calculations for the required number of luminaires?
8. Differentiate between unrecoverable and recoverable light loss factors.
9. Why is it necessary to include luminaire dirt depreciation and room surface dirt depreciation factors?
10. Why is the room surface dirt depreciation factor affected by the luminaire distribution type?
11. List the six classifications of luminaires according to their distribution pattern.
12. Why are systems that use indirect luminaires generally the least efficient?
13. What is the significance of the luminaire spacing criterion?
14. What is the unit power density?
15. What factors are involved in the quality of light?
16. Why is glare a major concern?
17. What is the shielding angle?
18. How does a light-colored ceiling with a high reflectance factor help reduce glare?
19. Why is it recommended that suspended luminaires have some upward component of light?
20. Why do luminance ratios affect the quality of the lighting?
21. What is diffuse light?
22. Why should automatic dimming and programming of lighting systems be considered?

PROBLEMS

1. Select the recommended illuminance value for a science laboratory in a high school. The task background reflectance is 50% and the demand for speed and/or accuracy is not important.
2. Calculate the ceiling, room, and floor cavity ratios for a 17 by 24 ft room with a 13 ft ceiling. The workplane is 3 ft above the floor and the luminaires are suspended 2 ft from the ceiling.
3. The ceiling, walls, and floor reflectance factors for the room in Problem 2 are 90%, 50%, and 30%, respectively. Determine the effective ceiling and effective floor cavity reflectances.
4. Calculate the coefficient of utilization for the room in Problems 2 and 3 using the luminaire 3 in Table 5.5.
5. Determine the luminaire dirt depreciation (LDD) factor for luminaire 3 operating in a dirty atmosphere with cleaning every 2 years.

6. Determine the room surface dirt depreciation (RSDD) factor for Problem 5 if the room cavity ratio is 3.0.
7. Calculate the light loss factor for Problems 5 and 6 if the lamps used are the 40 W, 430 mA standard fluorescent.
8. Calculate the maximum spacing in feet permitted between rows for luminaire 3 mounted in the room as in Problem 2.
9. If the fluorescent luminaires in Problem 8 are to be individually mounted, calculate the maximum center line to center line spacing permitted lengthwise in the rows if the luminaires are (a) 4 ft long; (b) 8 ft long.
10. Calculate the theoretical number of luminaires required to light the following room:

— Type of building: Industrial
— Area/activity: Woodworking, fine bench work
— Average age of workers: 35 years
— Demand for speed and/or accuracy: Important
— Task background reflectance: 25%
— Size of room: 42 by 60 ft; 21 ft ceiling
— Height of workplane: 3 ft
— Reflectance factors: Ceiling 80%, walls 50%, and floor 10%
— Luminaire type: 4, Table 5.5
— Luminaire mounting: Suspended, 3 ft
— Lamps: 400 W, clear metal halide
— Atmosphere: Medium
— Interval between cleaning: 12 months

11. Select a practical layout for the lighting in Problem 10. Calculate the luminaire spacings crosswise between rows and lengthwise between luminaires in each row. Check that your selected layout conforms to the spacing criterion.
12. Calculate the unit power density of the lighting system selected in Problem 11.
13. Calculate the theoretical number of luminaires required to light the following room:

— Type of building: Commercial
— Area/activity: General office, reading handwritten carbon copies
— Average age of workers: 35 years
— Demand for speed and/or accuracy: Important
— Task background reflectance: 60%
— Size of room: 36 by 54 ft; 9 ft ceiling
— Height of workplane: 2.5 ft
— Reflectance factors: Ceiling 80%, walls 50%, and floor 30%
— Luminaire type: 2, Table 5.5; 2 ft wide with four lamps
— Luminaire mounting: Recessed in ceiling
— Lamps: 34 W, 48 in., SS II energy-saving fluorescent
— Atmosphere: Clean
— Interval between cleaning: 18 months

14. Select a practical layout for the lighting in Problem 13. Calculate the luminaire spacings crosswise between rows and lengthwise between luminaires in each row. Check that the selected layout conforms to the spacing criterion.
15. Calculate the unit power density of the lighting system selected in Problem 14. Energy-saving ballasts are to be used along with the energy-saving lamps.
16. Two designs for lighting an industrial area show that:

— Design A requires 60 of luminaire 3 each having two 1500 mA, 96 in. fluorescent lamps.
— Design B requires 48 of luminaire 4 each having one 250 W HPS lamp.

Operating costs are to be based on 5000 hr operation per year and group relamping at 75% of rated life of the lamps. The basic costs are as in Example 5.16, except that energy costs are $0.08 per kWh. Calculate the years to recover the extra costs using luminaire 4.
17. An office area has 100 of luminaire 2 each having four 40 W, WW standard fluorescent lamps. Calculate the years to recover the extra costs to relamp with 34 W energy-saving lamps instead of the standard 40 W lamps. The costs of the lamps and the ballast watts are as in Example 5.17. Hours of operation are 3000 h per year and energy costs are $0.06 per kWh.

6 Protection of Electrical Systems

OBJECTIVES

After studying this chapter, you will be able to:

- Realize the objectives of system protection.
- Recognize the difference between an overload and a short circuit.
- Refer to the *National Electrical Code* requirements for overcurrent protection.
- Identify the stresses imposed by fault currents.
- Identify the types of short-circuit faults.
- Do elementary calculations for fault currents.
- Use the per unit method of calculations.
- Explain asymmetrical fault currents.
- Discuss the general ratings of protective devices.
- Identify inverse-time and instantaneous-response characteristics.

INTRODUCTION

All electrical systems have the common purpose of providing electrical energy to the utilization equipment as safely and reliably as is economically feasible. The utilization equipment then converts the electrical energy to other forms, such as mechanical, light, and heat energy. The design of the electrical system to transmit the electrical energy to the utilization equipment must focus on two basic requirements. First, the system must be adequate to deliver to each piece of equipment the necessary energy on a continuous basis under normal conditions. Second, the system must be designed to minimize power outages and damage in the event that abnormal conditions occur on the system. It is this second requirement that will now be addressed. The next five chapters cover the means of protecting electrical systems and the protective devices involved.

Since nothing manufactured can be deemed to be perfect, it must be assumed that equipment will fail. Failure on any part of an electrical system can result in the uncontrolled flow of tremendous amounts of energy that can cause major damage in split seconds. Protective systems cannot prevent the failure of equipment. Their purpose then is to remove the faulted segment of the system as quickly and safely as possible. The protection of electrical systems should be designed with the following order of priorities in mind:

—To prevent injuries to personnel
—To prevent fires
—To minimize the damage to electrical equipment
—To minimize the disturbances to the system

That the protection of people and property is paramount is emphasized in the *National Electrical Code* (*NEC*). This code is the nationally accepted guide for the safe installation of electrical conductors and equipment and is the basis for all electrical codes used in the United States. *NEC* Article 90—Introduction, Section 90-1; Purpose, states the following: (*a*) *Practical Safeguarding—The purpose of this code is the practical safeguarding of persons and property from hazards arising from the use of electricity*. The titles *National Electrical Code* ® and *NEC* ® are registered trademarks of the National Fire Protection Association.

Next in order of priorities is the desirability of keeping any damage to the electrical equipment to the absolute minimum so that normal operation can resume as quickly as possible. Finally, it makes economic sense, especially with large systems, to restrict any power outages to as small a section as possible so that the balance of the system can continue to operate normally. This requirement for the least amount of shutdown of the system involves coordination of the protective devices, which is a fairly complicated matter. This topic is therefore dealt with at length in Chapter 16 at the end of the book after protective devices and electrical systems themselves have been fully discussed.

6.1 TYPES OF ABNORMAL CONDITIONS

The following is a list of abnormal conditions that can occur on a system and for which corrective action should be taken:

1. Overloads
2. Short circuits
3. Under voltage
4. Single phasing of three-phase systems
5. Overvoltages and transient surges

6. Incorrect synchronizing of frequencies
7. Incorrect phase sequence
8. Reverse power flow

We will deal with these in reverse order. Items 6, 7, and 8 are abnormal conditions that can only arise on a large system that combines two or more sources of power operating in parallel at the same time. This type of system is complex, and the protection against these types of abnormal conditions is beyond the scope of this book. Item 5 is an abnormal condition associated with lightning. The application of lightning or surge arresters is briefly covered in Section 15.2.2. Items 3 and 4 are abnormal conditions that are of major concern where motors are involved. Therefore, these particular conditions are dealt with in Sections 14.2 and 14.2.1 when discussing motor starters. That leaves overloads and short circuits, which are the most common of the abnormal conditions that occur on electrical systems. Even the small systems in our residences must be fully protected against these.

First, let us fully understand the difference between an overload and a short circuit.

Overload This is caused by an excessive demand from the utilization equipment. During an overload, currents continue to flow only in the normal circuit conductors. An overload can be tolerated for a short period of time (minutes) before corrective action has to be taken. An overload is not caused by the failure of any electrical component of the system.

Short circuit This is caused by an electrical failure such as the breakdown of insulation. The resulting fault currents can be very large, in the tens of thousands of amperes, depending on the capacity of the system. These fault currents can flow in abnormal current paths, such as from one phase to ground. Since the damage can be immediate, the faulted part of the system must be disconnected as quickly as possible (within cycles).

An example of an overload is the mechanical overloading of a motor that results in the motor drawing above-normal current. Another example is above-normal demand from a group of utilization equipment that is all supplied through the same system. Overload currents are considered to range up to 600% of the full-load capacity of the section of the system involved. This relates to the fact that a stalled induction motor (the rotor is jammed or locked) can draw up to 600% of its full-load current rating. Any fault currents in excess of 600% are then assumed to be the result of a short circuit.

The *National Electrical Code* uses the term *overcurrent* as follows: *Any current in excess of the rated current of equipment or the* *ampacity of a conductor. It may result from overload, short circuit, or ground fault.* Article 240 of the *NEC* covers overcurrent protection. Sections 240-20(a) and 240-21 require that a fuse or an overcurrent trip unit of a circuit breaker be connected in series with each ungrounded conductor and that this overcurrent device be connected at the point where the conductor to be protected receives its supply. The term *device* is defined *as a unit of an electrical system that is intended to carry but not utilize electrical energy.* An ungrounded conductor is one that is operating at some potential above ground as opposed to a conductor that is solidly connected to ground (that is, the neutral of a system). Fuses and circuit breakers are discussed in Chapters 7 and 8 of this book. System grounding and ground faults are covered in Chapter 10. Ampacities of conductors and the selection of ratings for overcurrent devices are covered in Chapters 11 to 14.

6.2 STRESSES IMPOSED BY FAULT CURRENTS

Fault currents impose two types of stresses on the electrical system and its components.

Mechanical stresses These stresses are the result of the fault currents flowing in adjacent parallel conductors. The magnetic fields created by the currents produce a strong mechanical force that can either repel or attract the adjacent conductors. This force is proportional to the square of the current. Thus a fault current that is 20 times normal creates a force that is 400 times greater than with normal current flowing. This magnitude of force can bend the conductors and break their supports. Equipment must therefore be braced to withstand the forces created by the maximum possible fault current. This is discussed further in Chapters 14 and 15 with regard to the bracing of bus bars in motor control centers and switchboards.

Thermal stresses These stresses are the result of the heat generated in the conductors by the fault currents. The heat generated is proportional to the product of the square of the current multiplied by the time that the current flows (I^2t). The heat can very quickly raise the temperature of the conductors to the point where the insulation is damaged. In extreme cases, the material may vaporize. With large fault currents, the protective device must operate very rapidly (within cycles) to limit the buildup of heat. This is discussed further in Section 11.2 with regard to the short-circuit rating of conductors.

6.3 TYPES OF SHORT-CIRCUIT FAULTS

There are two types of short-circuit faults, as follows:

Arcing fault This type of fault is usually the result of insulation breakdown. An arc then jumps between two phases of the system or between one phase and an adjacent grounded metal surface. Because of the relatively high resistance of the arc, the resulting fault current tends to be smaller. However, this type of fault can be the most destructive because of the intense energy that is concentrated in the small area of the arc, coupled with the fact that the protective device may be slow in responding to the smaller fault current. The protection of low-voltage systems against arcing ground faults requires special consideration. This is fully discussed in Sections 10.4 and 10.5.

Bolted fault This type of fault results from a solid connection accidentally being made between two phases of the system or between one phase and an adjacent grounded metal surface. Bolted faults can be caused by such mishaps as incorrect connections, a metal tool touching bare conductors, or a loose conductor dropping down and welding itself to a steel enclosure. As a result of the extremely low resistance of the connection, the resulting fault currents can be very large. However, with the proper protection, this type of fault may actually be less destructive because the energy is spread over a large area and the protective devices are activated very rapidly by the large current.

6.4 CALCULATION OF FAULT CURRENTS

It is essential to calculate the maximum fault current that can flow at any given point on the electrical system to ensure the correct selection of equipment. Refer to Sections 110-9 and 110-10 of the *National Electrical Code,* which require that equipment intended to break current at fault levels shall have an interrupting rating sufficient for the system voltage and the current that is available at the line terminals of the equipment. In addition, the overcurrent protective devices, the total impedance, the component short-circuit withstand ratings, and other characteristics of the circuit to be protected shall be selected and coordinated so that the circuit protective devices can clear a fault without the occurrence of extensive damage to the electrical components of the circuit.

The fault current calculations can be very complex, especially on the higher-voltage systems (above 1000 volts). Fortunately, with low-voltage systems, the procedure can be simplified by making a few basic assumptions. As long as these assumptions have the effect of slightly increasing the calculated value of the maximum possible fault current, they err on the side of safety. This ensures that equipment is chosen with sufficient withstand and interrupting capacity. The maximum fault currents on low-voltage systems occur with three-phase, line-to-line bolted faults. Therefore, calculations are done on this basis. With balanced three-phase faults, the calculations can be done on a per phase basis, providing phase-to-neutral values are used. The following examples are simplified so that this initial presentation of the calculations can be more easily understood. Make certain at this point that you are familiar with the circuit theory in Chapter 1.

Let us start off by considering the simple circuit as shown in Figure 6.1(a). The source voltage E is 100 volts and the rated load current I_L of the circuit is 1.0 ampere. The impedance Z_S of the system connecting the load to the source is 5.0 ohms. Thus, with the load current at rated value, the load must have an equivalent impedance Z_L of 95 ohms for a total Z_B of 100 ohms. (These values have been chosen for easy calculation rather than to represent typical circuit values. Also, for the sake of simplicity, the correct vector addition of the resistance and reactance components of the impedance is ignored.) A bolted fault then occurs on the system as shown in Figure 6.1(b), which shorts out all the load impedance. The fault in effect creates a new circuit with a much lower impedance. Now the current that flows (fault current I_{SC}) is restricted only by the 5.0 ohm impedance Z_S, which represents the total impedance of the system between the source and the fault, including the return path. Thus the

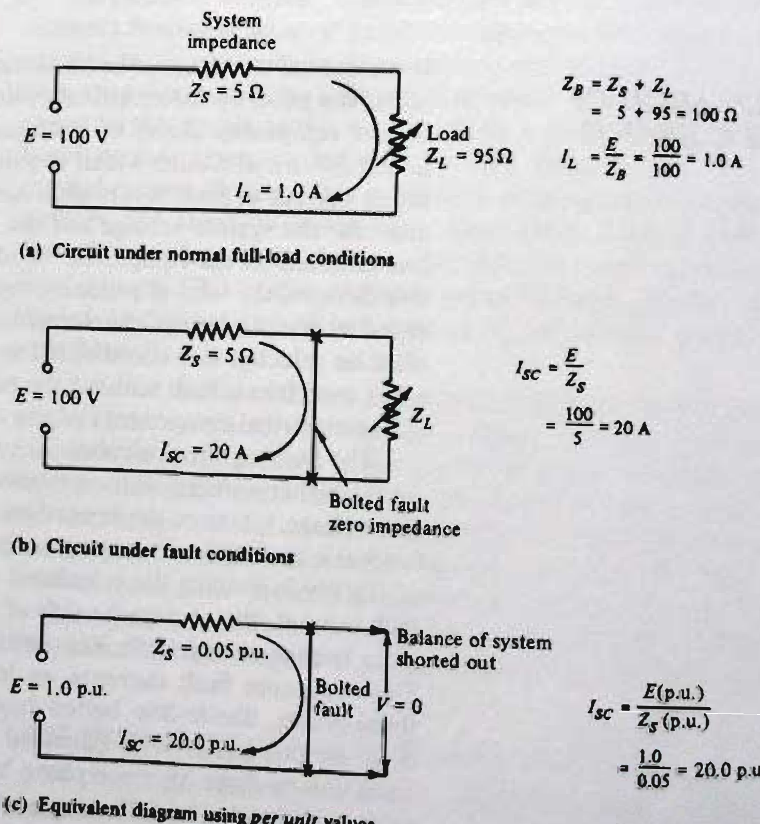


FIGURE 6.1

Calculation of a short-circuit fault current short-circuit current, by Ohm's law, is 20 amperes or 20 times the rated current of the circuit.

Next let us make this example more universal by designating the source as 100% instead of 100 volts, meaning that the source voltage is at 100% of its rated value, whatever that may be. Next designate the total impedance of the system under full-load conditions as 100% instead of 100 ohms. However, if calculations are done using these percentage values, they do not work out properly. With 100% voltage applied to the system and with 100% impedance, 100% current should flow. But, mathematically, $I = E/Z = 100/100 = 1.0$. This difficulty can easily be overcome by using per unit values instead of percent values. Thus, with 1.0 per unit voltage applied and with 1.0 per unit impedance, the current is 1.0 per unit. The value of the single impedance that, if inserted in the system with rated voltage applied, allows rated current to flow is called the *base impedance*. Therefore,

$$\text{Base impedance } (\Omega) = \frac{\text{rated line-to-neutral volts}}{\text{rated current}} \qquad \textbf{(6.1)}$$

If we compare the system impedance of 5.0 ohms with the base impedance of 100 ohms in Figure 6.1(a), then the system impedance is 5/100 or 0.05 per unit. The per unit value of any component in the system can be calculated as follows:

$$\text{Per unit value} = \frac{\text{actual value } (\Omega)}{\text{base impedance } (\Omega)} \qquad \textbf{(6.2)}$$

Figure 6.1(c) shows the per unit values applied to the circuit under fault conditions. The short-circuit current from Ohm's law is

$$\text{Per unit } I_{SC} = \frac{E(\text{p.u.})}{Z_S(\text{p.u.})} \qquad \textbf{(6.3)}$$

where Z_S is the equivalent system per unit impedance between the source and the point of the fault. The actual fault current in amperes can then be calculated as follows:

$$I_{SC}(\text{A}) = (\text{rated current}) \times (\text{per unit } I_{SC}) \qquad \textbf{(6.4)}$$

The short-circuit current in the example is 1.0/0.05, which equals 20.0 per unit. The short-circuit current in amperes is (1.0) × (20.0), which equals 20 amperes. This agrees with our original calculation in part (b).

The complexity of fault calculations comes in determining the equivalent system impedance Z_S between the source and the point of the fault, especially if there is more than one source of power.

Let us apply the per unit system of calculations to some sample systems.

■ EXAMPLE 6.1

A three-phase, 480 V system has a rated current of 50 A. The feeder has an impedance of 0.15 Ω. Calculate the per unit impedance of the feeder.

Solution

The line-to-neutral voltage is 480/1.732 = 277 V. From Eq. 6.1:

$$\text{Base impedance} = \frac{277}{50} = 5.54\ \Omega$$

From Eq. 6.2:

$$\text{Per unit impedance} = \frac{0.15}{5.54} = 0.027$$

■ EXAMPLE 6.2

Refer to Figure 6.2(a), which shows the diagram of a typical electrical system. Power is supplied over a primary feeder line to a 500 kVA transformer, which steps the voltage down to a utilization level of 208Y/120 V for distribution to a number of loads. (Refer to Section 1.6.1 for designation of voltages.) The calculated percentage impedance of the primary feeder line is 1.0% (or 0.01 per unit), and the transformer has an impedance of 5.0% (or 0.05 per unit). Calculate the short-circuit current on the secondary of the transformer under three-phase bolted fault conditions.

Solution

Figure 6.2(b) shows the equivalent circuit diagram of the system on a single-phase basis when operating under normal full-load conditions. Note that with the various parameters shown in per unit values there is no need to worry about voltage levels at any point. Figure 6.2(c) shows the system with a bolted fault at the secondary of the transformer. The maximum fault current on the low-voltage part of the system will occur at this point, as the impedance of the low-voltage feeders will not be a factor in limiting the fault current. The remaining impedances that will limit the short-circuit current are those of the primary feeder and the transformer. Since these impedances are in series, the total impedance is

$$Z_S = 0.01 + 0.05 = 0.06\ \text{p.u.}$$

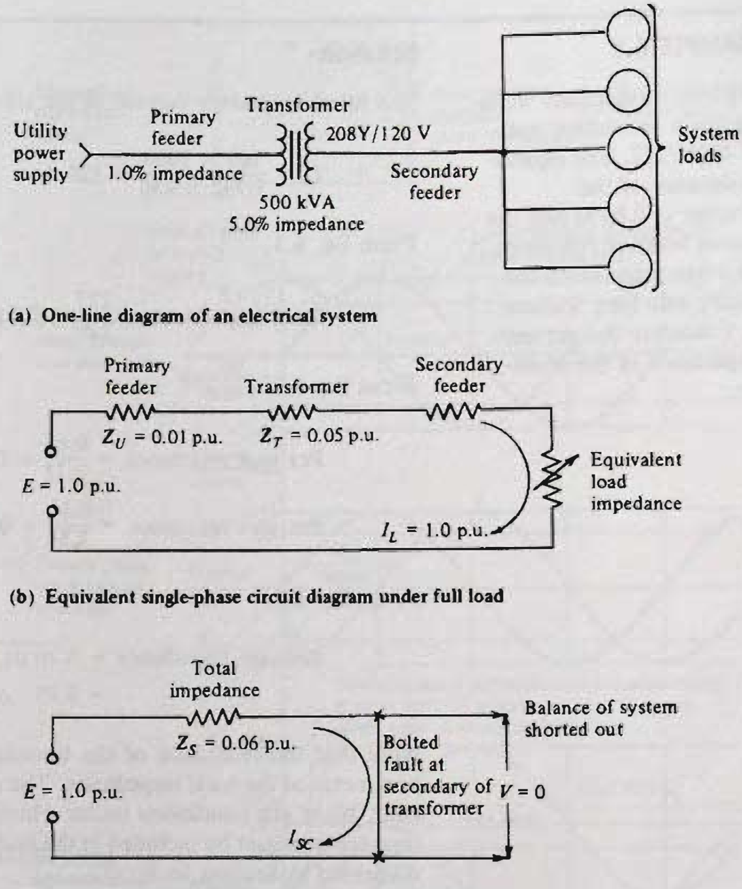
From Eq. 6.3,

$$I_{SC} = \frac{1.0}{0.06} = 16.67\ \text{p.u.}$$

The rated secondary current (on the 208Y/120 side of the transformer) is (from Eq. 1.14)

$$I_S = \frac{500 \times 1000}{1.732 \times 208} = 1388\ \text{A}$$

And, from Eq. 6.4,



(a) One-line diagram of an electrical system

(b) Equivalent single-phase circuit diagram under full load

(c) Equivalent single-phase circuit diagram with bolted fault

FIGURE 6.2

Diagrams for Example 6.2
Note: Figure 6.2(a) is in the form known as one-line (see Chapter 11). No switches or protective devices are shown because they have a negligible effect on the magnitude of the maximum possible fault current.

$$I_{SC} = 1388 \times 16.67 = 23{,}100 \text{ A}$$

Note: Since the voltages used in this example are rms values, the calculated value of the current is also the rms value. Note the importance of the transformer impedance in limiting the magnitude of the fault current. This is discussed in more detail in Section 16.2.

These examples are just an introduction to the calculation of fault currents. More detailed examples are presented in Chapter 16.

In Example 6.2, the total impedance Z_S is calculated by simply adding the impedance values without properly taking into account their respective resistance and reactance components. However, the effect of this shortcut is very minor. The following example shows the calculation of the percentage impedance of a transformer, taking into account the resistance and reactance values.

■ **EXAMPLE 6.3**

A 100 kVA, three-phase transformer has a secondary voltage of 480Y/277. The equivalent resistance of the transformer is 0.03 Ω and the equivalent leakage reactance is 0.11 Ω when referred to the secondary side (see Section 1.7.2). Calculate the percentage impedance of the transformer.

Solution

The rated secondary current of the transformer is (from Eq. 1.14)

$$I_S = \frac{100 \times 1000}{1.732 \times 480} = 120 \text{ A}$$

From Eq. 6.1,

$$\text{Base impedance} = \frac{277}{120} = 2.31\ \Omega$$

From Eq. 6.2,

$$\text{Per unit resistance} = \frac{0.03}{2.31} = 0.013$$

$$\text{Per unit reactance} = \frac{0.11}{2.31} = 0.048$$

From Eq. 1.8,

$$\text{Per unit impedance} = \sqrt{(0.013)^2 + (0.048)^2}$$
$$= 0.05 \quad \text{or} \quad 5.0\%$$

Note that the reactance of the transformer is by far the most important parameter of the total impedance. The resistance has a minor effect. However, there are conditions under which the effect of the resistance of the transformer must be included in the fault calculations. These conditions are discussed in Section 16.3.

6.5 ASYMMETRICAL FAULT CURRENTS

The previous calculations on fault currents assumed that the currents would remain symmetrical after the occurrence of a fault on the system. By *symmetrical* it is meant that *the fault current has the same axis as the normal current that was flowing prior to the fault* [see Figure 6.3(b)]. However, this is not always the case. Depending on the exact time at which the fault occurs during the cycle, the resulting fault current can be offset from the normal-current axis; that is, it becomes *asymmetrical*.

For an explanation as to why fault currents become asymmetrical, at least for the first few cycles, refer again to Figure 6.3. Power systems are highly inductive under fault conditions (that is, transformer reactances and the like). Figure 6.3(a) shows a theoretical circuit with a pure inductive reactance component and no resistance. The closing of the switch simulates a fault on the system; that is, the current that flows in this circuit represents the fault current

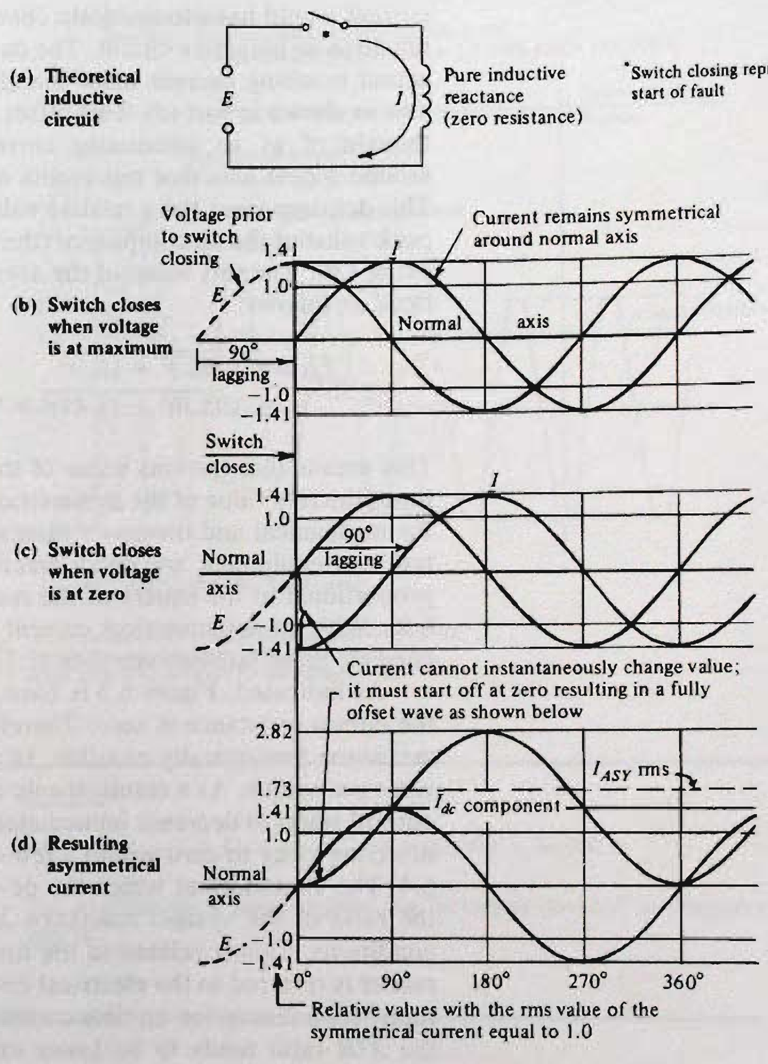


FIGURE 6.3

Theoretical asymmetrical fault currents

that would flow in a shorted power system. The current in a pure inductive circuit must lag the voltage by 90 electrical degrees (see Section 1.4.1). Part (b) shows the voltage and current relationship for the case when the switch closes with the voltage at its maximum positive value. Since the current at that instant of time would normally be at zero, the current that then flows in the circuit remains symmetrical about the normal axis, as shown. Part (c) shows the case when the switch closes with the voltage at zero. If the current is drawn with its normal 90 degree lagging relationship and projected back to the time that the switch closes, it would have to be at its maximum negative value. This cannot happen, as it means that the current would have to instantly change in magnitude, which it cannot do in an inductive circuit. The current must start off at zero. The actual resulting current must therefore be offset from the normal axis as shown in part (d). This offset or asymmetrical current can be thought of as an alternating current component I_{ac} alternating around a new axis that represents a direct current component I_{dc}. This dc component has a relative value of 1.41, which is equal to the peak value of the ac component (the rms value of the ac component being 1.0). The rms value of the asymmetrical current I_{ASY} is calculated as follows:

$$\begin{aligned} I_{ASY} &= \sqrt{(I_{ac})^2 + (I_{dc})^2} \\ &= \sqrt{(1.0)^2 + (1.41)^2} = \sqrt{3.0} = 1.73 \end{aligned}$$

This means that the rms value of the asymmetrical current is 1.73 times the rms value of the symmetrical current. As can be imagined, the mechanical and thermal stresses imposed on the electrical system and equipment are much greater. These stresses are directly proportional to the square of the rms value of the current (Section 6.2). With an asymmetrical current of 1.73 times the symmetrical current, these stresses are then $(1.73)^2$, or three times as great.

As indicated, Figure 6.3 is based on the theoretical case where the circuit resistance is zero. Therefore, the relative values are the maximum theoretically possible. In practice, all circuits must have some resistance. As a result, the dc component of the asymmetrical current starts to decrease immediately after the fault occurs, usually decaying away to zero within a few cycles. This is shown in Figure 6.4. The exact rate at which the dc component decays depends on the ratio of the system reactance X and resistance R under fault conditions. This is related to the time constant of the system. The reader is referred to the electrical circuit books listed in the Bibliography for a discussion on time constants. With low-voltage systems, the X/R ratio tends to be lower and the rate of decay is faster. Conversely, with high-voltage systems, the X/R ratio tends to be higher and the rate of decay is slower. Studies have been done on typical power systems and multiplying factors have been recommended to account for asymmetrical fault currents in the design of electrical systems and equipment. Figure 6.4 shows the rate of decay for a system with an X/R ratio of 6.6, which is typical for low-voltage power systems (below 1000 volts). At the end of a half-cycle, the rms value of the asymmetrical current is 1.33 times the rms value of the symmetrical current. On systems above 1000 volts, the recommended multiplying factor is 1.6. The use of the multiplying factor is illustrated in the following example.

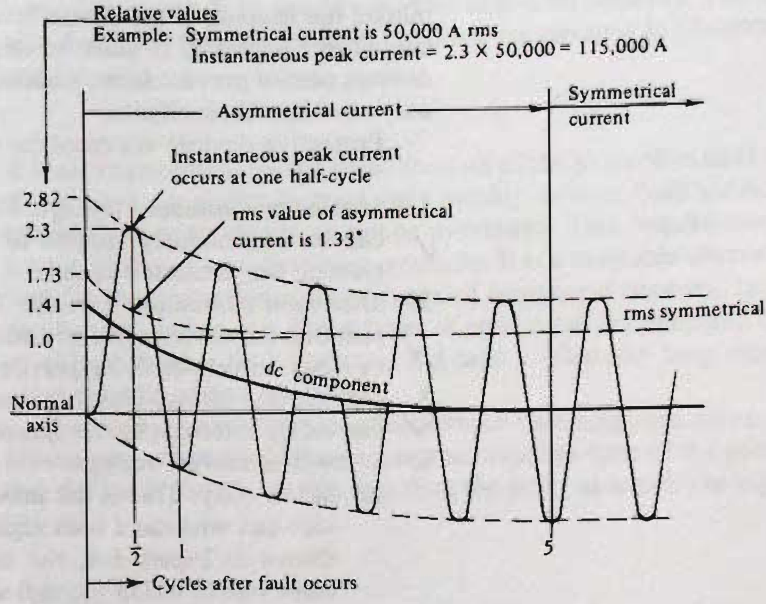


FIGURE 6.4

Asymmetrical fault current for X/R ratio of 6.6

* Value depends on rate at which dc component decays away, which in turn depends on the X/R ratio of system; an X/R ratio of 6.6 is typical for low-voltage systems

■ EXAMPLE 6.4

Calculate the rms value of the asymmetrical fault current at the end of one half-cycle for one phase of the secondary low-voltage system in Example 6.2.

Solution

$$I_{ASY} = 1.33 \times I_{SC} = 1.33 \times 23{,}100 = 30{,}700 \text{ A}$$

The application of these multiplying factors is covered in Chapters 8, 11, and 16.

6.6 FUNCTIONS OF PROTECTIVE DEVICES

The protective device has two major functions: (1) to detect an abnormal condition on that portion of the system that it is protecting, and (2) to automatically and safely disconnect the faulted portion from the balance of the system. Protective devices such as fuses and most low-voltage circuit breakers combine both the detection unit and the disconnecting means in the one unit. Other types of protective devices separate the two functions. For example, medium- and high-voltage circuit breakers normally only perform the disconnecting function. They must be used in conjunction with separate protective relays that detect the abnormal conditions and then initiate the tripping of the circuit breaker. Protective relays are discussed in Chapter 9. It must be emphasized again that protective devices cannot prevent faults from occurring on the system, but can only minimize their effects.

Protective devices are rated for the following:

1. *Maximum continuous voltage:* This is the maximum voltage that can be continuously applied to the device without eventually causing the insulation to fail.
2. *Maximum continuous current:* This is the maximum load current that the device can carry continuously without the contacts or other current-carrying parts overheating.
3. *Interrupting rating:* This is the maximum current that the device can safely interrupt at the specified voltage.
4. *Short-time current ratings:*
   - **(a)** *Momentary:* This is the maximum rms current that the device can withstand with regard to mechanical stressing. As shown in Figure 6.4, the maximum stressing occurs one half-cycle (0.00833 second) after the fault starts. This rating is necessary to ensure that the device is not physically damaged before it can operate to disconnect the faulted part of the system.
   - **(b)** *Specified time:* This is the maximum rms current that the device can withstand for a specified time (0.5 s) with regard to thermal stressing. In the case of breakers, it is sometimes necessary under severe short circuits to delay their opening for a very short period of time in order to coordinate with other devices. This rating is necessary to ensure that the breaker is not damaged by heat before it can operate to disconnect the faulted part of the system.

These ratings apply to the basic protective device mechanism. The point at which the detection unit, which is incorporated into the protective device, starts to respond to an overcurrent is a separate rating. There are many more ratings of detection units than there are ratings of the basic devices. For example, in our residences there are 15, 20, 30, and 40 ampere circuits that need overcurrent protection set at these values. It is not justified to have circuit breaker mechanisms designed for each of these currents. Therefore, there is one breaker mechanism designed to handle up to 100 amperes into which detection units rated for specific currents are installed. Thus a breaker with a rating of 15 amperes stamped on the handle is in reality a 100 ampere breaker with a detection unit that is set to respond to any overcurrent above 15 amperes. Similarly, a 40 ampere fuse is actually a 60 ampere fuse body incorporating a fuse element that responds to any overcurrent above 40 amperes. The specific details of fuses and circuit breakers are covered in Chapters 7 and 8.

6.7 INVERSE-TIME AND INSTANTANEOUS-RESPONSE CHARACTERISTICS

A basic requirement for the detection unit of the protective device is that it have the ability to react very quickly to large fault currents, but to react very slowly to minor overloads. This requirement is known as the *inverse-time characteristic*. It is a desirable characteristic for the protection of most types of equipment (motors, feeder conductors, and so on). These types of equipment are damaged very quickly with large fault currents, but take a relatively long time to overheat with minor overloads.

Figure 6.5 shows the plot of an inverse-time response curve. An ideal arrangement is obtained when the response time of the protective device is always slightly less than the point at which the equip-

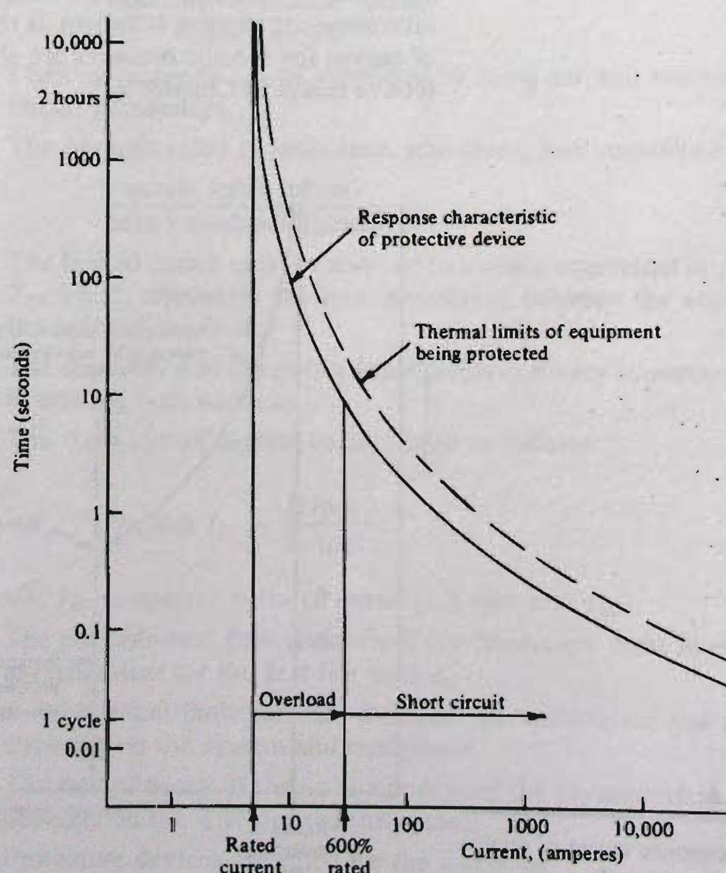


FIGURE 6.5

Inverse-time curves plotted on log–log scales ment is damaged. In this way, needless shutdowns for harmless short-duration overloads can be avoided. Inverse-time curves are usually plotted using log–log scales for both the current (horizontal) and time (vertical). This is necessary because the currents range from a few amperes under normal conditions up to tens of thousands of amperes under short-circuit fault conditions. Similarly, the response time can range from fractions of a second (cycles) for large currents up to hours for minor overloads. Examples of curves for specific fuses are shown in Chapter 7.

In the case of circuit breakers, it is also desirable that the detection unit have an element that responds immediately at a specific value of fault current to trip open the breaker. This is known as *instantaneous tripping*, which is defined as *tripping with no intentional time delay*. Note that breakers take some finite time to fully open the circuit because of the inertia of their moving parts. Figure 6.6 shows a typical time response curve for a circuit breaker that combines the inverse-time element and the instantaneous element. The point at which the breaker changes from inverse-time tripping to instantaneous tripping is known as the *knee* of the curve. Examples of curves for specific breakers are shown in Chapter 8 and for protective relays in Chapter 9.

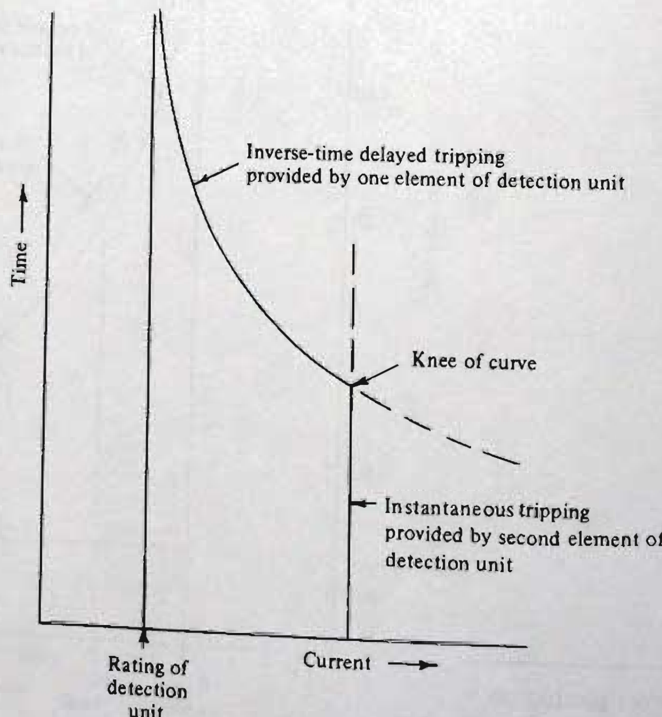


FIGURE 6.6

Typical response curve of dual-element circuit breaker

SUMMARY

- Electrical systems must operate in a safe manner.
- Overloads can be tolerated for short periods of time.
- Short circuits must be disconnected immediately.
- All circuits and equipment must be protected against overcurrents.
- Fault currents impose severe mechanical and thermal stresses on the system and equipment.
- Arcing faults have lower fault currents but can cause extensive damage if not properly detected.
- Bolted faults have higher fault currents but can be quickly detected and removed from the system.
- Calculations of fault currents are necessary to ensure the proper selection of devices and equipment.
- Base impedance is the value of a single impedance that, if inserted in a circuit with rated voltage applied, allows rated current to flow.
- Base impedance (ohms) is

$$\frac{\text{rated line-to-neutral voltage}}{\text{rated current}}$$

- Fault calculations can be simplified by using per unit values for the circuit parameters.
- The per unit value of resistance, reactance, and impedance is

$$\frac{\text{actual value (ohms)}}{\text{base impedance (ohms)}}$$

- The faulted circuit must be reduced to a single equivalent impedance Z_S, which represents the total impedance between the source and the point of the fault.
- The impedance of the power transformer is a very important factor in limiting fault currents.
- The short-circuit current is calculated as follows:

$$\text{Per unit } I_{SC} = \frac{E\text{ (p.u.)}}{Z_S\text{ (p.u.)}}$$

  and I_{SC} (amperes) = (rated current) × (per unit I_{SC}).
- The currents that flow under fault conditions are most likely to be asymmetrical for the first few cycles.
- Asymmetrical fault currents increase the mechanical and thermal stressing on the system and equipment.
- The rate of decay of the dc component of the asymmetrical current depends on the X/R ratio of the system.
- Protective devices are rated for the following:

— Maximum continuous voltage rating
— Maximum continuous current rating
— Interrupting rating
— Short-time ratings: momentary and specified time

- The detection unit of a protective device should have an inverse-time characteristic.
- Circuit breakers can have a combination of inverse-time delayed tripping and instantaneous tripping.

QUESTIONS

1. Explain the difference between an overload and a short circuit.
2. Explain the term overcurrent.
3. Why can an overload be left on the system for a relatively long period of time (minutes)?
4. Why must a short circuit be disconnected from a system within a very short period of time (cycles)?
5. What causes mechanical stressing under fault conditions?
6. What causes thermal stressing under fault conditions?
7. Explain the difference between an arcing fault and a bolted fault.
8. Why is the arcing fault potentially the most destructive type of fault?
9. Why is it necessary to calculate the maximum fault current that can flow at any given point on a system?
10. What is the base impedance of a system?
11. What is an asymmetrical current?
12. What are the two major functions of a protective device?
13. List the four ratings of protective devices.
14. Describe the inverse-time characteristics.
15. Why is it desirable for a protective device to have an inverse-time response characteristic?
16. What is meant by instantaneous tripping?

PROBLEMS

1. Refer to Figure 6.1(a). The voltage $E = 120$ V, the system impedance $Z_S = 0.1\ \Omega$, and the load impedance $Z_L = 1.5\ \Omega$. Calculate (a) the normal load current I_L of the circuit, (b) the fault current I_{SC} as per Figure 6.1(b), and (c) the per unit values for Z_S and I_{SC} as per Figure 6.1(c). Assume the impedances are primarily resistive.
2. Repeat Problem 1, except $E = 277$ V, $Z_S = 0.025\ \Omega$, and $Z_L = 0.529\ \Omega$.
3. A three-phase, 208 V system has a rated current of 100 A. A feeder has an impedance of 0.018 Ω. Calculate the per unit impedance of the feeder.
4. Refer to Figure 6.2(a). The transformer is 1000 kVA, its impedance is 5.75%, the primary feeder impedance is 0.75%, and the secondary voltage is 480Y/277 V. Calculate the short-circuit current on the secondary of the transformer under three-phase bolted fault conditions.
5. Repeat Problem 4, except the transformer is 1500 kVA, its impedance is 5.0%, and the primary feeder impedance is 0.5%.
6. A 200 kVA, three-phase transformer has a secondary voltage of 208Y/120 V. The equivalent resistance of the transformer is 0.002 Ω and the equivalent leakage reactance is 0.009 Ω. Calculate the percentage impedance of the transformer.

7 Fuses

OBJECTIVES

After studying this chapter, you will be able to:

- Interpret time–current characteristic curves of fuses.
- Recognize the categories of low-voltage fuses.
- Explain the term current limiting.
- Explain dual-element fuses.
- Recognize time-delay fuses.
- Recognize the classifications of low-voltage fuses.
- Coordinate low-voltage fuses.
- Recognize the major types of high-voltage fuses.
- Identify the advantages of fuses.
- Identify the disadvantages of fuses.

INTRODUCTION

The protection of electrical systems all started with Thomas Edison, as did so many other aspects of the electrical industry. In 1880, Edison applied for and was granted a patent entitled *Safety Conductor for Electric Lights*. This patent stated in part:

> The safety device consists of a piece of very small conductor . . . [having] such a degree of conductivity as to readily allow the passage of the amount of current designed for its particular branch. If . . . an abnormal amount of current . . . is diverted through a branch, the small safety wire becomes heated and melts away, breaking the overloaded branch circuit. It is desirable, however, that the few drops of hot molten metal resulting therefrom should not be allowed to fall upon carpets and furniture and also that the small safety conductor should be relieved of all tensile strain; hence I enclose the safety wire in a jacket or shell of nonconducting material.

Since Edison had earlier developed the incandescent lamp and was in the process of building electrical systems to supply electrical power to customers installing the new lighting, he naturally was interested in protecting the circuits to these electric lights. The term *electric fuse* came into use some time later.

Edison's description of the fuse is still valid today. The transition from his fuse to the modern fuse has been primarily in the development of special alloys for the fusible element, with the use of fillers surrounding the element and hermetically sealing the element in a strong shell. The *National Electrical Code* defines the *fuse* as an *overcurrent protective device with a circuit opening fusible part that is heated and severed by the passage of current through it*. Thus the fuse combines the current sensing and interrupting functions into the one element.

Many types of fuses are now available for different applications. It is no longer satisfactory to just specify that a fuse shall be, for example, *100 amperes, 250 volts*. Apart from having different ampere and voltage ratings, fuses have widely different interrupting ratings, different response characteristics, and different current-limiting capabilities. Fuses with fast overload response times are used for the protection of solid-state devices, which have low overload capabilities. Fuses with relatively slow overload response times are used on motor circuits where large starting currents must be handled. Fuses are further divided into low voltage (for systems 1000 volts and below) and medium and high voltage (for systems above 1000 volts). Today, the proper application of fuses requires a sound knowledge of the types available. The discussions in this chapter are limited to those fuses used for the feeders and circuits normally encountered in the electrical systems in buildings.

7.1 RESPONSE CHARACTERISTICS OF FUSES

A fuse does not instantly open when the current exceeds its rating, nor should it. The fusible element within the fuse responds to the heat generated by the passage of the current through it. The heat is a function of I^2t; thus the fuse inherently has an inverse time–current response, which is a desirable characteristic (see Section 6.7 and Figure 6.5). The response times of fuses of the same voltage and ampere rating can vary widely. This is controlled by the type of material and construction used for the fusible element. These times are plotted as a function of the current on log–log, time–current graphs. The general form of the graph used by industry is shown in Figure 7.1. The vertical time scale extends from 0.01 to 1000 seconds, and the horizontal current scale extends from 0.5 to 10,000 amperes. However, note that this latter scale is often modified by a factor of 10, 100, or even 1000. Figure 7.1 indicates *current in am-*

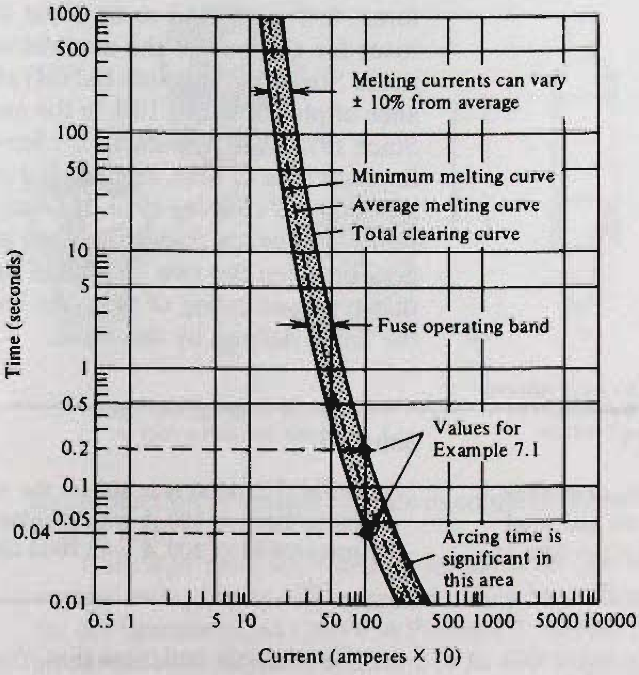


FIGURE 7.1

Typical fuse response curves

peres × *10,* which means that all values marked on the scale are multiplied by a factor of 10; for example, 100 on the scale is actually 1000 amperes.

Before attempting to read fuse curves, we should look at some related terminology. In the past, such terms as *opening time* and *blowing time* have been used. However, these terms can be misleading. The operation of the fuse is divided into two time intervals. The first is the time required for the fusible element to heat up to the point where it starts to melt, designated the *melting time*. The second is the time for the severed element to separate and for the resulting arc to be fully extinguished, designated the *arcing time*. The total of the melting plus the arcing time is then properly referred to as the *total clearing time*. For currents in the overload range, the melting times are relatively long and the arcing times are insignificant. However, for high short-circuit currents, the arcing time is significant relative to the melting times (see Figure 7.4).

The precise melting characteristics of the fusible element depend on the purity of the metals and/or the mixture of the ingredients in the alloy used and on its exact thickness and length. No matter how strict the quality control maintained by the manufacturer, there is bound to be some discrepancies between individual fuses for any one of the manufacturer's types. The American National Standards Institute (ANSI) standards allow a maximum tolerance of plus or minus 10% in the melting current for any given time. Since 1972, fuse manufacturers have been issuing two sets of curves for each type of fuse, one labeled *minimum melt time* and the other labeled *total clearing time*. If these two curves for any one type and rating of fuse are traced onto one sheet as shown in Figure 7.1, the area between the two lines then represents the operating band for that type and rating of fuse. An individual fuse will operate within the limits defined by this band.

■ EXAMPLE 7.1

Using Figure 7.1, determine the minimum melt and total clearing times for the fuse at 1000 A.

Solution

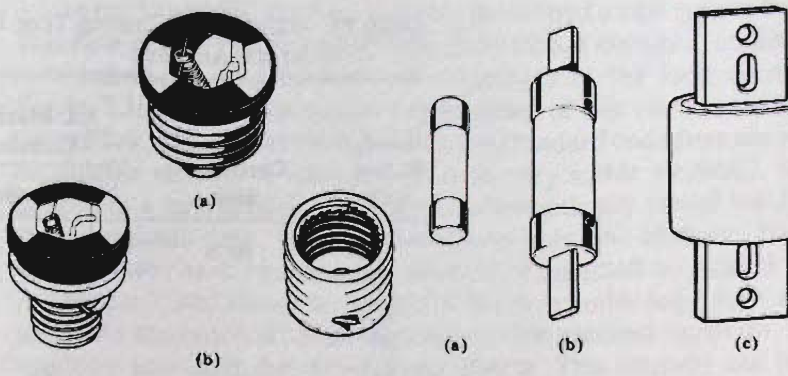
— In Fig. 7.1, 1000 A is 100 on the scale (that is, 100 × 10)
— Intersection of 100 A with minimum melt curve is 0.04 s
— Intersection of 100 A with total clearing curve is 0.2 s

The example indicates that, from a large sampling of this same type of fuse, none will melt in less than 0.04 second and none will take longer than 0.2 second to totally clear the circuit at 1000 amperes. The curves in Figure 7.1 have been purposely shown with an exaggerated tolerance band to emphasize this effect. The spread of operating times for most fuses is nevertheless significant, and the minimum melt and total clearing curves must both be used when coordinating fuses with other types of protective devices (see Sections 16.4 and 16.5). Examples of curves for specific types of fuses are shown in Figures 7.10, 7.11, 7.15, and 7.16.

7.2 CATEGORIES OF LOW-VOLTAGE FUSES

The *NEC* recognizes two principal categories of fuses: the plug fuse and the cartridge fuse. Figure 7.2 shows the various plug and cartridge configurations.

Plug fuses are rated for 125 volts and are available with current ratings up to 30 amperes. Their use is limited to circuits not exceeding 125 volts between conductors or, if the system has a grounded neutral conductor, not exceeding 150 volts to ground. Plug fuses of the Edison-base type can be used only for replacement of existing fuses. The type S plug fuse must be used on new installations. This type of base is constructed so that a fuse of a higher ampere range cannot be inserted into the same fuseholder. Adapters are available to convert Edison-base holders so that they can accept the type S fuse. Plug fuses are mainly used for residential wiring. Their use for



Plug Fuses. (a) Edison Base Fuse
(b) Type S Fuse and Adapter

Cartridge Fuses. (a) Ferrule Type, 0–60 A
(b) Knife-Blade Type, 70–600 A
(c) Bolt Type, 601–6000 A

FIGURE 7.2

Principal low-voltage fuse categories as recognized by the *NEC*

the protection of branch circuits in commercial and industrial buildings is rare.

Cartridge fuses are rated up to 600 volts and are available with current ratings up to 6000 amperes. They have three different physical configurations, as shown in Figure 7.2: ferrule type, from 0 to 60 amperes; knife-blade type, from 70 to 600 amperes; and bolt type, from 601 to 6000 amperes. Fuses up to 600 amperes are rated for either 250 or 600 volts. There are also special fuses from 0 to 60 amperes that are rated for 300 volts. Fuses above 600 amperes are rated for 600 volts only. Fuses rated for 250 volts can be used on 120, 208, and 240 volt systems. Fuses rated for 300 volts can be used on circuits for systems having a grounded neutral and with no conductor operating at more than 300 volts to ground (that is, a 480Y/277 volt system). Fuses rated for 600 volts can be used on any circuit up to 600 volts (120, 208, 240, 480, and 600 volts). The fuses for each voltage rating have different dimensions so that they cannot be interchanged in the fuseholder.

The ampere ratings that are available up to 600 amperes are shown in Table 7.1. These ratings are actually the ratings of the fusible element within the fuse cartridge. The different ratings are grouped into cartridge sizes as shown in the table. For example, the 15, 20, 25, and 30 ampere fuses all have the same cartridge size and therefore, for the same voltage rating, they have the same physical dimensions (see Figure 7.8). Fuses are available with ratings below 15 amperes, but these are used for the protection of special equipment. The 15 ampere rating is normally the smallest size used for the protection of branch circuits in buildings.

There are many classifications of cartridge fuses with regard to operating characteristics and interrupting ratings. These are discussed in Section 7.5.

TABLE 7.1 Ratings and Clearing Time Limits for Low-Voltage Fuses up to 600 Amperes

Fuse Rating (A)	Cartridge Size	UL Maximum Allowable Clearing Times (min)	
		135% Rating	200% Rating
15	30 A	60	2
20			
25			
30			
35	60 A	60	4
40			
45			
50			
60			
70	100 A	120	6
80			
90			
100			
110	200 A	120	8
125			
150			
175			
200			
225	400 A	120	10
250			
300			
350			
400			
450	600 A	120	12
500			
600			

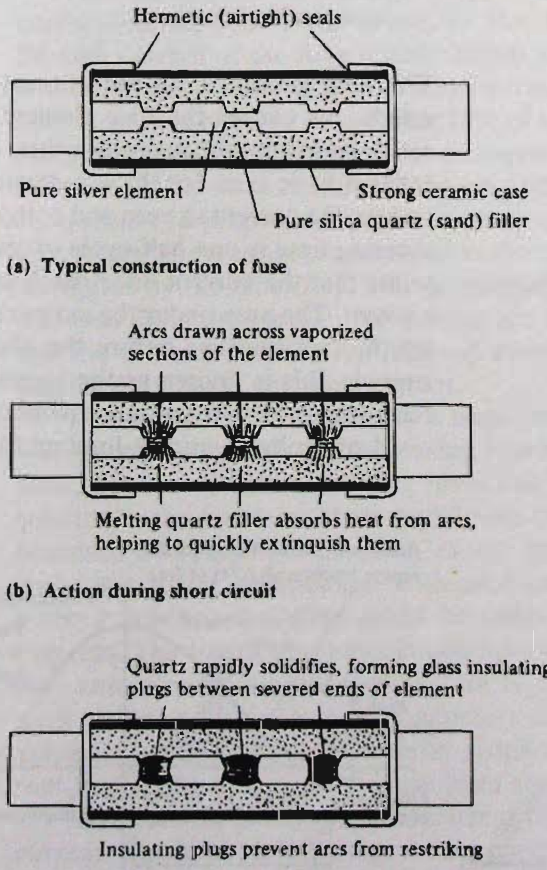
See Figure 7.8 for the dimensions of each size of cartridge.

7.3 CURRENT-LIMITING FUSES

The standard low-voltage code fuses that were available for many years had interrupting ratings of only 10,000 amperes. This became inadequate for many low-voltage systems where the available fault currents were well above this level. Furthermore, the fusible elements were generally made of zinc, a metal that tends to crystallize and deteriorate with age, resulting in unreliable operation. As a result of these problems, for the overcurrent protection of low-voltage circuits, the trend was toward the use of air circuit breakers.

In the late 1940s, the fuse industry developed a new type of fuse. This fuse is very fast acting on high short-circuit currents, so fast in fact that it can actually limit the magnitude of the fault current. Figure 7.3(a) shows the typical construction of this *current-limiting* type of fuse. The major changes from the standard code fuse are that the fusible element is made of silver (a very stable element), it is packed in a quartz filler, and then it is hermetically sealed inside a strong ceramic case. The diagram shows only one element. High-current fuses have two or more elements connected in parallel.

Figure 7.3(b) shows the action of the fuse under large fault currents. As the notched sections of the fusible element vaporize, the resulting arcs melt the surrounding quartz. This absorbs the heat from the arcs, quickly extinguishing the arcs and clearing the circuit. Then the molten quartz rapidly cools and solidifies, forming insulating plugs between the severed ends of the fuse links and preventing the arcs from restriking, as shown in Figure 7.3(c). The heat and



(a) Typical construction of fuse

(b) Action during short circuit

(c) Immediately after arcs extinguished

FIGURE 7.3

Construction and operation of current-limiting fuses pressure created by the arcs are safely contained within the strong fuse casing. These high interrupting capacity, current-limiting fuses are a one-time nonrenewable type that is discarded after operation and replaced by a completely new fuse. In contrast, the older, standard code fuses are generally the renewable type with a reusable outer cartridge; only the fuse link is replaced after operation.

Figure 7.4 shows the plot of the fault current against time and the resulting ability of the fuse to limit the magnitude of the let-through current. The current shown in the diagram is the asymmetrical fault current described in Section 6.5 and shown in Figure 6.4. Since the fuse acts so fast, only the first cycle of this prospective fault current need be shown. *NEC* Section 240-11 defines a *current-limiting overcurrent device* as:

> A device which, when interrupting currents in its current limiting range, will reduce the current flowing in the faulted circuit to a magnitude substantially less than that obtainable in the same circuit if the device were replaced with a solid conductor having comparable impedance.

The heat produced as the current rises very rapidly under fault conditions causes the fuse element to melt before the current can reach its instantaneous peak value, as shown in the diagram. It then takes a finite time for the arc quenching process within the fuse to reduce the current to zero and completely open the circuit. The total clearing time is one half-cycle or less. The maximum instantaneous value that the current does reach is known as the *peak let-through current*. The area under the curve represents the total energy that is let through the fuse before the short-circuit current is fully interrupted. This is known as the *thermal energy let-through* and is referred to as the I^2t value (remember, energy also involves time).

Low-voltage current-limiting fuses are available with interrupt-

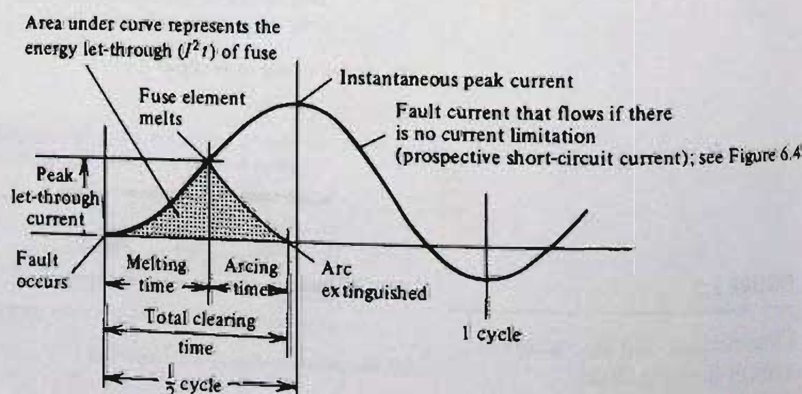


FIGURE 7.4

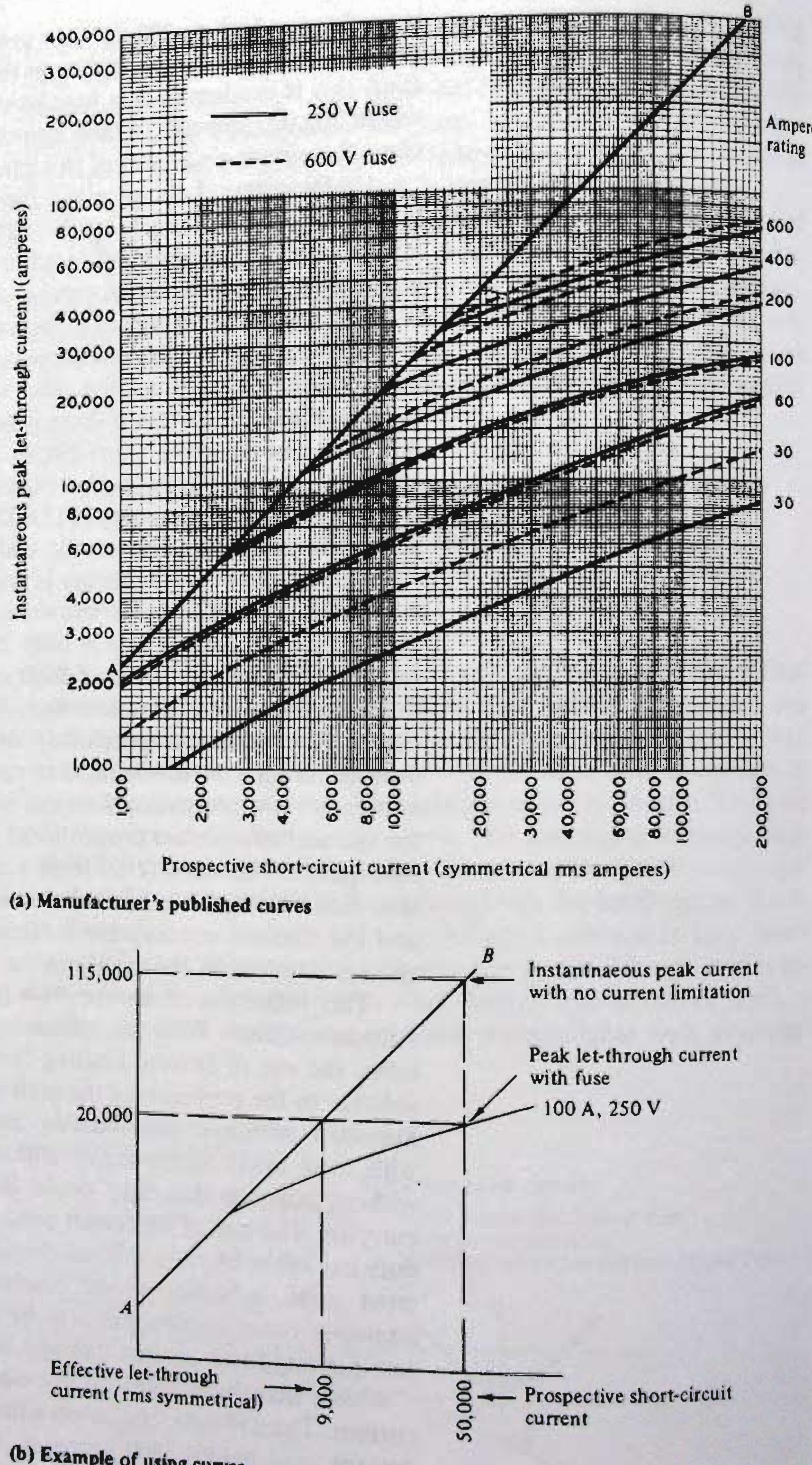
Typical current limitation on high short-circuit currents ing ratings as high as 200,000 rms symmetrical amperes. As shown, the fuse does not actually interrupt this magnitude of current. However, this is academic, as a fuse so rated can be placed in a circuit where 200,000 amperes of fault current is available, and it will safely clear the circuit on a fault of this magnitude.

Underwriters Laboratories, Inc. (UL) standards specify the maximum permitted peak let-through currents and thermal energy let-through (I^2t) values for the various classes of fuses. Manufacturers publish peak let-through current curves for their current-limiting fuses. A typical set of curves is shown in Figure 7.5(a). The diagonal line *AB* represents the instantaneous peak value that the current could reach for the associated value of the prospective rms symmetrical short-circuit current if there is no current limitation. For example, if the prospective short-circuit current is 50,000 symmetrical rms amperes as shown in the example in Figure 7.5(b), then the instantaneous peak current is 115,000 amperes. This agrees with the value shown in Figure 6.4 at the end of one half-cycle.

Now assume that the feeder is protected by 250 volt, 100 ampere current-limiting fuses. As shown in the example, the peak let-through current of the fuse is only 20,000 amperes. This translates into an effective rms value of 9000 amperes. Thus the value of the fault current is reduced to less than 20% of what it would be with no current limitation. As previously discussed in Section 6.2, under fault conditions the mechanical stresses imposed on the system and equipment are proportional to the square of the peak current, and the thermal stresses are proportional to the square of the rms current multiplied by the time (I^2t). With a reduction of the fault current to less than 20%, the mechanical stresses are reduced to less than 4% and the thermal stresses are reduced even further because of the shorter duration of the fault current.

This reduction of stresses is a tremendous advantage for low-voltage systems. With the increasing trend to larger-capacity systems, the use of current-limiting fuses can provide an inexpensive solution to the problems of the high levels of available fault current. Standard switches, panelboards, motor controllers, and the like, with their lower short-circuit withstand capabilities, can be used without concern that they could be damaged by the heavy fault currents. The size of the feeder conductors required for short-circuit duty can often be reduced (see Section 11.2 and Example 11.18). In most cases, a feeder whose conductors have been sized for the ampacity requirements will also be properly protected by the current-limiting fuses against damage from short circuits.

Note that these fuses do not current limit for all levels of fault current. The 250 volt, 100 ampere fuse used in our example does not current limit below 2500 amperes. However, current limitation is very seldom required at this low level of fault current.



(a) Manufacturer's published curves

(b) Example of using curves

FIGURE 7.5

Typical current limitation curves for a low-voltage fuse

7.4 DUAL-ELEMENT TIME-DELAY FUSES

The requirements for the fusible element of the fast-acting current-limiting type of fuse just discussed are high conductivity, high but abrupt melting point, and small mass to reduce the heating time. While providing the very desirable current-limiting feature on high currents, these characteristics also mean that the fuse blows too frequently on harmless, low-level overload currents.

The requirements for the fusible element of a fuse that will provide satisfactory time delay on overloads are relatively lower conductivity, lower melting point (because the heat has time to dissipate), and a large mass to provide the time delay. These are the exact opposites to the requirements for high currents. To overcome these conflicts, the dual-element fuse was developed, with one element for overloads and one element (or a pair) for short circuits (see Section 6.1 for the differences between overloads and short circuits). These elements are connected in series within the one cartridge. Figure 7.6 shows an example of the construction of a dual-element fuse. Figure 7.7 shows a typical response curve for the dual-element fuse. The two elements of the fuse are coordinated so that the overload time-delay element melts first on currents up to approximately 500% of the fuse rating, and the short-circuit element(s) then takes over and melts first on currents above this point. Thus the fuse has time delay in the overload region and still has fast current-limiting action on the high fault currents.

For the time delay not to be so excessive that the fuse does not provide proper overload protection, it is necessary to set limits on the total clearing times for specific percentages of the rated current of the fuse. Table 7.1 shows the maximum clearing times acceptable by the Underwriters Laboratories, Inc. for 135 and 200% rated current for fuses up to 600 amperes. Figure 7.7 shows these points plotted on a graph for a 100 ampere fuse.

The response curve for a single-element fuse is also plotted in Figure 7.7 for comparison with the dual-element fuse of the same rating. Both minimum melt curves are compiled from one manufacturer's data. Both meet the UL requirements for maximum overload clearing times. However, at 500 amperes (that is, 500% of the fuse rating), as indicated on the graph, the dual-element fuse does not

FIGURE 7.6

Construction of a dual-element fuse

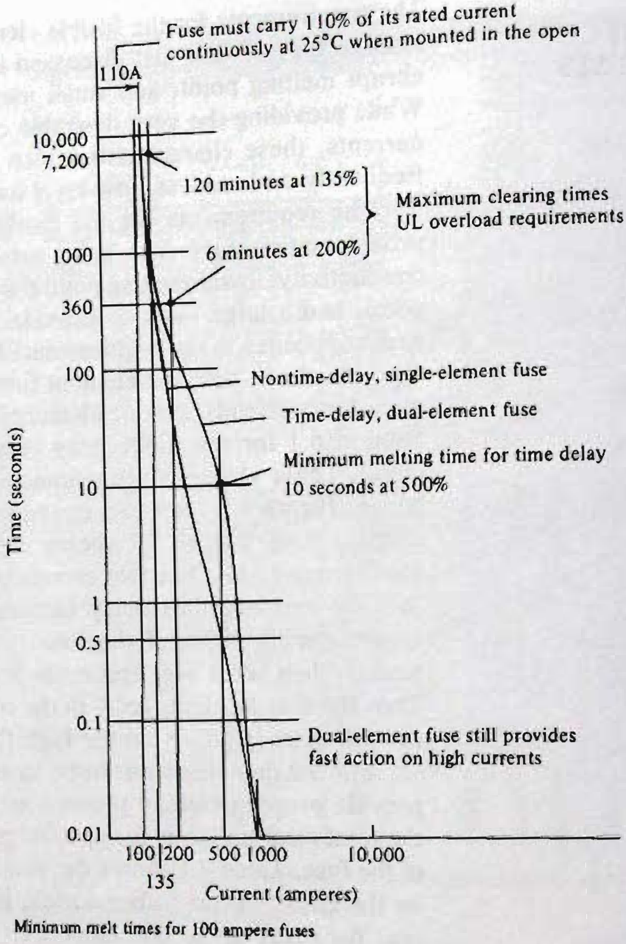


FIGURE 7.7

Comparison of response times for nontime-delay and time-delay fuses

melt until 10 seconds, whereas the single-element fuse melts in only 0.5 second, a difference of 20 to 1. This shows that there can be tremendous differences in the response characteristics of fuses even though they have the same current and voltage ratings.

The increased melting times of the dual-element fuse in the overload region led to the creation of a further category of fuse, the time-delay fuse. To be labeled *time delay*, a fuse must have *a minimum melting time of 10 seconds at 500% of its rating*. Fuses that do not meet the 10 second minimum time are then classified as *nontime delay*. Referring again to the curves in Figure 7.7, the dual-element fuse shown is a time-delay fuse and the single-element fuse is a nontime-delay fuse. A time-delay fuse does not necessarily have to be a dual-element fuse, but for practical purposes most, if not all, time-delay fuses are in fact dual element.

Time-delay fuses are particularly advantageous on motor circuits. This is discussed in Section 13.1.1. Smaller-rated fuses can be used for overcurrent protection, leading to reduced sizes and costs for switches, as shown in Example 13.2 and Figure 13.6(b).

7.5 CLASSIFICATIONS OF LOW-VOLTAGE FUSES

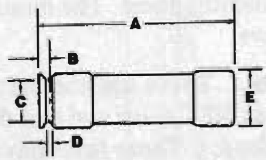
Since there are now many different types of cartridge fuses on the market, the Underwriters Laboratories, Inc., has established letter classifications to identify them. The more commonly used classifications are as follows:

UL Class H Fuses. These are the cartridge fuses that were formerly referred to as *NEC fuses* and that do not meet the standards of any of the other classes. These fuses have only 10,000 ampere interrupting capacity and they are not current limiting. Fuses are rated for 250 or 600 volts with current ratings up to 600 amperes. The standard dimensions for the different cartridge sizes and voltage ratings were adopted in 1904 and still apply today. These fuses can be either the one-time, nonrenewable or the renewable type. The renewable type cannot be labeled as time delay. Because of their low interrupting rating, class H fuses are not normally used nowadays for new systems.

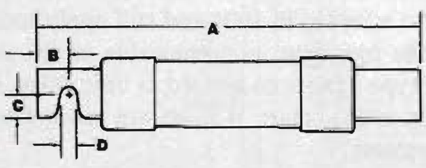
UL Class J Fuses. These are nonrenewable current-limiting fuses with an interrupting rating of 200,000 amperes rms symmetrical. They are only rated for 600 volts with current ratings up to 600 amperes. They must meet standards for the maximum peak let-through currents and the thermal energy let-through (I^2t) values at 50,000, 100,000, and 200,000 rms symmetrical amperes. New standard dimensions were developed for class J fuses, making them smaller than class H, so they are not interchangeable with any other class of fuse. There are no time-delay standards for class J fuses.

UL Class L Fuses. These are basically the same as class J except that their current ratings range from 601 to 6000 amperes and they may be labeled as time delay, although there are no UL standards for time delay above 600 amperes.

UL Class R Fuses. These are nonrenewable current-limiting fuses with an interrupting rating of 200,000 amperes rms symmetrical. They have similar electrical characteristics to the older class K, but they have a rejection feature so that other classes of fuses cannot be inserted into the same fuseholder. They are rated for 250 and 600 volts with current ratings up to 600 amperes. There are two subclasses, RK-1 and RK-5; the main difference between the two is in the degree of current limitation. Class RK-1 fuses have lower peak let-through currents and thermal energy let-through (I^2t) values. They can be either nontime delay or time delay (minimum melt time of 10 seconds at 500% of fuse rating). They have the same 250 and 600 volt dimensions as the class H fuses, so they can be used as replacements for these fuses, thus providing a much higher interrupting capability. Figure 7.8 shows the rejection feature for the class R fuses and includes a table of dimensions for the different cartridge sizes.



(a) Outline dimension of 0 to 60 ampere fuses



(b) Outline dimension of 70 to 600 ampere fuses

Dimensions

Fig. Ref.	Ampere Ratings	A	B	C	D	E	Wt. (lbs.)
LPN-RK (250V)							
A	0-30	2	5/32	3/8	5/64	9/16	—
	35-60	3	3/16	5/8	3/32	13/16	—
B	70-100	5 7/8	1/2	23/64	9/32	—	0.30
	110-200	7 1/8	11/16	35/64	9/32	—	0.69
	225-400	8 5/8	15/16	51/64	13/32	—	1.75
	450-600	10 3/8	1 1/8	63/64	17/32	—	3.25
LPS-RK (600V)							
A	0-30	5	3/16	5/8	3/32	13/16	—
	35-60	5 1/2	1/4	7/8	3/32	1 1/16	—
B	70-100	7 7/8	1/2	23/64	9/32	—	0.80
	110-200	7 5/8	11/16	35/64	9/32	—	2.00
	225-400	11 5/8	15/16	51/64	13/32	—	4.60
	450-600	13 3/8	1 1/8	63/64	17/32	—	5.60

FIGURE 7.8

Outline dimensions for UL class R fuses

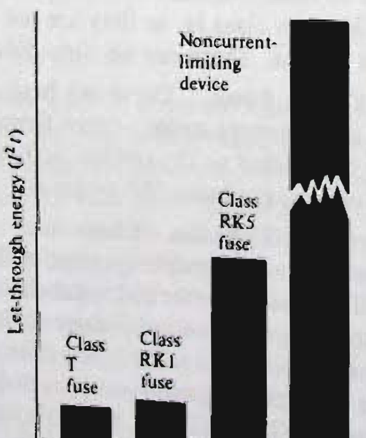


FIGURE 7.9

Relative values of let-through energy for three UL classifications of fuses

The energy (I^2t) let-through during the interval of time required for the fuse to clear the circuit is an important measure of the degree of protection provided by a fuse.

UL Class T Fuses. These are nonrenewable current-limiting fuses with an interrupting rating of 200,000 amperes rms symmetrical and are nontime delay only. They are rated for 250 and 600 volts with current ratings up to 600 amperes. They are very fast acting, with lower peak let-through currents and thermal energy let-through (I^2t) values than the other classes. They have new standard dimensions that make them even smaller than the class J fuses, and therefore they are not interchangeable with any other class of fuse.

Figure 7.9 shows the relative let-through energy values of class T, RK-1, and RK-5 fuses. Figure 7.10 shows a typical set of curves

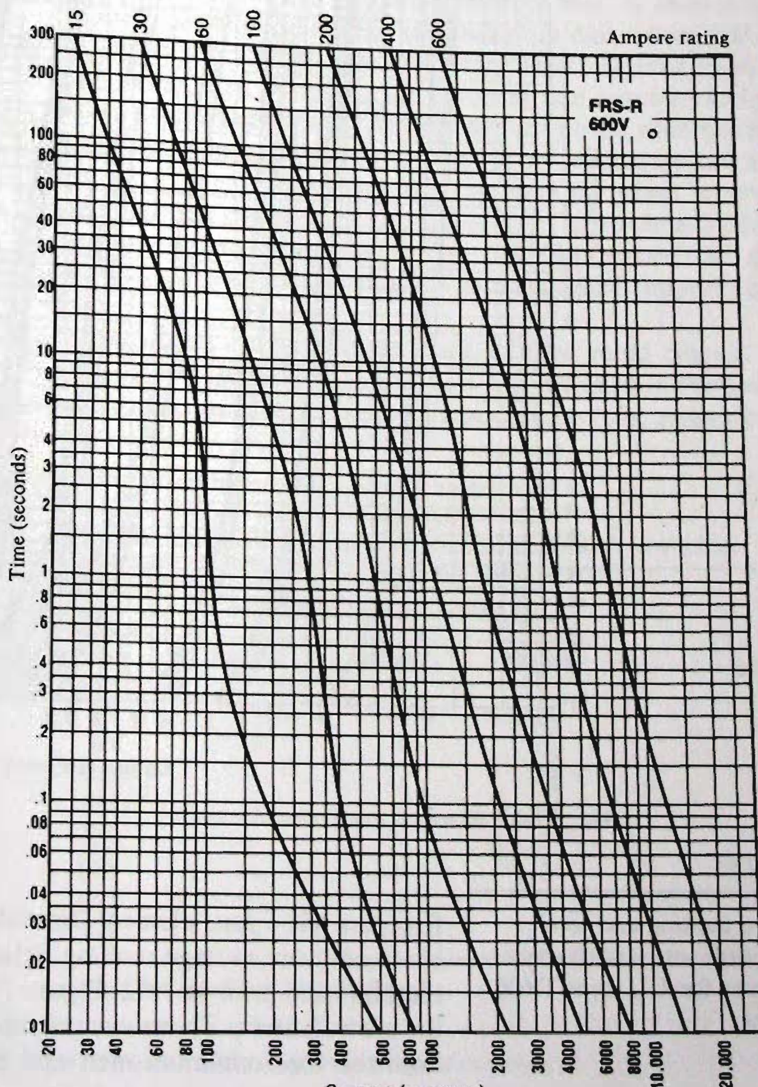
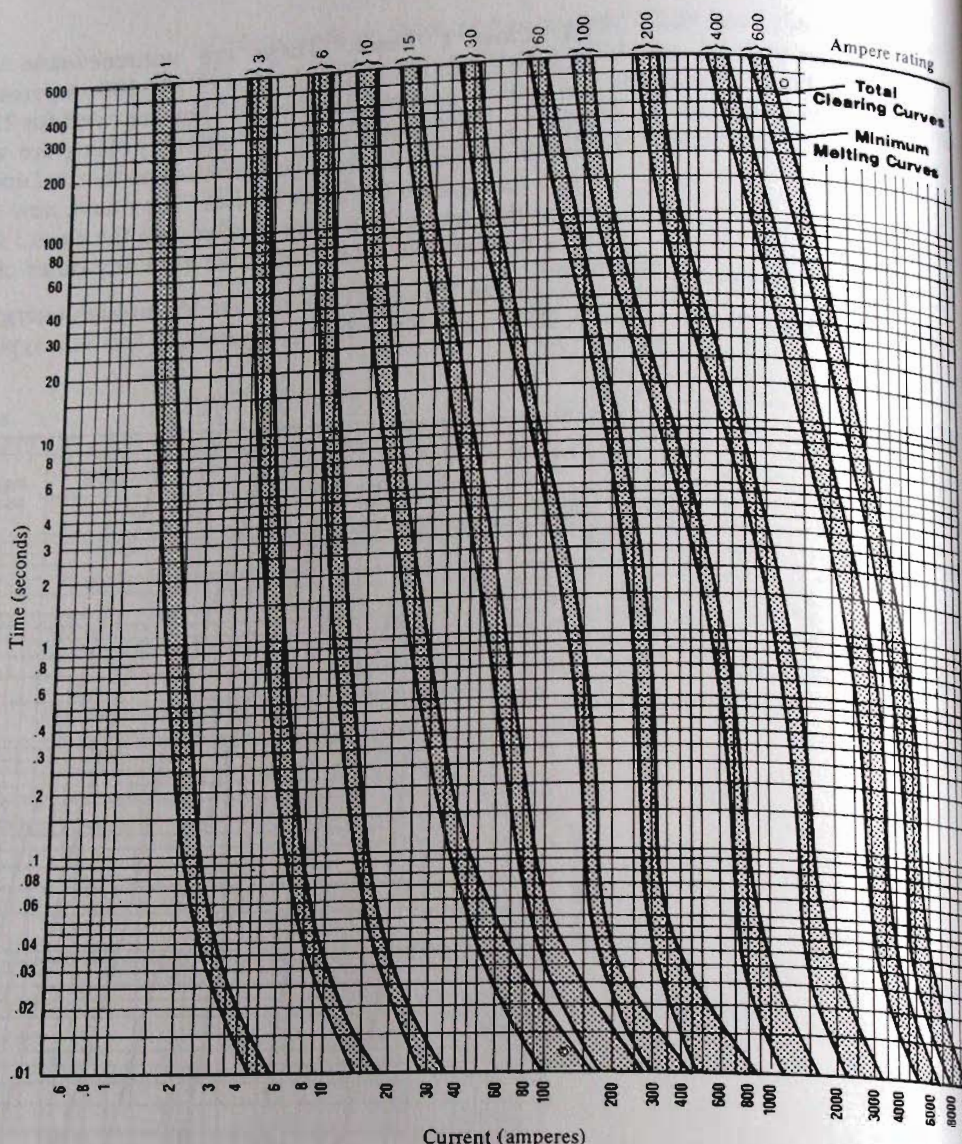


FIGURE 7.10

Average melting time–current characteristic curves for UL class RK-5, time-delay, dual-element 600 volt fuses

Note: Not all of the available ampere ratings are shown.



Note: Not all of the available ampere ratings are shown.

FIGURE 7.11

Minimum melting and total clearing time–current characteristic curves for UL class T 600 volt fuses

for class RK-5 dual-element, time-delay fuses. Note that the curves show only the average melting times for each rating, which was the method used prior to 1972. Figure 7.11 shows a typical set of curves for class T fuses. These curves show the new method of indicating both the true minimum melt and the total clearing times for each rating.

Refer to Section 6.6, which lists the required ratings for protective devices. There are no short-time current ratings listed for fuses. Since they operate so fast, the short-time ratings are not necessary.

7.6 FUSIBLE SWITCHES

Section 240-40 of the *National Electrical Code* requires that disconnecting means shall be provided on the supply side of all cartridge fuses so that each individual circuit containing fuses can be independently disconnected from the source of supply. The switch for the disconnecting means and the fuseholders for accommodating the fuses are usually mounted together in one enclosure. A common form of fusible switch, designated general use, is shown in Figure 7.12(a). The standard ratings and enclosure dimensions for general-use switches are shown in Table 7.2. Switches used in motor circuits, designated motor-circuit switches, are required to be horsepower rated as covered in Section 13.2.2. Fused switches mounted in combination with motor starters in one enclosure are shown in Figure 14.3(a). Fusible switches can also be group mounted in a panelboard as shown in Figure 7.12(b). For large-capacity feeders or service entrances, special fusible bolted-pressure switches and power-service protectors rated from 800 to 6000 amperes are available.

Fuses are tested to carry 110% of their rated current continuously at 25°C ambient temperature when mounted in the open. However, fuses respond to heat no matter how it is generated. When

TABLE 7.2 Standard Ratings of General-Use Fusible Switches

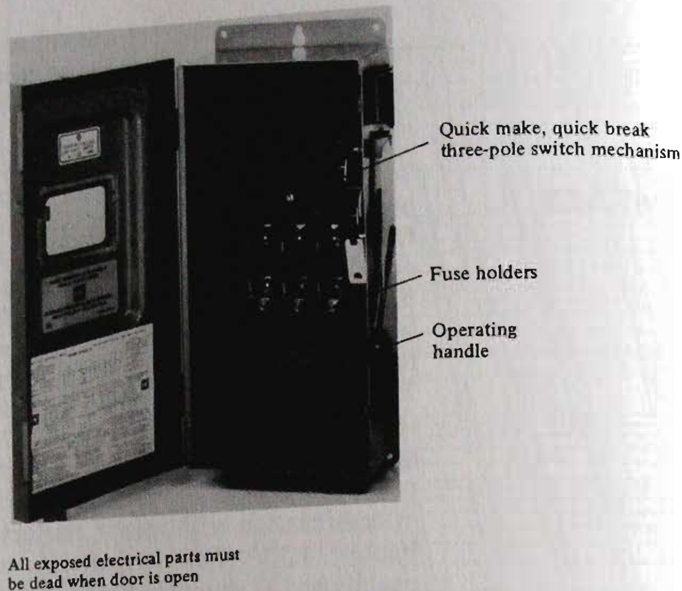
Ampere Rating	Approximate Dimensions (in.)		
	Height	Width	Depth
30	15	8	$5\frac{1}{2}$
60	15	8	$5\frac{1}{2}$
100	20	11	$7\frac{1}{2}$
200	28	14	$8\frac{1}{2}$
400	40	24	12
600	46	24	12
800	50	32	13
1200	56	38	13

Switches are rated for 250 and 600 volts.

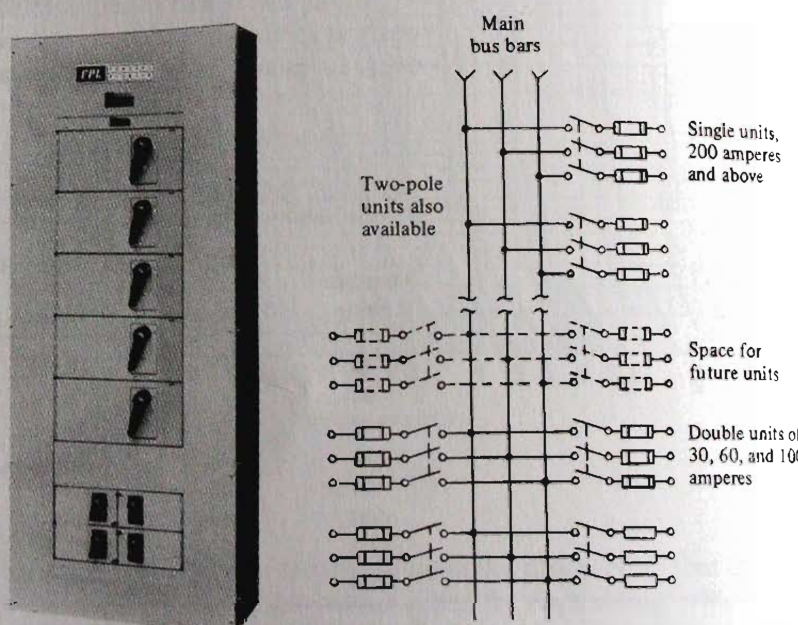
Switches are two and three pole.

See Table 13.4 for horsepower ratings of switches.

Manufacturers should be consulted for exact dimensions.



(a) Individual general-use fusible switch



(b) Fusible switches group mounted in a panelboard

FIGURE 7.12

Low-voltage fusible switches

fuses are operating within their switch enclosures, heat accumulates due to the load current, with the result that the ambient temperature inside the enclosure is usually well above 25°C. Therefore, the fuses may no longer be able to carry their rated current on a continuous basis. This matter is dealt with at more length in Section 11.8 with regard to applying fuses for overcurrent protection to feeders. The selection of switch sizes and fuses for motor circuits is covered in Sections 13.1.1 and 13.3.

7.7 COORDINATING LOW-VOLTAGE FUSES

Coordination of protective devices in an electrical system, as mentioned in the Introduction to Chapter 6, is very desirable. With proper coordination, a faulted circuit is completely isolated by the protective device nearest to the fault without disturbing any of the other protective devices in the system, thereby preventing further shutdowns of the system. The following is the method of achieving coordination using fuses. At this point, the reader should review Section 6.4 for the concepts of a system under fault conditions.

Refer to Figure 7.13. Part (a) shows the one-line diagram of a simple distribution system. See the Introduction to Chapter 11 for an explanation of the one-line diagram. Fuse A is the overcurrent protection for a feeder, and fuse B is the overcurrent protection for one

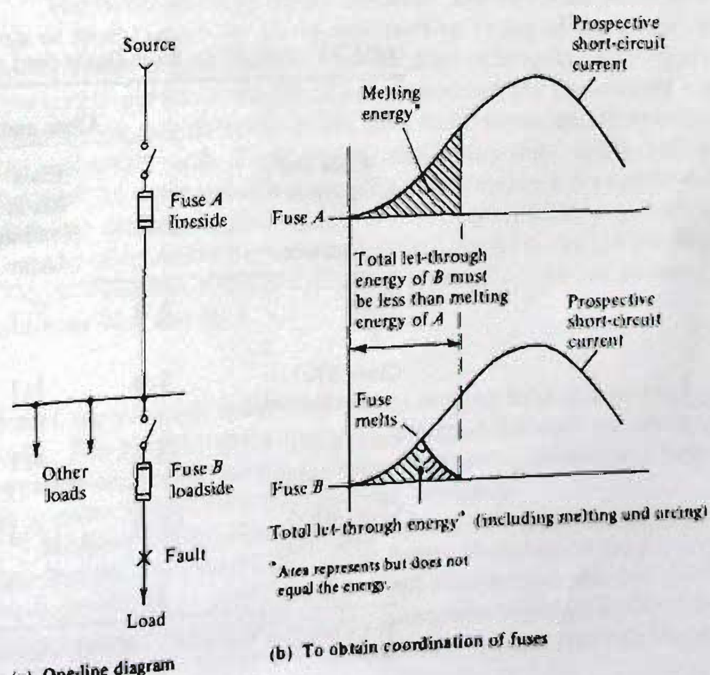


FIGURE 7.13

Coordination of low-voltage current-limiting fuses of the branch circuits being fed by the feeder. Assume that a short-circuit fault occurs on the branch circuit at the point marked with an × on the diagram. The resulting fault current that flows is instantly *seen* by both fuses. The two fuses are connected in series between the source and the point of the fault and are subjected to exactly the same current. Therefore, coordination can only be achieved if fuse B reacts fast enough to completely open the faulted circuit before fuse A has reached the point where it starts to blow. Figure 7.13(b) shows the general principle for obtaining coordination between fuses. The total let-through energy of fuse B, which includes the energy during both its melting and arcing periods, must be less than the energy required to bring the fusible element of fuse A to its melting point. If this is the case, then the fault current is interrupted before fuse A can operate. The faulted circuit is now isolated, and the balance of the system can continue to operate normally. Note that if fuse A even just reaches its melting point it will end up blowing and shutting down all the other circuits as well.

The coordination of fuses of the same manufacturer is fairly straightforward. Most manufacturers provide a selectivity ratio guide for use with their fuses. Typical ratios are shown in Table 7.3. The term *lineside* means the fuse that is closest to the source (fuse A in Figure 7.13), and *loadside* means the fuse closest to the fault (fuse B).

TABLE 7.3 Selectivity Ratio Guide for Low-Voltage Fuses

Class and Type of Fuse, Lineside	Class and Type of Fuse, Loadside: Class J	Class RK-1, Nontime Delay	Class RK-1, Time Delay	Class RK-5, Time Delay	Class T
Class J	3:1	3:1	3:1	8:1	3:1
Class RK-1, nontime delay	3:1	3:1	3:1	8:1	3:1
Class RK-1, time delay	3:1	3:1	2:1	8:1	3:1
Class RK-5, time delay	1.5:1	1.5:1	1.5:1	2:1	1.5:1
Class T	3:1	3:1	3:1	8:1	3:1

These ratios are typical only and apply when the fuses are all from the same manufacturer.

■ **EXAMPLE 7.2**

In Figure 7.13, both fuses are UL class J and fuse B is 100 A. Determine the smallest rating for fuse A that will coordinate with fuse B.

Solution

— From Table 7.3, the selectivity ratio is 3 : 1.
— Smallest rating for fuse A = 3 × 100 = 300 A.
— From Table 7.1, 300 A is standard rating.

■ **EXAMPLE 7.3**

In Figure 7.13, fuse A is UL class RK-5 time delay and fuse B is UL class RK-1 time delay. Fuse B is 90 A. Determine the smallest rating for fuse A that will coordinate with fuse B.

Solution

— From Table 7.3, the selectivity ratio is 1.5 : 1.
— Smallest rating for fuse A = 1.5 × 90 = 135 A.
— From Table 7.1, the nearest standard rating above 135 is 150 A.

Note, in Example 7.3, that if the fuse types were reversed (fuse A, class RK-1 and fuse B, class RK-5) then the selectivity ratio would be 8 : 1, which would make coordination virtually impossible. The problem here is that the class RK-1 fuse operates much faster on high fault currents than does the class RK-5 fuse.

The ratios specified by the manufacturer cover all possible levels of fault current up to the interrupting rating of the fuses. For lower levels of fault current, the specified selectivity ratios may be lowered to permit closer fuse sizing. However, the fuse curves compiled by the manufacturer would have to be compared to determine the allowable ratio. Furthermore, the ratios only apply between fuses of the same manufacturer. The coordination between fuses of different manufacturers is much more complex and again requires detailed information from each manufacturer to make comparisons. The coordination of fuses with other types of devices is covered in Sections 16.4 and 16.5.

7.8 MEDIUM-VOLTAGE FUSES

Fuses are available for voltage levels ranging from 2.3 to 161 kilovolts. The higher-voltage fuses are designed for outdoor use only, typically on electric utility systems. Fuses used indoors are limited to systems of 34.5 kilovolts (medium voltages).

Medium-voltage fuses are divided into two general categories: distribution fuse cutouts and power fuses. Distribution fuse cutouts were developed primarily for overhead distribution circuits. Power fuses were developed primarily for substation-type applications and are available with higher-voltage, load-current, and interrupting rat ings. They are also available in forms suitable for use within buildings. The following discussion covers only the power-type fuses typically used indoors in switchgear enclosures. Power fuses can be divided into two basic types:

— Solid-material fuses
— Current-limiting fuses

7.8.1 Solid-Material Power Fuses

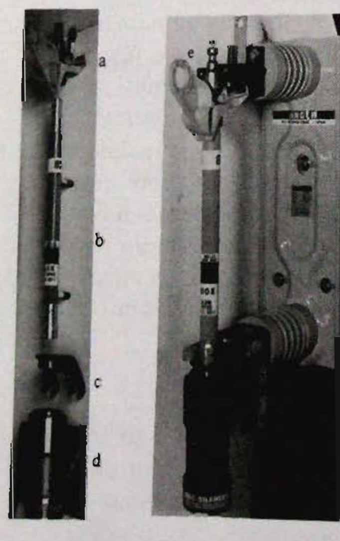
The solid-material power fuse interrupts fault currents through the combined action of high-speed elongation and deionization of the arc. When an overcurrent melts the fusible element, a spring-driven arcing rod is rapidly driven upward, elongating the arc drawn in the solid-material-lined bore of the interrupting chamber within the fuse. The heat from the confined arc reacts with the solid material, creating gases that deionize and extinguish the arc.

To eliminate the problem of the expulsion of any hot gases from the fuse, an exhaust control device is used to reduce the velocity of the gases to the point that they cannot cause any burning or flashovers within the confined space of a switchgear enclosure. The solid-material power fuse is considered to be a nonexpulsion type with regard to the minimum electrical clearances required for indoor mounted fuses.

A typical solid-material power fuse is shown in Figure 7.14. The exhaust control device, item d, is assembled on the bottom of the replaceable fuse unit, item b. The complete fuse assembly is available with maximum continuous current ratings of 200 and 400 amperes. The ampere rating of the replaceable fuse unit selected then sets the point above which the fuse will respond to an overcurrent. Typical dimensions and interrupting ratings for 5 and 15 kilovolt fuses are shown in Table 7.4. The interrupting ratings are given in both amperes and equivalent three-phase symmetrical MVA (1 million volt–amperes). The three-phase MVA ratings are given to make an easy comparison with circuit breakers, which, in themselves, are three-phase devices.

As shown on the outline diagram in Table 7.4, the fuse is hinged to allow for easy removal. However, this feature does not allow the fuse to be used as a disconnecting means for the circuit.

Typical minimum melting and total clearing time–current characteristic curves are shown in Figures 7.15 and 7.16, respectively. Minimum melt and total clearing times are discussed in Section 7.1. The ampere ratings of the replaceable fuse units are shown at the top of each curve. The E rating designates that the fuse complies with the National Electrical Manufacturers Association (NEMA) standards for medium- and high-voltage fuses; that is,

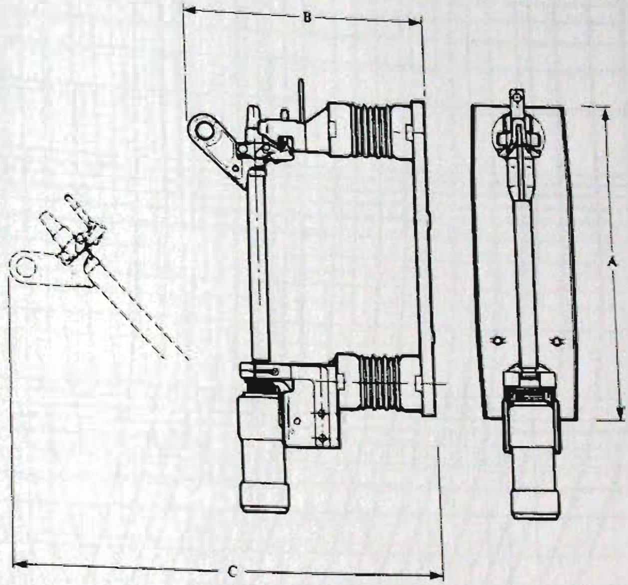


a, Upper end fitting; b, Fuse unit; c, Lower end fitting; d, Exhaust control device; e, Blown-fuse target

FIGURE 7.14

Medium-voltage, solid-material power fuse

TABLE 7.4 Typical Ratings and Dimensions of 5 and 15 Kilovolt Solid-Material Power Fuses for Indoor Use



Kilovolt Class	Maximum Fuse Rating (A)	Dimensions (in.)[a]			System Voltage (kV)	Interrupting Ratings[b]		
						Amperes		Three-phase
		A	B	C		Symm.	Asymm.	Symm.[c] (MVA)
5 kV	200	28	$13\frac{3}{4}$	$25\frac{1}{2}$	4.16	17,200	27,500	125
	400	28	$15\frac{1}{4}$	$29\frac{1}{4}$		37,500	60,000	270
15 kV	200	$22\frac{3}{8}$	$17\frac{1}{4}$	$31\frac{1}{2}$	13.8	14,000	22,400	335
	400	32	$17\frac{3}{4}$	$34\frac{1}{2}$		25,000	40,000	600

[a] Approximate only.

[b] With exhaust-control device. Based on X/R ratio of 15.

[c] Equivalent value for 3 fuses (one in each phase of circuit).

Manufacturers should be consulted for confirmed ratings.

Source: Courtesy of S&C Electric Co.

That the fuse shall carry its rated current continuously, that a fuse rated 100 ampere or less shall melt in 300 seconds at an rms current within the range of 200 to 240% of the continuous rating of the fuse element, and that a fuse rated above 100 amperes shall melt in 600 seconds at an rms current within the range of 220 to 264% of the continuous rating of the fuse element.

The ampere ratings of the replaceable fuse units range from 3E up to 200E for the fuse assembly rated for a maximum of 200 amperes continuous and from 3E up to 400E for the fuse assembly rated

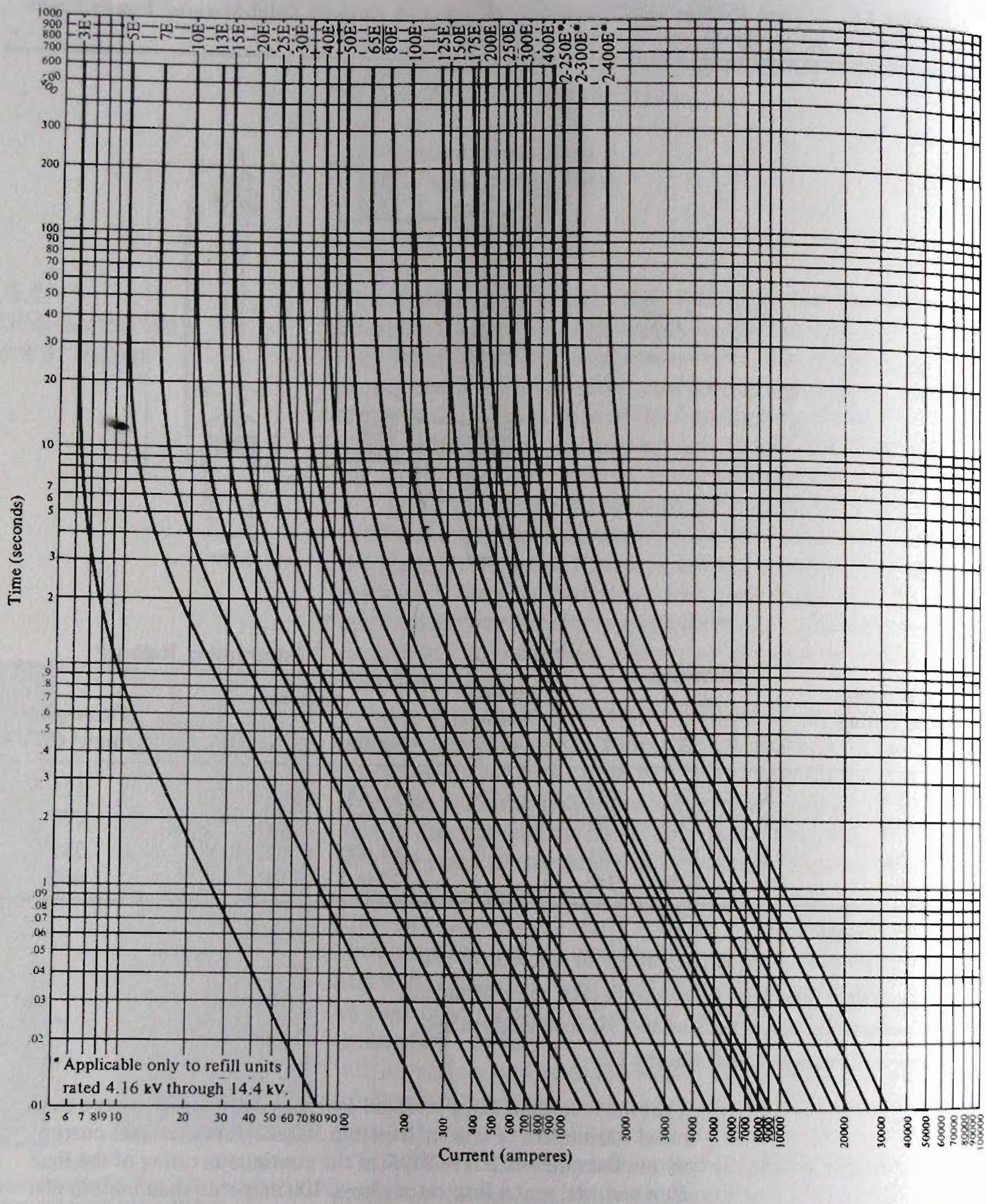


FIGURE 7.15 Typical minimum melting time–current characteristic curves for 5 and 15 kV solid-material power fuses

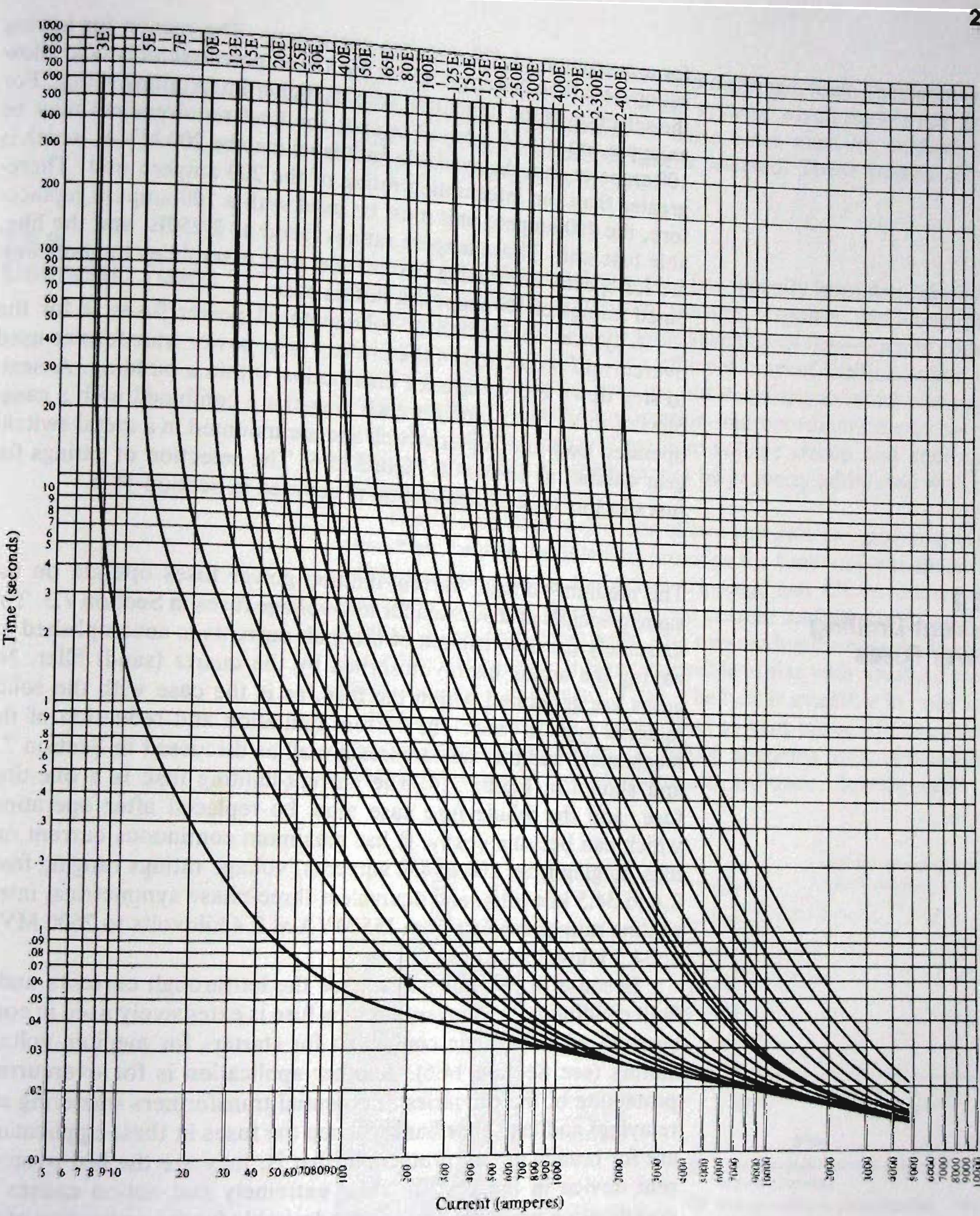


FIGURE 7.16 Typical total clearing time-current characteristic curves for 5 and 15 kV solid-material power fuses

for a maximum of 400 amperes continuous. The reason for having ratings less than 200 amperes for the 400 ampere assembly is to allow the selection of the larger unit with its higher interrupting rating. For example, on a 4.16 kilovolt circuit, the load requirements may be 100 amperes, but the available fault level may be 200 MVA, which is greater than the interrupting rating of the 200 ampere unit. Therefore, the 400 ampere unit must be used with a 100 ampere replaceable fuse unit. Those ampere ratings listed as 2-250E, and the like, are for special units using two parallel fuse assemblies to give combined ratings of 500 amperes, in this case.

A typical application of solid-material power fuses is for the overcurrent protection of the primary of a power transformer used to step down the voltage for distribution within a building. Assemblies of three fuses (one for each phase) are combined with a gang-operated load-interrupter switch and are mounted in a metal switchgear cabinet as shown in Figure 15.6. The selection of ratings for fuses in this type of application is covered in section 16.5.

7.8.2 Current-Limiting Power Fuses

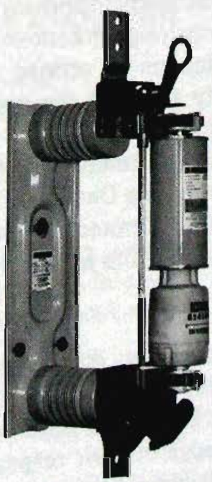
The medium-voltage, current-limiting power fuses operate on the same principle as discussed for low-voltage fuses in Section 7.3. The extremely fast interruption of the fault currents is accomplished by having the arcing energy absorbed by the quartz (sand) filler. No gases are generated within the fuse, as is the case with the solid-material type of fuse. The current limitation and reduction of the mechanical and thermal stresses are all as discussed in Section 7.3 and shown in Figure 7.4. The current-limiting fuse is a one-time fuse, and the whole fuse case must be replaced after operation, which can become costly. It has maximum continuous current ratings ranging from 100 to 450 amperes, voltage ratings ranging from 2.4 to 34.5 kilovolts, and equivalent three-phase symmetrical interrupting ratings ranging from 155 MVA at 2.4 kilovolts to 2600 MVA at 34.5 kilovolts.

Because of its ability to reduce the let-through currents under fault conditions, the current-limiting fuse is extensively used in combination with magnetic contactors for starters for medium-voltage motors (see Section 14.6). Another application is for overcurrent protection of the primaries of potential transformers (metering and relaying) and capacitor banks. Since the fuses in these applications are for branch circuit protection (that is, they are the last overcurrent device in the circuit), their extremely fast action causes no coordination problems and is very desirable for the protection of the equipment from damage. Current-limiting fuses may be used at other points in the system, but their fast action may cause coordination problems with downstream devices. Also, because of their extreme current chopping action when clearing a fault, they can cause high transient overvoltages on the system, which may break down the insulation. Applications of these fuses must be studied very carefully so that the proper fuse is selected. These studies are beyond the scope of this textbook.

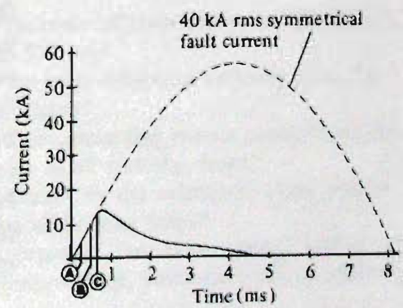
7.8.3 Electronic Fuses

A fault-interrupting electronic fuse has recently been developed that incorporates unique overcurrent sensing, response, and interrupting techniques. This fuse offers a wide selection of time–current characteristic curves, combined with efficient current-limiting action in a compact, self-contained package not requiring external sensing or control power. Improved protection and coordination can be provided for a wide variety of medium-voltage circuit and equipment applications, some of which cannot be properly addressed with previously available devices.

The electronic fuse consists of two separate components: (1) an electronic control module that provides the time–current characteristics and the energy to initiate tripping, and (2) an interrupting module that carries the normal load current and then interrupts the current under fault conditions. The two modules are joined together in a complete package that is compatible in size with standard power fuses, as shown in Figure 7.17(a). The fuse is available in both 5 and 15 kilovolt ratings, with a continuous current rating of 600 amperes and an interrupting rating of 40,000 amperes rms symmetrical. Models rated for 25 and 34.5 kilovolts are under development.



(a) Fuse assembly



Event	Time
Ⓐ Control module sends trip signal to power cartridge	250 μs
Ⓑ Current transfer to current-limiting element completed	480 μs
Ⓒ Current-limiting element melts; current-limiting action begins	640 μs

(b) Operating sequence with 6 kA trip setting

FIGURE 7.17

Medium-voltage 5 and 15 kV, 600 A electronic fuse

The electronic control module is a self-powered unit with all the control power and energy to operate the interrupting module being obtained from the current flowing in the lines through a current transformer. The output of the built-in current transformer feeds a full-wave rectifier, which then provides a signal to the logic circuitry that is proportional to the line current and is used by the logic circuitry to determine when to trip. Two types of logic circuits are employed, one with time-delay tripping characteristics and one with instantaneous tripping characteristics. These two circuits can be used alone or in combination to provide a variety of time–current characteristics.

The interrupting module contains two sections: a main current section that carries the current normally and a current-limiting section. The main section, when required to operate on a fault, separates at high speed to transfer the current to the current-limiting section, which then interrupts the current. These two sections are electrically in parallel, with the main section carrying almost all the current during normal operation. When a fault occurs, the control module sends an appropriate signal to a power cartridge, which initiates operation of the interrupting module. The sequence of operation is shown in Figure 7.17(b).

The electronic fuse is suitable for a number of important applications. One application is the protection of power transformers. The availability of the flexible time–current characteristics permits the selection of fuses for the primary protection of the transformer that coordinates extremely well with the secondary-side protective device (a low-voltage power circuit breaker). In addition, the instantaneous tripping logic of the fuse provides current-limiting action in the event of a transformer primary fault. A second important application is one requiring protective devices that can provide a full range of coordination in service entrance and feeder protection, which previously required the use of expensive, relayed, circuit-breaker-type equipment.

The reader is referred to the manufacturer's bulletin entitled "A New Fault-Interrupting Device for Improved Medium-Voltage System and Equipment Protection" as listed in the Bibliography for more detailed application information for this fuse.

SUMMARY

- Modern fuses have many different characteristics, and it is no longer satisfactory to just specify a voltage and current rating for them. Each type must be studied so that the application of fuses is done with full knowledge of their respective characteristics. The following is a summary of the advantages and disadvantages of the modern fuse as compared with other types of overcurrent protection.

- Advantages
  - —Low initial cost
  - —Simple, no parts to maintain
  - —Compact, require little space
  - —High current interrupting capabilities
  - —Provide current limitation, thus materially reducing or eliminating the possibility of the conductors or equipment being damaged by mechanical or thermal stresses under fault conditions
  - —Can provide good selective coordination on electrical faults, thus eliminating unnecessary shutdowns
  - —Inherently fail-safe; that is, if they fail, they open the circuit, thus making it safe
- Disadvantages
  - —Must be replaced after each operation; longer downtime
  - —Can cause single phasing, which is detrimental for motors
  - —Not adjustable; time–current characteristics are fixed
  - —Affected by ambient temperature, which may cause needless blowing of fuses
  - —Can be replaced by another fuse with incorrect ratings or characteristics (unless there is a rejection feature)
  - —Require the stocking of replacement fuses for each type used
  - —Cannot by themselves be used as an isolating means for the circuit; they must be mounted in combination with a switch

QUESTIONS

1. Explain why the basic fuse is a direct-acting, single-element device.
2. Why is the fuse a fail-safe device?
3. Explain the difference between the minimum melting and the total clearing times.
4. What are the two principal *NEC* categories of fuses?
5. Define a current-limiting fuse.
6. What is meant by the peak let-through current?
7. Explain the advantages of designing a fuse with two different types of elements in series (that is, a dual-element fuse).
8. What is the criterion that a fuse must meet in order to be labeled time delay?
9. On what type of circuit are time-delay fuses particularly advantageous? Explain.
10. Why are UL class H fuses no longer recommended for new electrical installations?
11. What is the main difference between UL class K and class R fuses?
12. What is the main difference between class RK-1 and RK-5 fuses?
13. Why is a disconnecting means required on the supply side of all cartridge fuses?
14. What is meant by the selectivity ratio with regards to coordinating fuses?
15. Briefly describe the interrupting action of the medium-voltage, solid-material-type power fuse.
16. Why are equivalent three-phase interrupting ratings given for medium-voltage fuses?
17. What is a typical application for solid-material power fuses?
18. Why is the overcurrent protection of medium-voltage motor circuits a good application for current-limiting power fuses?

PROBLEMS

1. Using Figure 7.10, determine the average melting times at 2000 A of the following fuses: (a) 100 A, (b) 200 A, and (c) 600 A.
2. Using Figure 7.11, determine the minimum melting and total clearing times for (a) 200 A fuse with a current of 1000 A, and (b) 30 A fuse with a current of 100 A.
3. Using Figures 7.15 and 7.16, determine the minimum melting and total clearing times for a 50E fuse with a current of 200 A.
4. Using Figure 7.5, determine the effective let-through symmetrical rms current with a 200 A, 250 V current-limiting fuse if the prospective short-circuit current is 70,000 symmetrical rms amperes.
5. Refer to Figure 7.13. Both fuses are class RK-5, time delay. Fuse B is rated for 60 A. Determine the smallest standard rating for fuse A that will coordinate with fuse B.
6. Repeat Problem 5, except fuse A is class T.

8 Circuit Breakers

OBJECTIVES

After studying this chapter, you will be able to:

- Discuss the means of safely interrupting large currents.
- Explain the operation of circuit breakers.
- Understand the significance of frame sizes and trip ratings.
- Differentiate between the molded-case, the power, and the encased types of low-voltage circuit breakers.
- Explain the operation of thermal–magnetic trip units.
- Interpret time–current characteristic curves of breakers.
- Discuss interrupting and short-time ratings of breakers.
- Discuss the characteristics of solid-state trip units.
- Identify the problems of coordinating molded-case breakers.
- Understand the principle of fused circuit breakers.
- Explain the operation of current-limiting circuit breakers.
- Recognize medium-voltage air circuit breakers.
- Identify the advantages of circuit breakers.
- Identify the disadvantages of circuit breakers.

INTRODUCTION

Within a few years of the introduction of the fuse, the growing electrical industry started looking for an alternative method of providing protection for electric circuits. They wanted a device that would not be destroyed by its operation, that could simply be reset to restore power, and that could also be used as a means of switching for the circuit. Out of this development work came the circuit breaker, which is an electromechanical device. The *National Electrical Code* defines the *circuit breaker* as *a device designed to open and close a circuit by nonautomatic means and to open the circuit* *automatically on a predetermined overcurrent without injury to itself when properly applied within its rating.*

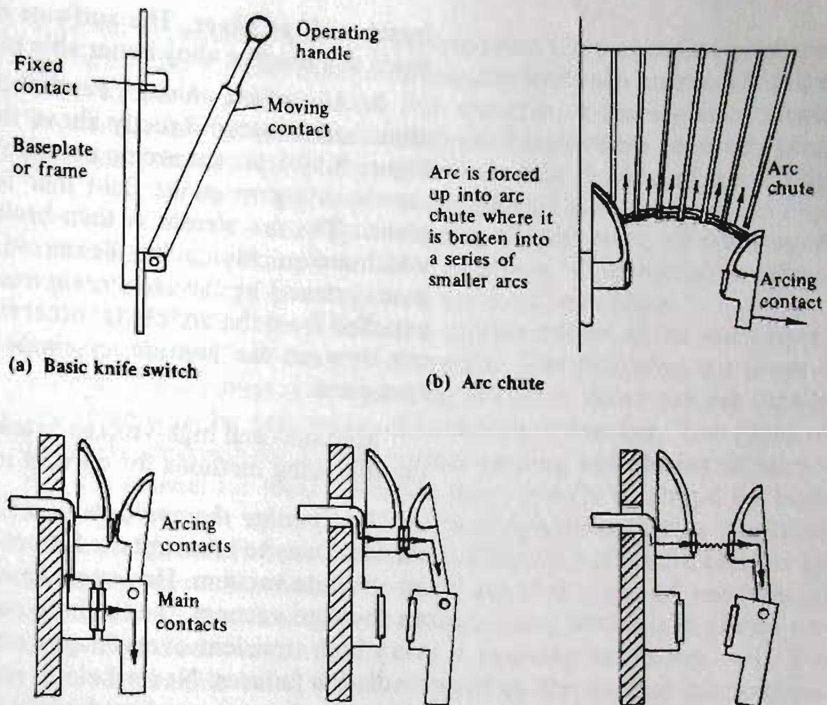
As with other equipment, circuit breakers are divided into those rated for 1000 volts and less (low voltage) and those rated for more than 1000 volts (medium and high voltage). Low-voltage circuit breakers were also divided into two distinct categories, molded-case and power types. However, in the past few years the distinction between these two types has become less clear-cut as a new type of encased breaker has been introduced that combines the characteristics of each type. Low-voltage breakers are universally operated in air, so it is not necessary to designate them as *air circuit breakers* as this is understood. Medium- and high-voltage breakers, on the other hand, use mediums other than air in which to open the circuit and therefore must be designated as being air, oil, gas, and so on.

Apart from having different voltage and continuous current ratings, breakers have widely different interrupting ratings, response characteristics, and methods of operation. The proper application of circuit breakers requires a good knowledge of all the characteristics and options available for each type. Sections 6.6 and 6.7 discuss the necessary ratings for protective devices and the inverse time and instantaneous tripping of circuit breakers. These are now dealt with in detail. The discussions in this chapter are limited to circuit breakers used for circuits and feeders normally encountered in the electrical systems within buildings.

8.1 INTERRUPTING ACTION OF CIRCUIT BREAKERS

The simplest circuit-opening device is the manually operated knife switch, as shown in Figure 8.1(a). This switch has the basic parts required of any circuit-opening device: a fixed contact, a moving contact, an operating handle, and a base-plate or frame. However, as anyone who has opened a knife switch under load has witnessed, there is a luminous discharge drawn between the separating contacts of the switch. This discharge is called an *arc,* and it consists of a stream of positive and negative ions. The current flowing in a circuit cannot be instantaneously interrupted. As a result, the arc continues until the switch contacts have separated far enough to finally extinguish the arc. The arc can make the opening of the switch very unsafe and unreliable when interrupting a circuit under heavy loads. Also, the arc burns would soon destroy the surfaces of the contacts. A circuit breaker must provide a safer and more reliable interrupting action. The following are the means by which low-voltage circuit breakers can be made to safely interrupt large fault currents with a minimum of contact damage.

1. *Fast speed of operation* The duration and severity of an arc depends in part on the speed with which the contacts can be



(a) Basic knife switch

(b) Arc chute

(c) Simplified diagram of breaker contact mechanism showing main and arcing contacts

FIGURE 8.1

Methods of interrupting current

separated. Therefore, powerful springs are used to rapidly force the contacts open. These springs are compressed (charged) during the closing operation. The breaker contacts are then mechanically held closed and are released by a separate trip mechanism. An operator can initiate the opening of the breaker but has no control over the speed with which the contacts separate.

2. *Use of arcing contacts* The arc burn can cause pitting, which eventually affects the ability of the contacts to carry the load current when closed. To offset this, two parallel sets of contacts are used for each pole of the breaker, a main current carrying set and an auxiliary or arcing set, as shown in Figure 8.1(c). When the breaker is tripped open, the main contacts separate first, transferring the current flow to the arcing contacts. The arcing contacts then separate a split second later, drawing the arc between them and leaving the main contacts free of any arcing. This allows the surfaces of the main current carrying contacts to be made of a high-conductivity

metal such as silver. The surfaces of the arcing contacts are then made of a tougher alloy better able to withstand the effects of arcing.

3. *Use of arc chutes* Parallel plates enclosed in the form of a chute are mounted directly above the arcing contacts, as shown in Figure 8.1(b). As the arcing contacts separate, the resulting arc creates a strong magnetic field that forces the arc upward into the plates. The arc stream is then broken into a series of small arcs, which are quickly cooled, deionized, and extinguished. The ionized gases created by the arc stream must be deionized before they are expelled from the arc chute; otherwise, secondary arcing could occur between the lineside terminals of the breaker, which are still energized.

Medium- and high-voltage breakers can also incorporate one of the following methods for current interruption:

1. *Opening the contacts in a vacuum* This would seem to be the ideal way to interrupt the flow of current as an arc cannot exist in an absolute vacuum. However, apart from the difficulty of obtaining an absolute vacuum, the extreme current chopping effect can create very high transient overvoltages on the system, which can lead to insulation failures. Nevertheless, recent advances in the technology of vacuum circuit opening devices have overcome these problems. Vacuum circuit breakers are now available for use on systems up to 15 kilovolts. Medium-voltage motor starters using vacuum contactors are also available (see Section 14.6).

2. *Air blast* A blast of compressed dry air is forced between the separating arcing contacts to further aid in driving the arc into the arc chute and to aid in cooling the arc.

3. *Using a medium other than air* The contacts are enclosed in oil or SF_6 gas, both of which have good dielectric properties and are very effective in quenching the arc and preventing it from restriking.

The air blast, the oil, and the SF_6 gas breakers are relatively expensive. The oil circuit breakers require special fireproof vaults if used indoors. The air blast and SF_6 gas circuit breakers require complicated enclosures and pressure systems. Therefore, these types of breakers are used mainly in large substations and for this reason are not covered in any further detail in this book.

8.2 OPERATION OF CIRCUIT BREAKERS

As well as providing overcurrent protection, a circuit breaker can, and usually does, serve also as the circuit switching device. Therefore, it must incorporate a means of being opened and closed. Breakers are either single pole or multipole. The term *pole* refers to each set of contacts that are connected into a separate line or phase of the circuit. The electrical code requires that each ungrounded line of a circuit must be broken. For example, a three-phase circuit requires a three-pole breaker. Multipole breakers are generally gang operated; that is, each pole is simultaneously closed and opened by one common operating handle or mechanism such as shown in Figure 8.4. Similarly, when the breaker is tripped open, all poles open even if the fault is only on the one phase. Thus circuit breakers cannot cause single phasing, as is the case with fuses.

Figure 8.2 is a diagrammatical representation of the main operating components of the typical breaker. The following is a general outline of the methods of operating breakers. More precise details are given with the description of each type of breaker. Two types of methods are available for the normal opening and closing of breakers: (1) manual for local operation only, and (2) electrical for both local and remote operation. Electrical operation is also desirable when the size of the breaker makes it difficult to close the breaker by manual means. Furthermore, there are two types of mechanical arrangements for closing the breaker, direct action and stored energy. The direct action method is a one-step operation, with the operating handle being directly linked to the contact mechanism. The stored energy method is a two-step operation. First, a spring is compressed either manually or by a small electric gear motor. Then the spring is released, which forces the contacts closed. This permits larger breakers to be safely closed manually or, in the case of electrical operation, it allows a much smaller motor to be used. In either method, during the closing sequence, a separate set of springs is compressed. The contacts are then mechanically latched into the

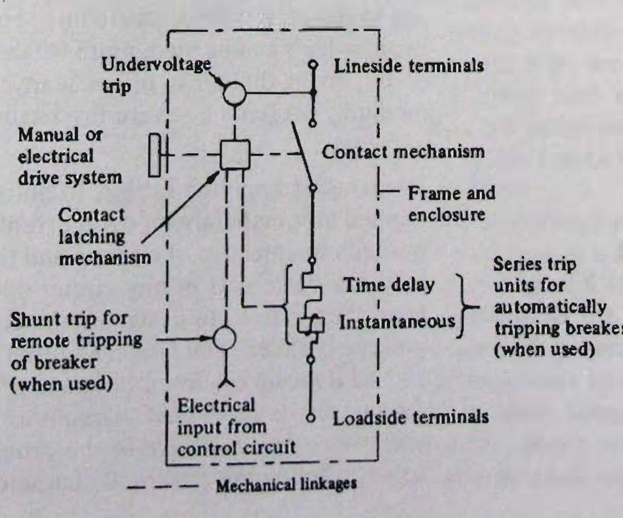


FIGURE 8.2

Diagrammatic representation of the operating parts of a circuit breaker closed position. The breaker is opened by either manually or electrically activating the trip mechanism and releasing the energy stored in the opening springs. The actual speed with which the contacts close and open is controlled by the springs. The quick-make, quick-break action cannot be affected by the operator.

The electrical operation of a breaker requires either a separate source of supply or a control circuit that is tapped off the line side of the breaker. This may also require a small control transformer to step down the voltage to a suitable level for the control system. Remote operation requires control wiring to be run to separate close-trip switches.

All breakers must be *trip free*; that is, *the breaker contacts cannot be held closed by the closing mechanism if the trip mechanism has been activated*. Thus, even if the operating handle is held in the closed position, the breaker contacts will still trip open. This is also a desirable safety feature. If a breaker is manually closed on a short circuit, the instantaneous tripping of the breaker does not kick back the handle, which could injure the operator.

As mentioned in Section 6.6, the two main functions of a protective device are to sense the circuit conditions and then to interrupt the circuit at a predetermined set of time and overcurrent conditions. The means of automatically tripping breakers under these overcurrent conditions are discussed for each type of breaker.

8.3 LOW-VOLTAGE CIRCUIT BREAKERS (GENERAL)

Low-voltage circuit breakers are universally air circuit breakers, meaning that the arc interruption takes place in air. Therefore, in referring to low-voltage breakers, it is not necessary to designate them as "air" circuit breakers, as this is understood. For low-voltage systems, it is desirable to have circuit breakers that are operated in air, which makes them more versatile in their application. The use of oil, even though it offers many advantages as an interrupting medium, presents a severe fire hazard, requiring fireproof vaults.

8.3.1 Frame Size Designations

In terms of applying ratings to automatic circuit breakers (that is, tripped automatically on overcurrents), there are two separate components to consider, the frame and the trip unit. As shown in Figure 8.1(a), a basic part of any circuit-opening device is the frame. This term then is used to designate the characteristics and size of a low-voltage breaker. The Underwriters Laboratories, Inc. defines *frame size* as *a group of circuit breakers of similar physical configuration. Frame size is expressed in amperes and corresponds to the largest ampere rating available in the group*. The frame size of a breaker sets the following electrical characteristics:

— Maximum continuous voltage rating (insulation level)
— Maximum continuous current rating
— Maximum interrupting rating
— Maximum permissible rating of trip unit

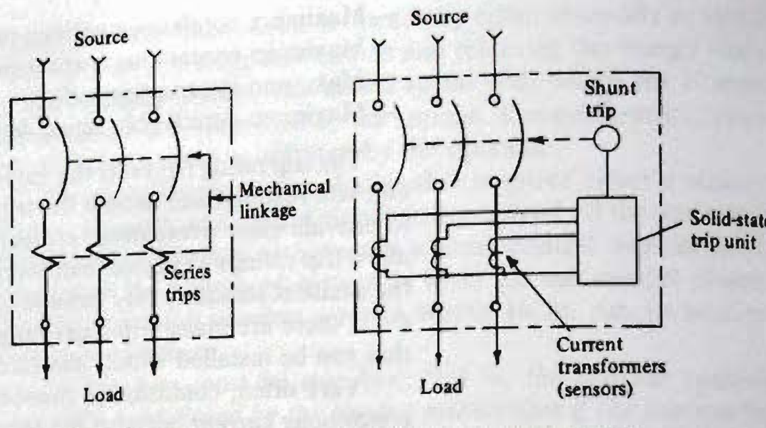
The trip rating then sets the value of the current above which the unit will respond and initiate the tripping of the breaker. To be able to provide close overcurrent protection for circuits, there are many more trip ratings available than there are frame sizes. For example, the smallest standard-duty molded-case frame is 100 amperes. However, there are many trip units ranging from 15 up to 100 amperes that can be installed within this frame size.

Very often, confusion is caused by the use of the phrase *rated continuous current* because the term is actually being used to indicate the current that the breaker can carry continuously before being tripped. However, the continuous current rating of the frame itself is set by the ampacity of the current-carrying parts (the contacts, terminals, and connections). It is preferable to use the term *trip rating* for the current above which the breaker will trip and then use the continuous current rating to designate the size of the frame. Many references to circuit breakers just indicate the one current rating, for example 70 amperes. However, this is incomplete because it presumably just refers to the trip rating. The frame size would normally be 100 amperes, but if a higher interrupting capacity is required, then the frame size may be 225 amperes. Therefore, both ratings should be specified. Specific ratings for breakers are covered in the following sections for each type of breaker.

8.3.2 Means of Automatically Tripping Breakers

Low-voltage circuit breakers generally have integrally mounted trip units that both monitor the circuit current and then automatically initiate tripping action based on their built-in time–current characteristics. There are two types of integrally mounted trip units, the series and the solid-state types. The series trips are thermal and/or magnetic units that are connected in series with each line of the circuit, as shown in Figure 8.3(a). They are acted on by the passage of the circuit current through them and, by means of a mechanical linkage, operate directly to trip the breaker.

The solid-state trip unit requires current transformers or sensors in each line of the circuit to reduce the current to a suitable level for input to the sensing circuits, as shown in Figure 8.3(b). The sensing circuits then function to initiate an output to the shunt trip that opens the breaker. The series trips are still generally used in the molded-case breakers, with the solid-state units being available for the larger ratings. The solid-state units have largely replaced the series trips on the power circuit breakers. More details on the trip units are given in the following sections on each type of breaker.



(a) Breaker with series trips (b) Breaker with solid-state trips

Also see Figure 10.16 for addition of ground-fault protection.

FIGURE 8.3

Methods of tripping automatic low-voltage circuit breakers

An optional feature that can be easily added to circuit breakers is undervoltage protection. This option is not available when fuses are used for circuit protection. A voltage-sensitive coil is connected to the line side of the circuit breaker, as shown in Figure 8.2, which trips the breaker if the supply voltage drops to an unsatisfactory level. Also, it prevents the breaker from being closed until the voltage is restored to 80% or more of its normal value.

8.3.3 Interrupting and Short-Time Ratings

Since the late 1950s, the interrupting ratings for low-voltage circuit breakers have been stated in symmetrical amperes. The ratings are based on the assumption that the X/R ratio of the typical low-voltage system is 6.6. Refer to Section 6.5 and Figure 6.4 for symmetrical and asymmetrical currents and X/R ratios. As indicated, the rms value of the asymmetrical current one half-cycle after the fault occurs is 1.33 times the rms value of the symmetrical fault current on a per phase basis. However, on three-phase circuits, if the fault occurs at the instant of time that causes the maximum offset of current in one phase, then, because of the 120° phase relationship, the other two phases cannot also experience maximum offsets. The average of the asymmetrical currents of the three phases is 1.17 times the symmetrical fault current. Therefore, the asymmetrical rating of a low-voltage breaker is approximately 1.17 times its symmetrical rating. Breakers were originally rated only in asymmetrical amperes and standard values, such as 25,000 or 50,000, were selected. The symmetrical ratings are based on these values and therefore become 22,000 or 42,000 amperes, and so on. Specific interrupting ratings are given in the following sections for each type of circuit breaker.

Refer to Section 6.6 with regard to the short-time current ratings of protective devices. For low-voltage circuit breakers that are tripped instantaneously, no short-time ratings are listed. Since the breaker opens so rapidly (the contacts are starting to separate within one half-cycle), the short-time rating is assumed to be the same as the interrupting rating of the breaker. For circuit breakers with delayed short-time tripping, a short-time current rating is listed. This rating is also stated in symmetrical amperes. Specific short-time ratings are listed in the tables for the power and encased types of breakers as these breakers can be applied with delayed short-time tripping.

8.4 LOW-VOLTAGE, MOLDED-CASE CIRCUIT BREAKERS

In the early 1920s, a small, compact circuit breaker was developed that differed considerably from the standard low-voltage circuit breakers in use at that time, which were large, rugged types designed for high-amperage circuits. The small size and lower cost of this new type of breaker meant that it could economically be used in place of fuses for the protection of small-capacity, low-voltage circuits. The fact that they could be simply reset after a fault and that they were tamper proof were considerable improvements over the fuses. The term *molded case* was ultimately created to classify this type of breaker. The National Electrical Manufacturers Association standards defines the *molded-case circuit breaker* as *one that is assembled as an integral unit in a supporting and enclosing housing of insulating materials.*

Refer to Figure 8.4 for a typical three-pole molded-case circuit breaker. This cutaway view shows the contacts, the arc extinguish-

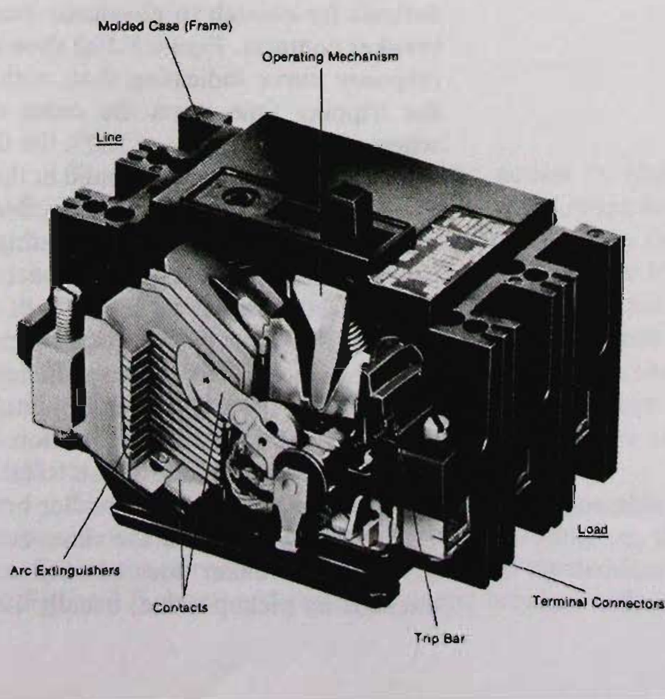


FIGURE 8.4

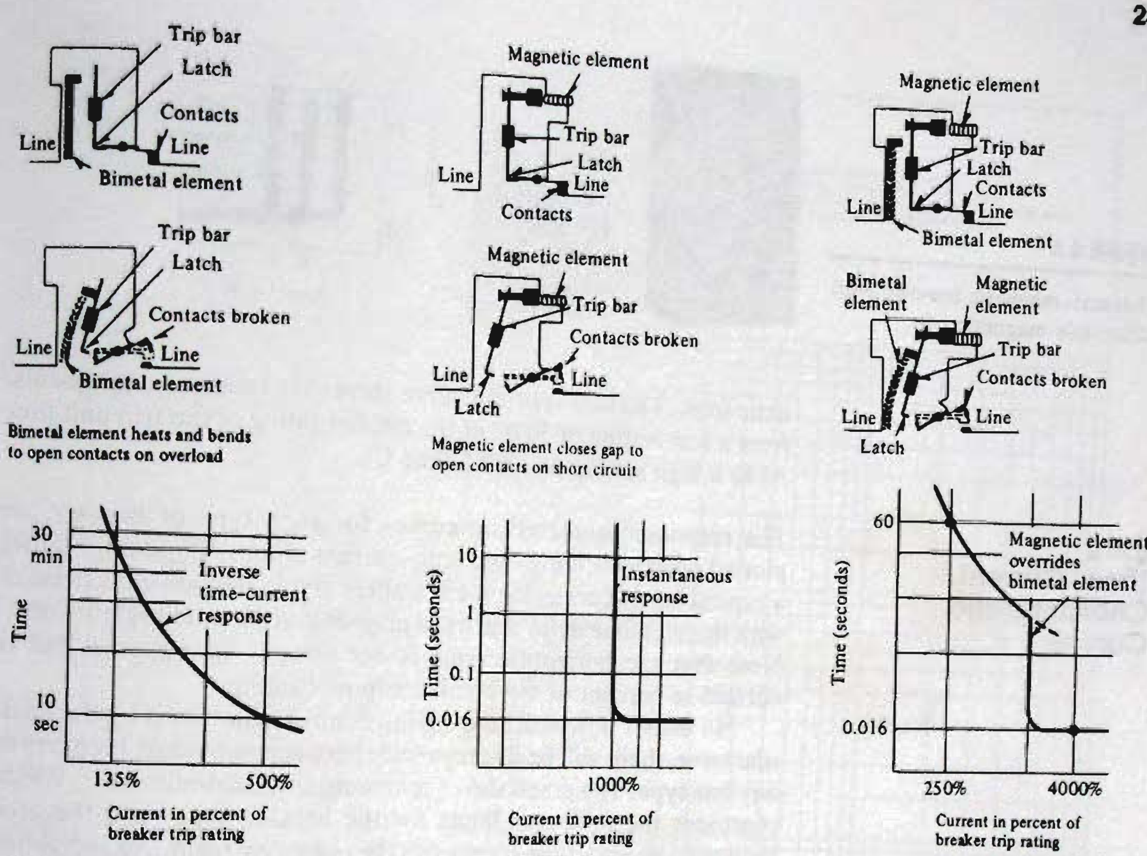
Cutaway view of a low-voltage, molded-case circuit breaker ers (arc chutes), the trip bar, and the operating mechanism. The handle of the mechanism operates through a toggle arrangement to snap the contacts open or closed. The action is quick-make, quick-break, meaning that the speed with which the contacts move is independent of how fast the handle is operated. In addition to indicating whether the breaker is on or off, the operating handle indicates when the breaker is automatically tripped by moving to a position midway between the extremes. This distinct trip point is advantageous where breakers are grouped in a panelboard because it clearly indicates the faulty circuit. To restore service after the breaker trips, the handle must first be moved to the fully off position to reset the mechanism and then to the on position.

8.4.1 Thermal–Magnetic Trip Units

The standard molded-case circuit breaker has a thermal–magnetic trip unit with detection elements connected in series with each pole, as shown in Figure 8.3(a). The thermal action provides inverse time-delayed tripping on overloads, and the magnetic action provides instantaneous tripping on short circuits (see Section 6.7 and Figures 6.5 and 6.6).

The thermal time-delayed tripping is achieved through the use of a bimetal element that is heated directly by the passage of the circuit current, as shown in Figure 8.5(a). The bimetal element has two bonded strips of metal with different rates of thermal expansion. The heat from an overload current causes the element to bend, the rate being dependent on the amount of current. Ultimately, the element deflects far enough to physically push the trip bar and unlatch the breaker contacts. Figure 8.5(a) shows a typical inverse time–current response curve indicating that, with an overload current of 135%, the tripping time is on the order of 30 minutes (1800 seconds), whereas with a current of 500% the time is down to 10 seconds. The thermal elements are calibrated in the factory and are not adjustable after the breaker has been assembled. A specific thermal element must be supplied for each trip rating.

The magnetic instantaneous action is achieved through the use of an electromagnet in series with the load current, as shown in Figure 8.5(b). The passage of a short-circuit current through the coil of the electromagnet creates sufficient force to attract the armature, thus moving the trip bar and unlatching the breaker contacts. The only delaying factor is the fraction of time (1 cycle or less) that it takes for the unlatching action to take place. Thus the action is said to be instantaneous. The smaller breakers have fixed magnetic trip elements, as shown in the time–current response curve in Figure 8.5(b). The breaker does not trip until the fault current reaches or exceeds its pickup value, usually 1000% of its rating.



(a) Thermal action

(b) Magnetic action

(c) Combined thermal-magnetic action

FIGURE 8.5

Thermal–magnetic trip units for molded-case circuit breakers

The combined thermal–magnetic action is shown in Figure 8.5(c), together with the typical time–current response curve. Thermal action with time-delayed tripping occurs up to the point where the current is large enough to activate the magnetic trip. Above this point, the magnetic action trips the breaker instantaneously. For example, a 250% overload current takes 60 seconds to deflect the bimetal element far enough to trip the breaker. On the other hand, a short-circuit current of 4000% (40 times the breaker trip rating) attracts the magnetic armature and trips the breaker instantaneously (0.016 second).

The larger molded-case breakers have adjustable instantaneous trip units. By adjusting the gap in the electromagnet, the actual value of the current required to activate the trip mechanism can be varied. Figure 8.6 shows a thermal–magnetic breaker with adjustable mag-

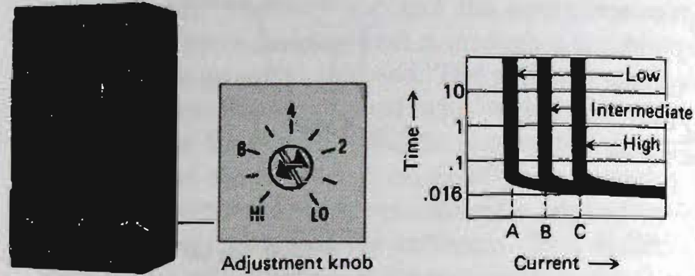


FIGURE 8.6

Thermal–magnetic breaker with adjustable magnetic trip

netic trips. The time–current curve shows the range of adjustments, from a low setting of 500% of the current rating of the trip unit (line A) to a high setting of 1000% (line C).

8.4.2 Time–Current Characteristic Curves

The response characteristic curves for each type of breaker are plotted on standard log–log, time–current graphs. Figure 8.7 shows a typical set of curves for a 150 ampere frame molded-case breaker with thermal time delay and fixed magnetic instantaneous trip units. Note that the horizontal scale is not directly in amperes, but is current in percent of the breaker trip unit rating.

No matter how strict the quality control maintained by the manufacturer, there will be discrepancies between individual breakers of any one type. The graph shows minimum and maximum lines, which represent the tolerance limits for the breaker type, and the area between the lines then represents the operating band. An individual breaker will operate within the limits defined by the band.

■ EXAMPLE 8.1

Using Figure 8.7, for a breaker with a 90 A trip unit, determine the minimum and maximum tripping times for a current of 360 A.

Solution

— 360 A is 360/90 = 4.0 or 400%.
— Intersection of 400% with minimum line is 12 s.
— Intersection of 400% with maximum line is 30 s.

These points are indicated on the graph. This means that, from a large sampling of breakers of this type using a 90 A trip unit, none will trip in less than 12 s and none will take longer than 30 s to totally clear the circuit at 360 A.

The actual time for the breaker to open and fully extinguish the arc once it has been tripped is insignificant in the time-delayed tripping region, but it is the major factor in the instantaneous tripping region. Therefore, the maximum interrupting time becomes virtually constant at 0.016 second for currents above the instantaneous tripping value. Note that the tolerances for the magnetic instantaneous

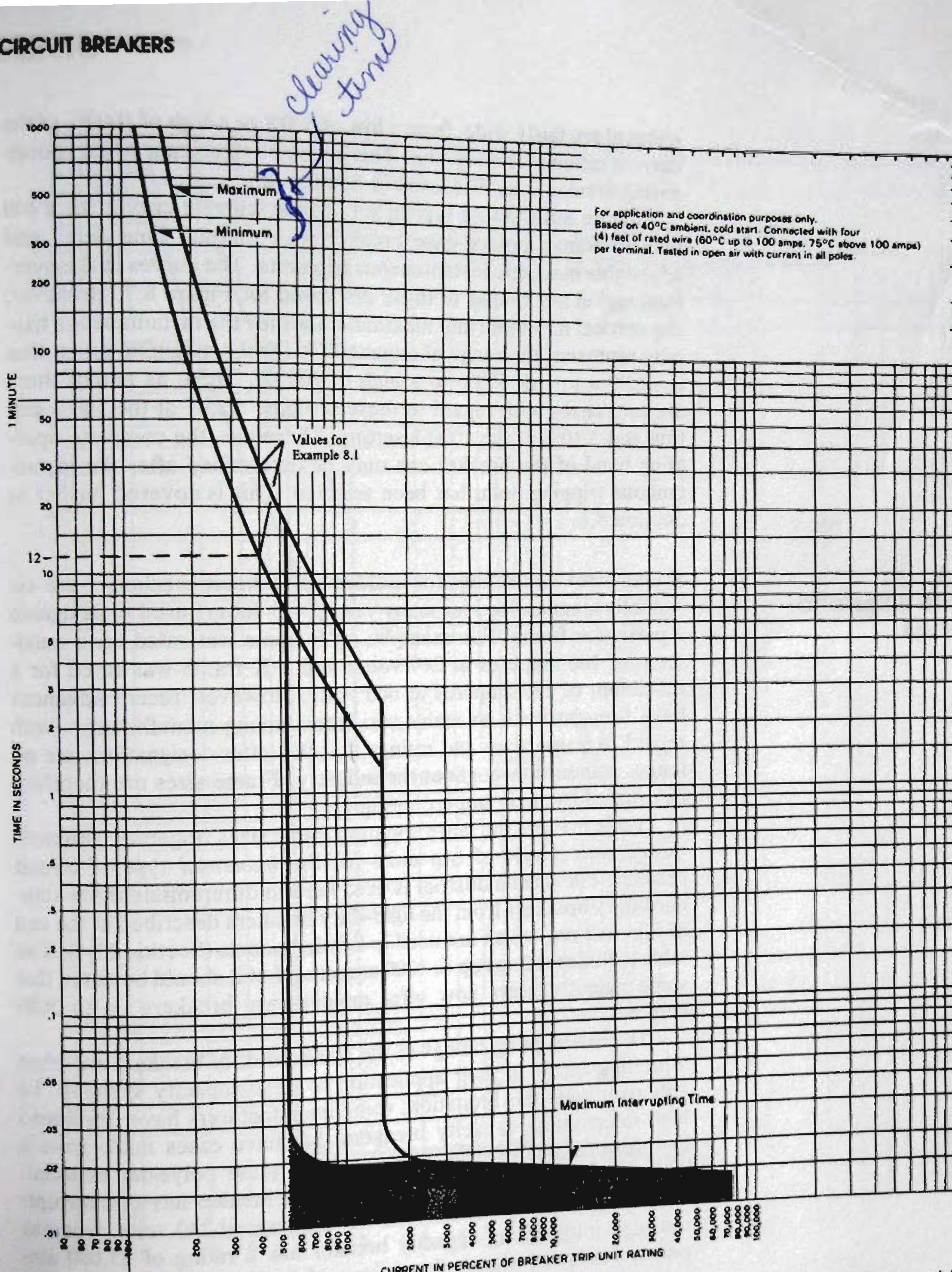


FIGURE 8.7 Typical time–current characteristic curves for molded-case breaker, 150 ampere frame, with thermal time delay and fixed magnetic instantaneous trip unit

element are fairly wide, from a low of 530% to a high of 1600% of the current rating of the trip unit. This becomes significant when coordinating breakers, as discussed in Section 8.6.

Figure 8.8 shows a typical set of time–current curves for a 400 ampere frame molded-case breaker with thermal time delay and adjustable magnetic instantaneous trip units. The curves in the overload region are similar to those discussed for Figure 8.7. However, the vertical minimum and maximum lines for the instantaneous tripping represent the range of adjustments for the magnetic units, that is, from a low of 500% to a high of 1000%. Then, as noted, there are tolerances with regard to these settings: ±25% at the 500% setting and ±10% at the 1000% setting. Therefore, the complete operating band of the breaker can only be determined after the instantaneous tripping point has been selected. This is covered further in Section 8.6.

8.4.3 Frame Sizes and Ratings

Frame sizes and ratings for molded-case circuit breakers were essentially standardized for many years, with letters used to designate a particular frame. For example, an E frame was rated for a maximum of 100 amperes at 240 volts, and a K frame was rated for a maximum of 225 amperes at 600 volts. However, recent advances have brought forth so many variations among manufacturers with regard to frame sizes and ratings that the letter designations are no longer standard throughout the industry. Frame sizes are therefore designated by their ampere rating.

Table 8.1 lists the more common frame sizes, together with their ratings and ranges of trip units for the *industrial* type of circuit breaker. The term industrial is used here to differentiate these standard-duty breakers from the light-duty breakers described at the end of this section, which are used in lighting panels (Section 12.4). The table includes ratings up to 1200 amperes, but it should be noted that some manufacturers now offer molded-case breakers up to 3000 amperes.

The interrupting ratings of the standard-duty breakers are often a limiting factor in their application to large-capacity systems. To help overcome this limitation, some manufacturers have developed high interrupting capacity breakers that have cases made from a high-impact, high-tensile, flame-resistant glass polyester material. As a comparison, the standard 225 ampere breaker has an interrupting rating of 25,000 rms symmetrical amperes at 240 volts, whereas the high interrupting capacity breaker has a rating of 65,000 amperes. Table 8.1 shows the ratings of both types. Note that the increase in ratings for the high interrupting capacity units is not nearly so great at 480 and 600 volts. These special breakers cost roughly 50% more than the standard breakers, but they offer a low-

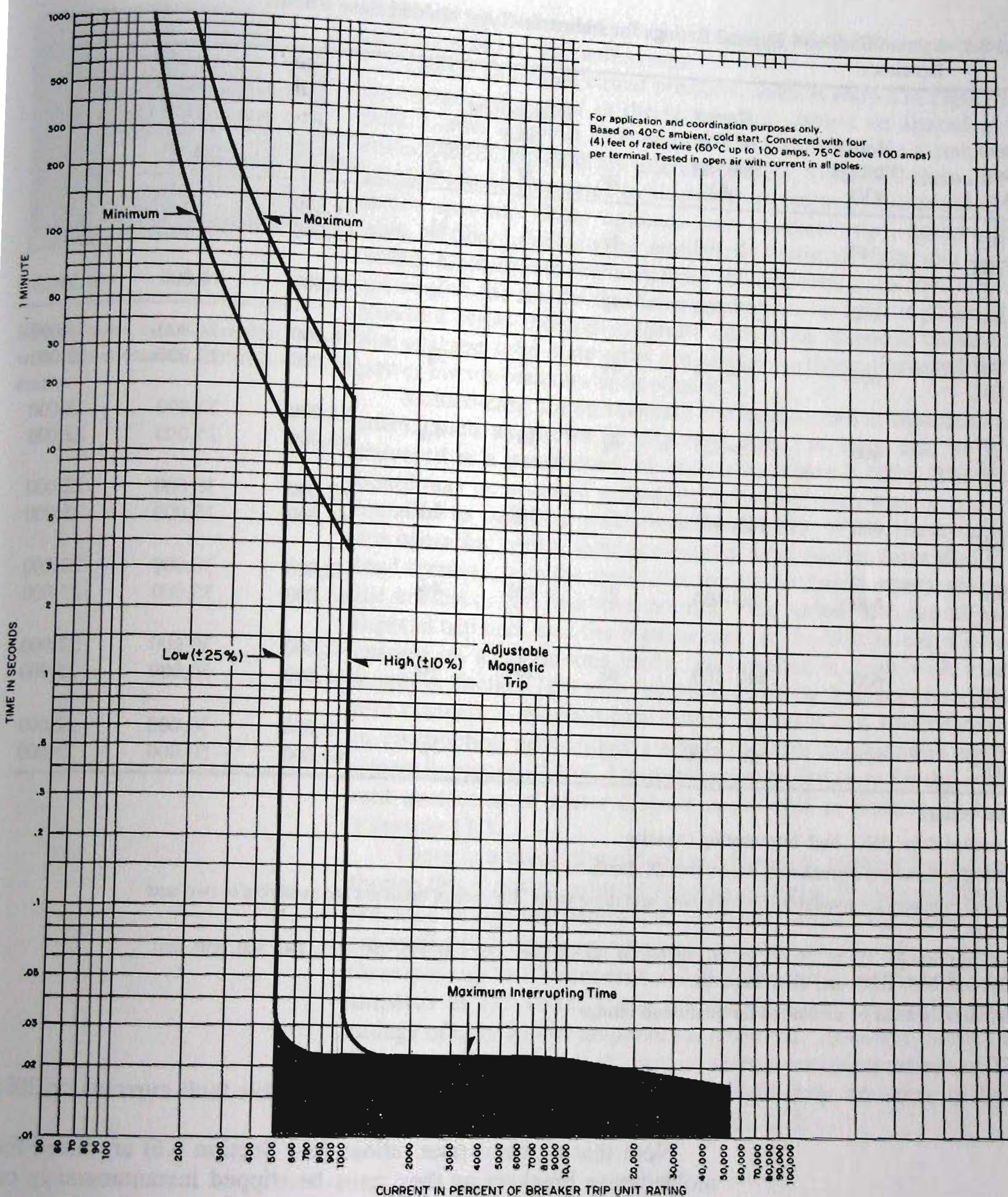


FIGURE 8.8 Typical time–current characteristic curves for molded-case breaker, 400 ampere frame, with thermal time delay and adjustable magnetic instantaneous trip unit

TABLE 8.1 Frame Sizes and Typical Ratings for Industrial-Type Molded-Case Circuit Breakers

Frame Size (A)	Rated Voltage (V)	Range of Trip Ratings (A)	Dimensions (in.)			Interrupting Ratings (rms symmetrical amperes)		
			W	H	D	240 V[a]	480 V[a]	600 V[a]
100 Std 100 HIC	240	15–100	$4\frac{1}{8}$	6	$3\frac{3}{8}$	10,000 65,000	— —	— —
100 Std	480	15–100	$4\frac{1}{8}$	6	$3\frac{3}{8}$	18,000	14,000	—
150 Std 150 HIC	600	15–150	$4\frac{1}{8}$	6	$3\frac{3}{8}$	18,000 65,000	14,000 25,000	14,000 18,000
225 Std 225 HIC	600	70–225	$4\frac{1}{8}$	10	$4\frac{1}{16}$	25,000 65,000	22,000 25,000	18,000 22,000
400 Std 400 HIC	600	125–400	$5\frac{1}{2}$	$10\frac{1}{8}$	$4\frac{1}{16}$	42,000 65,000	30,000 35,000	22,000 25,000
600 Std 600 HIC	600	250–600	$8\frac{1}{4}$	$10\frac{3}{4}$	$4\frac{1}{16}$	42,000 65,000	30,000 35,000	22,000 25,000
800 Std 800 HIC	600	400–800	$8\frac{1}{4}$	16	$4\frac{1}{16}$	42,000 65,000	30,000 50,000	22,000 25,000
1200 Std 1200 HIC	600	600–1200	$8\frac{1}{4}$	16	$5\frac{1}{2}$	42,000 65,000	30,000 50,000	22,000 25,000

[a] System voltage.

Std, standard duty; HIC, high interrupting capacity.

W, width (for three-pole breakers); H, height; D, depth.

100 ampere breakers are available in single, two, and three poles. Balance of breakers are available in two and three poles.

Standard trip ratings: 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90, 100, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500, 600, 800, 1000, and 1200 amperes.

Manufacturers should be consulted for confirmed ratings.

cost solution to the problem of high available fault currents on 208/120 volt systems.

Note that no short-time ratings (see Section 6.6) are listed for molded-case breakers as they must be tripped instantaneously on high fault currents. Note also that the interrupting ratings increase with lower system voltages. For example, a 400 ampere, standard-duty breaker rated for 600 volts has a rating of 22,000 amperes when

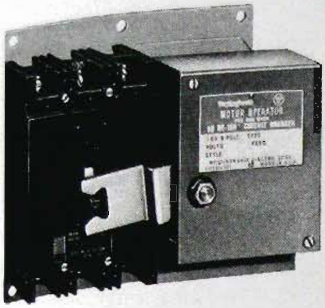


FIGURE 8.9

Molded-case circuit breaker with side-mounted motor operator

used on a 600 volt system, but has a rating of 42,000 amperes when used on a 240 or 208 volt system.

The smaller-rated circuit breakers, such as shown in Figure 8.4, are completely sealed in the factory and cannot be altered in the field. Larger breakers (400 amperes and above) have a removable cover and the trip units are interchangeable. Figure 8.9 shows how a breaker can be converted to electrical operation by the addition of a motor operator. Other options, such as shunt trips, undervoltage trips, auxiliary contacts for control, or alarm circuits, can also be added. Molded-case breakers from 600 amperes up to 3000 amperes are now on the market that have solid-state trip units in place of the standard series thermal–magnetic units. The response characteristics of these solid-state units are similar to those discussed for the power circuit breakers in Section 8.5.

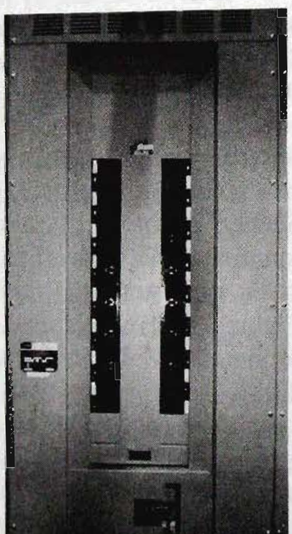
Molded-case circuit breakers can be mounted in separate enclosures, such as shown in Figure 8.10(a), or they can be group mounted in a panelboard, as shown in Figure 8.10(b). The panelboard may be installed separately in its own enclosure or it may be installed as part of a switchboard assembly. When these breakers are operating within their enclosures, heat accumulates due to the load currents, with the result that the ambient air temperature within the enclosure can be above normal. This added heat can affect the thermal trip unit, and the breaker may not be able to carry its rated current on a continuous basis. This matter is dealt with at more length in Section 11.8 with regard to applying breakers for overcurrent protection. Molded-case circuit breakers can also be mounted in conjunction with motor starters to form combination units, as shown in Figure 14.3(b). The application of breakers for the overcurrent protection of motor circuits is covered in Section 13.1.1 and Example 13.3.

There is a class of molded-case breakers labeled *light duty*, although this is not an industry recognized term. These small breakers are used in lighting panels and residential-type load centers. They are available in single pole up to 70 amperes at 120 volts, in two- and three-pole up to 100 amperes at 240 volts, and in single pole up to 30 amperes at 277 volts. These breakers normally have interrupting ratings of only 10,000 amperes symmetrical. However, some manufacturers offer this type of breaker with interrupting ratings of 22,000 amperes. The application of these light-duty breakers in lighting panels is covered in Sections 12.4 and 12.5.

8.4.4 UL Test Requirements

The following are a few of the many requirements of the Underwriters Laboratories, Inc., when they test molded-case circuit breakers for approval.

(a) Individually mounted in separate enclosure



(b) Group mounted in a panelboard

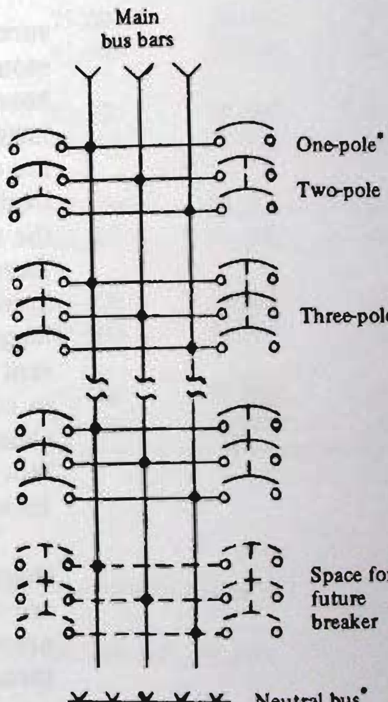


FIGURE 8.10

Mounting of molded-case circuit breakers

Each type of breaker first undergoes a calibration test to ensure that it provides proper overload protection. Maximum clearing times at 135% and 200% of the rated current of the trip unit are checked. These clearing times are similar to those listed in Table 7.1 for fuses. For example, a breaker with a 100 ampere trip unit must clear the circuit in a maximum of 120 minutes at 135% and 6 minutes at 200% of rated current.

To ensure that the breaker is suitable for use as a motor disconnecting means (see Section 13.2.2), it is tested at 600% of its normal current at rated voltage. Depending on the size, it must successfully open the circuit a specified number of times. For example, a 400 ampere breaker must safely interrupt 2400 amperes 50 times. The breaker is continuously loaded at its rated current in an ambient temperature of 25°C and checked for temperature rises, which must not exceed specified limits. An endurance test ensures that the breaker can successfully open and close a minimum number of times. For example, a 225 ampere breaker must operate a minimum of 8000 times at a rate of five operations per minute, with half the operations being made with rated current flowing.

The breaker must pass a short-circuit test to confirm its interrupting rating. With the breaker closed, it must first successfully interrupt its rated fault current. Then, after 2 minutes, the breaker is closed in on this fault current and again must successfully interrupt the current, all at the specified voltages.

The final test is the dielectric withstand test to check the insulation level of the breaker. A 60 hertz voltage equal to twice the rated voltage of the breaker plus 1000 is applied to the breaker for 1 minute. For example, the voltage applied to a 600 volt rated breaker is 2200 volts.

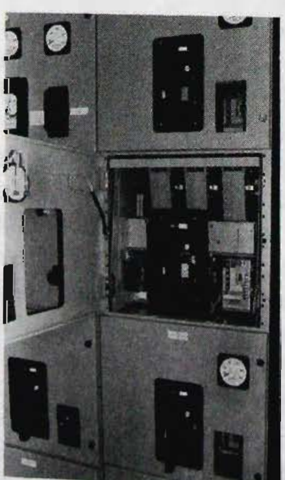
The foregoing is only a brief listing of the test requirements. The complete sequence of tests for molded-case circuit breakers is covered in UL Standard 489.

8.5 LOW-VOLTAGE POWER CIRCUIT BREAKERS

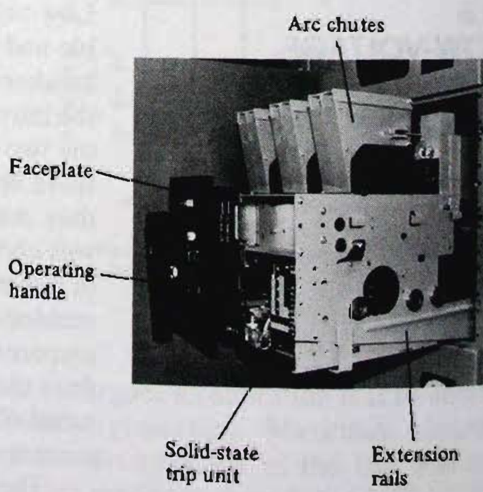
Low-voltage power circuit breakers are more rugged and more flexible and generally have higher ratings than the molded-case circuit breakers. The designation *power circuit breaker* was adopted after the introduction of the molded-case breaker to differentiate between the two types. The term unfortunately does not adequately describe these breakers, as all breakers in reality are power breakers in that they make and break power circuits. The term *power* presumably was chosen since these breakers can be used to handle large blocks of power, up to 4000 amperes at 600 volts, three-phase, whereas the molded-case breakers originally could only handle loads up to 600 amperes. The National Electrical Manufacturers Association defines the *low-voltage power circuit breaker* as *one for use on circuits rated 1000 volts alternating current and below, or 3000 volts direct current and below, but not including molded-case breakers*.

The power circuit breaker has an open-type heavy steel frame upon which the components are mounted, making them more readily accessible. These breakers tend to be heavier, larger, and more costly than molded-case breakers. Fixed breakers are available for mounting in individual enclosures but generally the breakers are of the drawout type for mounting in metal-enclosed switchboards as shown in Figure 8.11. Figure 8.11(a) shows the breaker in its fully engaged position (with the cubicle door open). Figure 8.11(b) shows the breaker in its drawout position. The breaker is moved into and out of its cubicle by means of a crank. Figure 8.12 is a rear view of the breaker itself, showing the disconnecting contacts at the rear by which the breaker is electrically connected or disconnected from the fixed plug-in contacts within the switchboard cubicle. These contacts cannot be used to make or break the load current as the breaker must be in the open position before it can be moved into or out of the cubicle. The drawout feature allows maintenance to be done on the breaker with complete safety, as it is fully disengaged from the live electrical connections in the switchboard. It also allows for the quick replacement of a faulty breaker. Figure 8.11(b) also shows the arc chutes mounted above the breaker contact mechanism [see Figure 8.1(b)]. Section 8.1 outlines the use of arcing contacts and arc chutes.

The breakers are closed using the two-step, stored-energy spring mechanism. Manual operation is accomplished by first compressing a heavy spring using the operating handle as shown in Figure 8.11(b). With the closing spring compressed, the breaker can be closed at any time by pushing the close button mounted on the breaker faceplate, which mechanically releases the spring. Electrical operation uses an electric gear motor to compress the spring.



(a) Breaker fully inserted into its enclosure



(b) Breaker in its fully withdrawn position

FIGURE 8.11

Drawout-type, low-voltage power circuit breakers

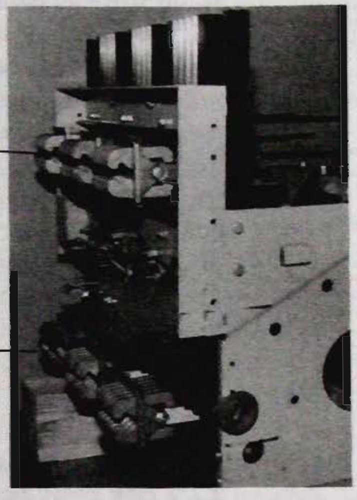


FIGURE 8.12

Rear view of drawout power circuit breaker

The breaker is then closed by electrically activating a small close solenoid, which releases the closing spring. The breakers are opened manually by pressing the separate trip button mounted on the breaker faceplate, which mechanically unlatches the breaker, allowing the opening springs to rapidly force the main contacts apart. The breakers are opened electrically by energizing a shunt trip coil from a remote push button, which then similarly unlatches the breaker contacts. Refer to Section 8.2 for an introductory discussion on the operation of breakers. The breakers can have optional undervoltage trip units and auxiliary control contacts for external alarm circuits and remote indicating lights.

8.5.1 Solid-State Trip Units

The trip units used with power circuit breakers are today almost universally of the solid-state type. These units have replaced the mechanical dual-magnetic trip units that were the standard for many years. The dual-magnetic type provides inverse time delay in the overload region by means of a dashpot mechanism that controls the rate of movement and thus the timing of the mechanism. On large fault currents, the magnetic force becomes great enough to bypass the restraining force of the dashpot and the breaker is tripped instantaneously. Calibration is provided by adjusting the tension of the springs that oppose the movement of the tripping elements. The solid-state trip units can easily duplicate these time–current characteristics, but, in addition, can provide more flexibility in the range of adjustments and more accuracy in their setting.

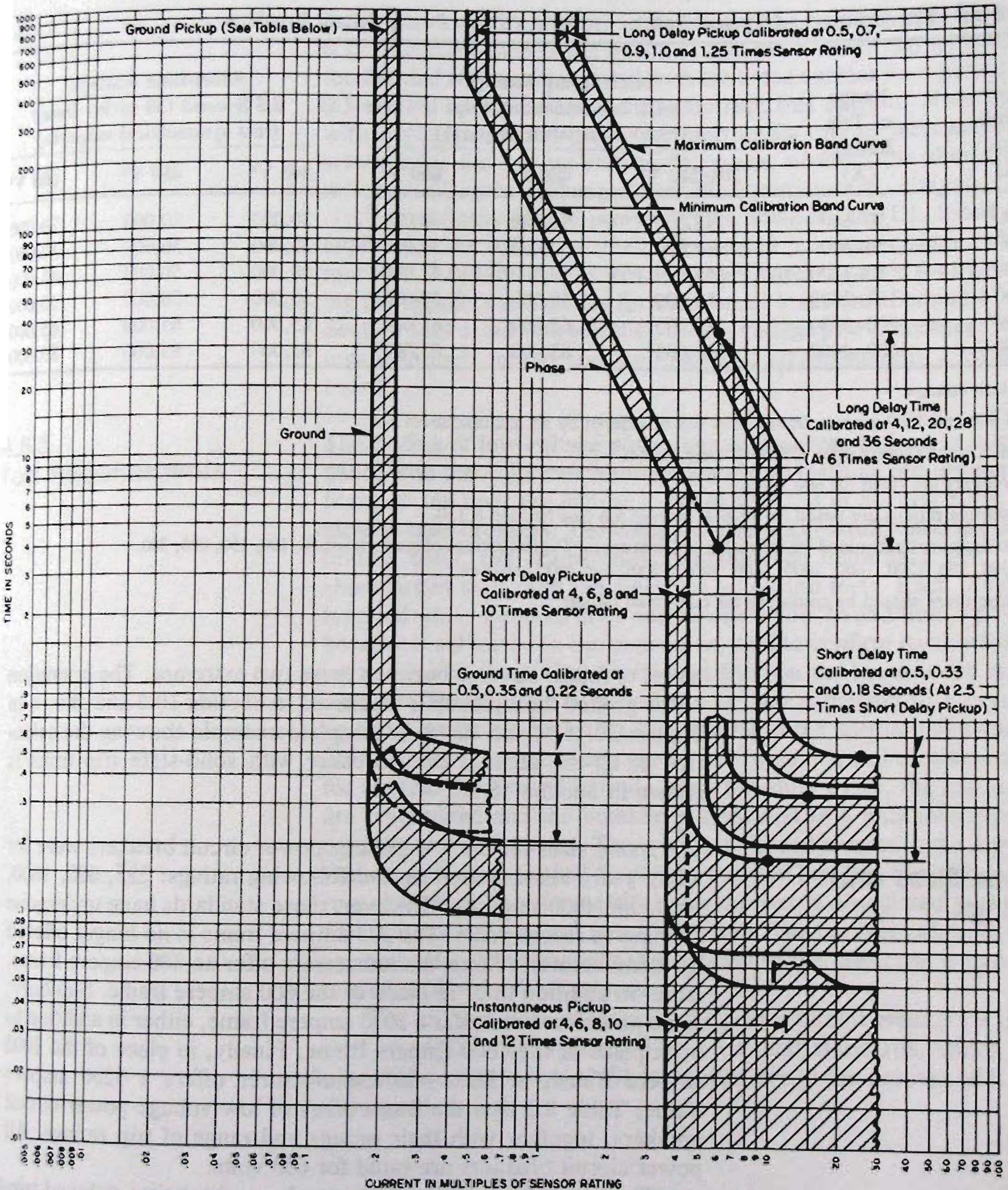
As shown in Figure 8.3(b), solid-state tripping requires three basic components: (1) the current transformers (or sensors as they are usually called), (2) the solid-state unit itself, and (3) a separate shunt trip mechanism. The sensors are connected into each pole of the breaker on the loadside of the main contacts. The sensors produce an output current that is proportional to the load current. This reduced current is fed into the solid-state detector circuits that monitor the current and, based on the preset response characteristics, initiate an output to the shunt trip to open the breaker. The shunt trip (or actuator) is a special design requiring very little power to activate it and mechanically unlatch the breaker. All necessary tripping energy is derived from the output current from the sensors. Thus the automatic tripping system is self-contained, requiring no separate source of power.

Seven different settings are available on the typical solid-state unit:

1. Long-delay pickup
2. Long delay time
3. Short-delay pickup
4. Short delay time
5. Instantaneous pickup
6. Ground pickup
7. Ground delay time

Figure 8.13 shows the typical time–current characteristic curves, together with the ranges of adjustments available for each setting. The term *pickup means the magnitude of the current at which the detector circuit timing function begins*. Note that the pickup settings on the adjustment dials are in multiples of the sensor rating. Thus the actual pickup points in amperes depends on the ampere rating of the sensors. For example, if the sensors are rated at 800 amperes and the long delay is set at 1.0, then the long-delay pickup point is at a load current of 800 amperes. If the sensors are rated at 1200 amperes and the long delay is set at 0.7, then the long-delay pickup is 1200 times 0.7 or 840 amperes. Many sensor ratings are available for each frame size as shown in Table 8.2, which, together with the adjustments on the dials, gives an almost unlimited range of actual pickup currents.

As with any manufactured device, there must be a tolerance allowance on the operation of the solid-state trip units. As noted in Figure 8.13, this tolerance is ±10 percent with regard to the current pickup values. The resulting band of operation is shown by the hatched area. Note that the minimum calibration band curve shows the response curve with the long-time and short-time adjustments set at their minimum values, and the maximum calibration band curve shows the response curve with these adjustments set at their maximum. The actual operating curve for any particular breaker can



Dial Setting	Ground Pick-Up Value—Amperes													
	Sensor Rating													
	50	100	150	200	300	400	600	800	1200	1600	2000	2400	3200	4000
A	12	57	60	65	80	110	145	180	260	330	400	530	640	800
B	16	67	75	85	110	150	205	260	385	505	600	770	1000	1200
C	22	75	85	100	130	185	250	325	480	625	760	960	1200	N.A.
D	33	100	120	145	200	270	385	500	730	870	1200	N.A.	N.A.	N.A.

All pick-up values may vary ±10%

FIGURE 8.13 Typical time–current characteristic curves for power circuit breaker with solid-state trip unit

TABLE 8.2 Frame Sizes and Typical Ratings for Low-Voltage Power Circuit Breakers

Frame Size (A)	Range of Trip Ratings (A)	Interrupting Ratings with Instantaneous Trips (rms symmetrical amperes)			Short-time Ratings, 0.5 Second (30 cycle) Delay (rms symmetrical amperes)		
		208/240 V[a]	480 V[a]	600 V[a]	240 V[a]	480 V[a]	600 V[a]
600[b]	50–600	42,000	30,000	30,000	30,000	30,000	30,000
800	50–800	42,000	30,000	30,000	30,000	30,000	30,000
1600[b]	50–1600	65,000	50,000	42,000	50,000	50,000	42,000
2000	50–2000	65,000	50,000	50,000	50,000	50,000	50,000
3000[c]	1200–3000	85,000	65,000	65,000	65,000	65,000	65,000
4000	1600–4000	130,000	85,000	85,000	85,000	85,000	85,000

[a] System voltage.

[b] The 600 and 1600 ampere frames may not be offered by all manufacturers.

[c] Some manufacturers offer a 3200 ampere frame.

All breakers are rated for 600 volts.

Interrupting ratings are based on an X/R ratio of 6.6 (see Section 8.3.3).

Trip ratings are determined by the rating of the sensors. Typical ratings of sensors are 50, 100, 150, 200, 300, 400, 600, 800, 1200, 1600, 2000, 2400, 3000 (3200), and 4000 amperes.

Manufacturers should be consulted for confirmed ratings.

be set to follow any line between these two extremes. The operation of the ground fault pickup is discussed in Section 10.5 and shown in Figures 10.16(b) and 10.18. A complete example showing the selection of all the settings on a breaker with solid-state trip units is shown in Section 16.5.

8.5.2 Frame Sizes and Ratings

The frame sizes for the low-voltage power circuit breakers were for many years standardized on the following ratings: 225, 600, 1600, 3000, and 4000 amperes. However, these standards have undergone changes in recent years. The 225 ampere frame is no longer offered by manufacturers. Some manufacturers offer an 800 ampere frame, either in addition to or in place of the 600 ampere frame. Similarly, some manufacturers offer a 2000 ampere frame, either in addition to or in place of the 1600 ampere frame. Finally, in place of the 3000 ampere frame, at least one manufacturer offers a 3200 ampere frame. Table 8.2 lists the frame sizes of low-voltage power circuit breakers, together with their ratings and range of trip ratings. All power circuit breakers are rated for 600 volts.

Since power circuit breakers can have short-time delayed tripping (see Section 8.3.3), short-time ratings are also included in the table. The short-time delayed tripping is usually selected for a line-side breaker so that the loadside devices can operate first to clear the faults (see Section 8.6 on coordination). This time delay substantially increases the thermal stressing on the breaker (see Section 6.2). The short-time rating indicates that the breaker can withstand the thermal stresses associated with the listed current for a period of 0.5 second (30 cycles) and then interrupt this current. Note that, with instantaneous tripping, the interrupting ratings increase substantially as the system voltage decreases, whereas the short-time ratings are largely unchanged with the lower system voltages.

The majority of the power circuit breakers are UL listed for application at 100% of their designated current ratings when mounted in suitable enclosures. This eliminates the need for oversizing the breakers and cables for continuous loads (see Section 11.8). Section 15.4 details the selection of low-voltage power breakers with regard to their ratings and their physical arrangement in a switchboard.

8.5.3 Test Requirements

The testing of low-voltage power circuit breakers is done in accordance with the American National Standards Institute requirements. Many of the tests are similar to those covered in Section 8.4.4 for molded-case breakers. The breakers must successfully pass the calibration tests, the temperature rise test, the endurance test, the short-circuit tests, and the dielectric withstand tests. Each breaker is tested while mounted in its normal enclosure. In addition, a power breaker is subjected to the momentary test to confirm its short-time rating. For this test, the overcurrent trips on the breaker are made inactive. The breaker is closed and is then subjected to a current equal to its short-time rating for a period of 0.5 second (30 cycles). This current is stopped for a period of 15 seconds and then repeated for another 0.5 second period. After this duty cycle, the trip units are reactivated and the breaker is subjected to a final interrupting capacity test at 635 volts. The breaker is forced to open at the instant that the power is applied to ensure that the breaker can also interrupt the offset or asymmetrical current that is associated with the first few cycles of a fault (see Figure 6.4). The breaker calibration is again checked, and finally it is subjected to the dielectric withstand test of 2200 volts for 1 minute.

The full sequence of tests for the power circuit breakers is covered by ANSI test standard 37.50. UL test standards, which are expected to follow the ANSI standards, are in the process of being developed.

8.6 COORDINATION OF CIRCUIT BREAKERS

The coordination of protective devices in an electrical system is first mentioned in the Introduction to Chapter 6 and again in Section 7.7 with regard to the application of fuses. Similarly, it is equally important to achieve coordination of the system protection when using circuit breakers.

First, let us look at the application of molded-case circuit breakers to system protection, such as the example shown in Figure 8.14. The breaker protecting the feeder to a group of branch circuits has a 400 ampere frame with a 300 ampere trip unit (designated the lineside breaker since it is closest to the source). The breaker protecting one of the branch circuits has a 150 ampere frame with a 100 ampere trip unit (designated the loadside breaker). With a fault at point A, it is desirable that the loadside breaker trip first and completely clear its circuit before the lineside breaker has a chance to trip, and shut down the balance of the circuits. This should ideally happen for all levels of overcurrent up to the maximum short-circuit current available at point A.

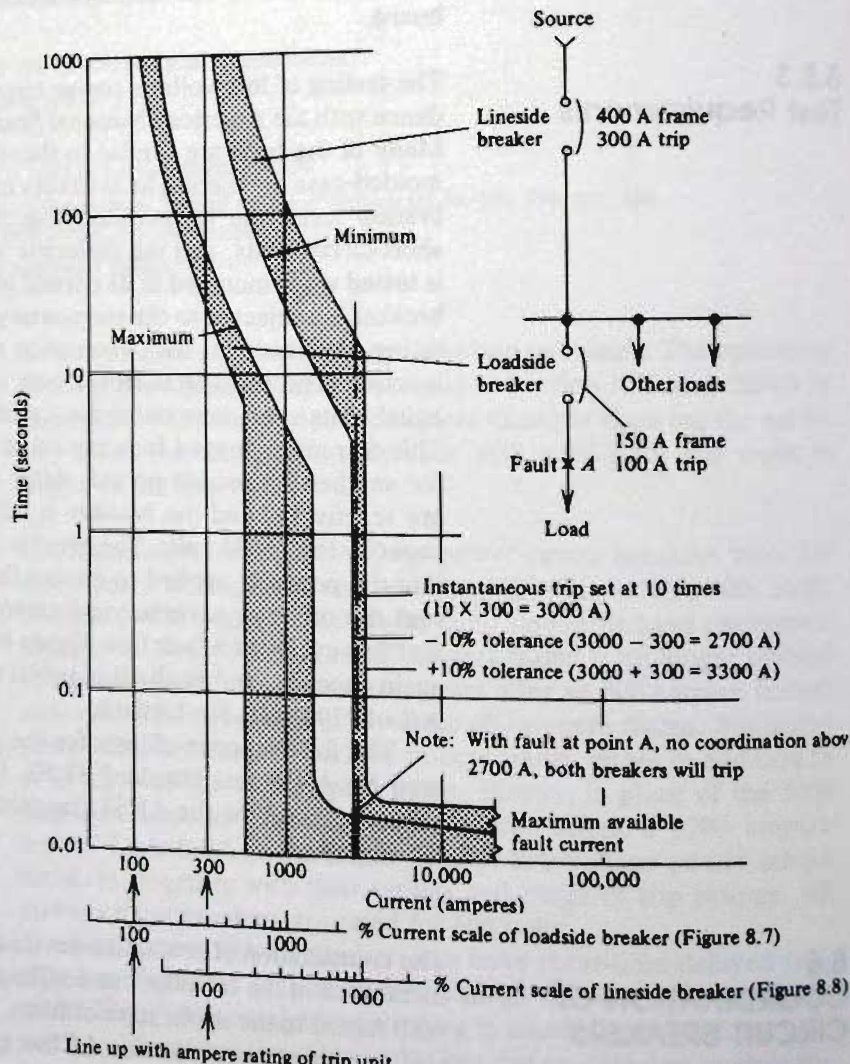


FIGURE 8.14

Coordination study for molded-case breakers

To check the complete coordination between the two breakers, it is necessary to copy the time–current characteristic curves for each onto a common graph referred to as an overlay. The preparation of overlays is discussed in greater detail in Section 16.4. Figure 8.14 shows the overlay for this example. The curves for the loadside breaker are copied from Figure 8.7 and those for the lineside breaker from Figure 8.8. The horizontal scale of the overlay must be in amperes so that the two sets of curves can be directly compared. To properly align the loadside breaker curves, the 100% line of Figure 8.7 must be lined up on the overlay with the 100 ampere line (with the breaker trip rating). Similarly, to align the curves for the lineside breaker, the 100% line of Figure 8.8 must be lined up with the 300 ampere line (with the breaker trip rating). In addition, since the lineside breaker has an adjustable magnetic trip, its setting must be selected and the resulting minimum and maximum instantaneous tripping lines properly drawn. It makes sense here to set the magnetic trip adjustment as high as possible (at 10 times) to obtain as much separation as possible between the two breaker curves. Thus, with a 300 ampere rated trip unit, the instantaneous trip will pick up at 3000 amperes subject to the tolerance allowance, which, as shown in Figure 8.8, is ±10% when the adjustment is set at the maximum. Thus the breaker could be tripped instantaneously on a current as low as 2700 amperes or as high as 3300 amperes. After the overlay of the two breaker curves has been completed, the extent of the coordination between the breakers is evident. With a fault at point A, on any current up to 2700 amperes, the loadside breaker can easily totally clear the circuit (as represented by its maximum line) before the lineside breaker reaches the point at which it could begin to trip (as represented by its minimum line). However, at currents above 2700 amperes, there is the possibility that the lineside breaker will be tripped instantaneously at the same time that the loadside breaker is opening to clear the fault. At currents above 3300 amperes, both breakers will definitely be tripped. Thus coordination is lost, because power is interrupted to all the branch circuit loads and not just the faulted circuit.

The fact that molded-case circuit breakers must be tripped instantaneously means that complete coordination cannot be obtained at the higher levels of fault current. This is a decided disadvantage against the application of these breakers for the overcurrent protection of feeders.

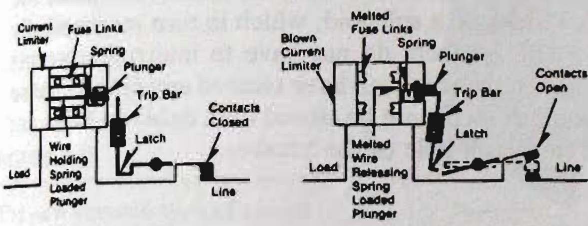
Next, let us consider the application of low-voltage power circuit breakers to system protection. Refer to the time–current characteristic curves for this type of breaker, as shown in Figure 8.13. As indicated on the graph and as discussed in Section 8.5.1, these breakers can be delayed from tripping in the short-time area (that is, with large faults), and coordination over the full range of possible fault currents is obtainable. For example, the loadside breaker can be set to trip instantaneously, and the lineside breaker can be set so that it will not trip for 0.18 second in the short-time region. Thus the loadside breaker has time to fully clear any faults that occur on the circuit that it is protecting before the lineside breaker has reached its tripping point. Refer to Section 16.5, which shows a complete coordination study of a system that in part uses the power circuit breakers for protection.

8.7 COMBINATION FUSED CIRCUIT BREAKERS

As the capacity of low-voltage electrical systems increased over the years, the interrupting capacities of circuit breakers became a limiting factor in their application to system protection. The development of low-voltage, current-limiting fuses that can be applied to systems with up to 200,000 amperes of available fault current offered a low-cost alternative to the use of circuit breakers. In addition, the fuses provide current limitation, which is a decided advantage in protecting systems from damage under fault conditions.

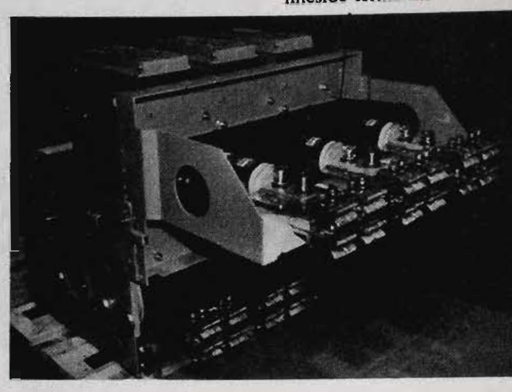
The solution, therefore, lay in combining the advantages of the circuit breaker with those of the current-limiting fuse. Figure 8.15(a) shows an example of a fused molded-case circuit breaker. The fuses are mounted in an extension to the standard molded enclosure and are available through a removable cover. Combination fused power circuit breakers are also available. The fuses are mounted on the lineside terminals at the rear of the breaker as shown in Figure 8.15(b) and are accessible by fully withdrawing the breaker from its enclosure. These breakers are listed with interrupting ratings of 200,000 rms symmetrical amperes.

The rating and characteristics of the fuse are chosen to properly coordinate with the circuit breaker characteristics so that the fuses do not take over and blow until the fault current is in excess of 80% of the interrupting capacity of the breaker. This coordination is shown in Figure 8.16. In this way, the breaker clears the circuit on all overloads and low-level fault currents, and the fuses only blow on the rare occurrence of high-level short circuits. When the fuses do blow, the peak let-through current and the thermal energy let-through (I^2t) are materially reduced, as discussed in Section 7.3 and shown in Figure 7.4. However, it should be noted that this current limitation does not take over until a much higher level of current than if fuses, rated to match the full-load current of the circuit, were used alone. Since the fuses used with the breakers function only to interrupt and current limit at the high current levels and do not themselves operate on overloads, they are often referred to as current *limiters* rather than fuses.



Method of preventing single phasing when one fuse blows.

(a) Fused molded-case circuit breaker



(b) Fused power circuit breaker

FIGURE 8.15 Low-voltage combination fused circuit breakers

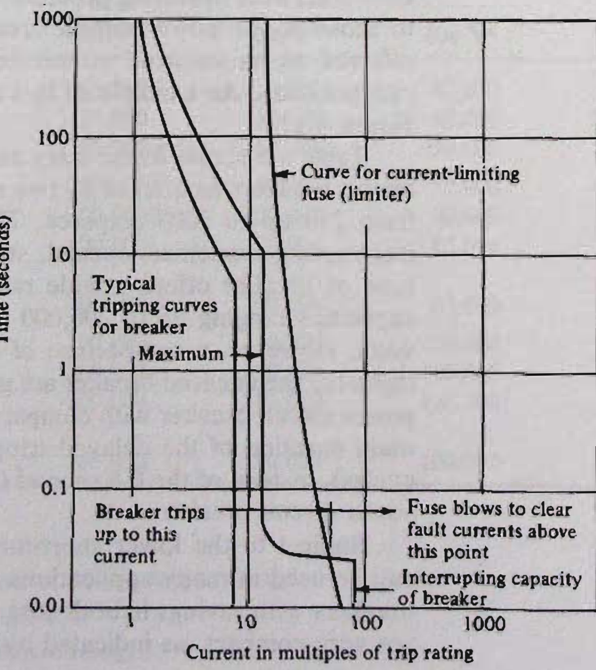


FIGURE 8.16

Curves showing typical coordination between breaker and fuse for combination fusible circuit breaker

To prevent single phasing of the feeder or circuit being protected by the fused breaker in the event that only one fuse blows, the units incorporate a method of automatically tripping the breaker should this occur. For the molded-case breakers, a plunger in the fuse (current limiter) is released when it blows, as shown in Figure 8.15(a). The movement of the plunger hitting the trip bar then opens the breaker. For the power circuit breakers, the primaries of small auxiliary transformers are connected in parallel across the terminals of each fuse. As long as the fuses are intact, no voltage is applied to the transformers. However, when a fuse blows and opens the circuit, the resulting voltage across the fuse terminals energizes the transformer, which picks up a solenoid, which in turn mechanically trips the breaker. The breakers do not have to interrupt currents beyond their rating as the fuse(s) will have cleared any faulted phase of the circuit. The breakers cannot be closed until unblown fuses are properly inserted into each pole of the breaker.

8.8 LOW-VOLTAGE ENCASED CIRCUIT BREAKERS

Not only has the distinction between molded-case and power circuit breakers been lessened by the development of larger frame molded-case breakers with solid-state trip units, but now at least two manufacturers offer a line of circuit breakers that incorporate features of both types. These new breakers are molded-case in that they have outer cases that are molded from strong, glass-reinforced plastic. However, their operating principles and range of options are similar to those of the power circuit breakers. They are variously being referred to as *encased* circuit breakers or even as *hybrid* circuit breakers. An example of this new type of breaker is shown in Figure 8.17.

Table 8.3 shows frame sizes and typical ratings for the encased circuit breakers as offered by one manufacturer. Frame sizes range from 250 up to 5000 amperes. There are three classifications of interrupting capacities: special, standard, and high. Thus this new type of breaker offers a wide range of ratings, with interrupting capacities ranging up to 200,000 rms symmetrical amperes at 240 volts. However, a comparison of the short-time ratings show that those for the encased breaker are generally lower than those for the power circuit breaker with comparable frame sizes. Also, the maximum duration of the delayed tripping can only be 0.3 second (18 cycles), instead of the 0.5 second (30 cycle) delay permitted for the power circuit breakers.

Subject to the lower short-time ratings, the encased breakers can be used in many applications formerly requiring power circuit breakers with savings in both cost and space. The encased breakers are very compact, as indicated by the dimensions shown in Figure

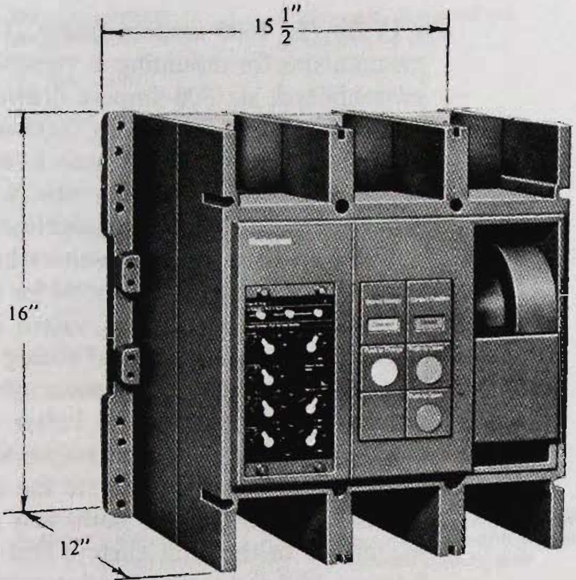


FIGURE 8.17

The new encased type of circuit breaker

TABLE 8.3 Frame Sizes and Typical Ratings for Low-Voltage Encased Circuit Breakers

	Frame Sizes (A)	Interrupting Ratings with Instantaneous Trips (rms symmetrical amperes)			Short-Time Ratings, 0.3 Second Delay (rms symmetrical amperes)
		240 V[a]	480 V[a]	600 V[a]	
Special interrupting capacity	250, 800	65,000	50,000	42,000	25,000
	1200	85,000	65,000	42,000	35,000
	1600, 2000	85,000	65,000	50,000	35,000
Standard interrupting capacity	250, 800	100,000	100,000	50,000	25,000
	1200	100,000	100,000	50,000	35,000
	1600, 2000, 2500, 3000	100,000	100,000	85,000	35,000
	4000, 5000	100,000	100,000	85,000	65,000
High interrupting capacity	250, 800	200,000	150,000	100,000	25,000
	1200	200,000	150,000	100,000	35,000
	1600, 2000, 2500, 3000	200,000	150,000	100,000	51,000
	4000, 5000	200,000	150,000	100,000	85,000

[a] System voltage.

All breakers are rated for 600 volts.

Interrupting ratings are based on an X/R ratio of 6.6 (see Section 8.3.3).

Trip ratings are similar to those listed in Table 8.2.

Manufacturers should be consulted for confirmed ratings.

8.17 for the 1600 ampere frame. They are available with drawout mechanisms for mounting in switchboards. In a typical 90 inch high switchboard, six 800 ampere drawout breakers can be mounted in one vertical section, or four 1600 ampere breakers or two 3000 ampere breakers, which can mean a reduction in the overall size of the switchboard. For a comparison with a switchboard layout using power circuit breakers, see Sections 15.4 and 15.5.

The encased circuit breakers have built-in, solid-state trip systems similar to those discussed for the power circuit breakers. As a further option, a tripping system incorporating a microprocessor rather than the conventional analog electronic circuitry is available. The use of the microprocessor allows the trip unit to perform a number of functions much better and provides a wider range of adjustments to the breaker response curve with a greater degree of accuracy. It can also indicate the cause of the tripping (overload, short circuit, or ground fault) and provide a digital readout of the magnitude of the fault current that caused the breaker to trip. See Section 16.5 for a coordination study using breakers with the conventional solid-state trip units.

The encased breakers have the two-step, stored-energy closing mechanism with the option of electrical operation, similar to the power circuit breakers. They have a full line of accessories, such as shunt trips for remote operation, undervoltage release, and auxiliary contacts for indicating lights, alarm circuits, and interlocking. They are UL listed for application at 100% of their designated frame ratings when mounted in suitable enclosures, which eliminates the need for oversizing breakers and cables for continuous loads (see Section 11.8).

8.9 CURRENT-LIMITING CIRCUIT BREAKERS

The standard breaker is not able to provide any current limitation when clearing a fault from the system. The inertia of the moving parts of the breaker means that the contacts, when operated just by the force from springs, cannot separate fast enough to extinguish the arc before the fault current has passed through its first instantaneous peak current at one half-cycle (see Figure 6.4). The development of the fused circuit breaker as discussed in Section 8.7 was a partial answer to the problem, but the use of fuses brings the disadvantage of having to replace them after operation, requiring spare fuses to be stocked.

However, two domestic manufacturers and at least one European manufacturer have recently developed true molded-case, current-limiting breakers that do not require fuses. One method of providing the extremely fast contact separation required for current limitation uses the slot motor principle, as shown in Figure 8.18. The

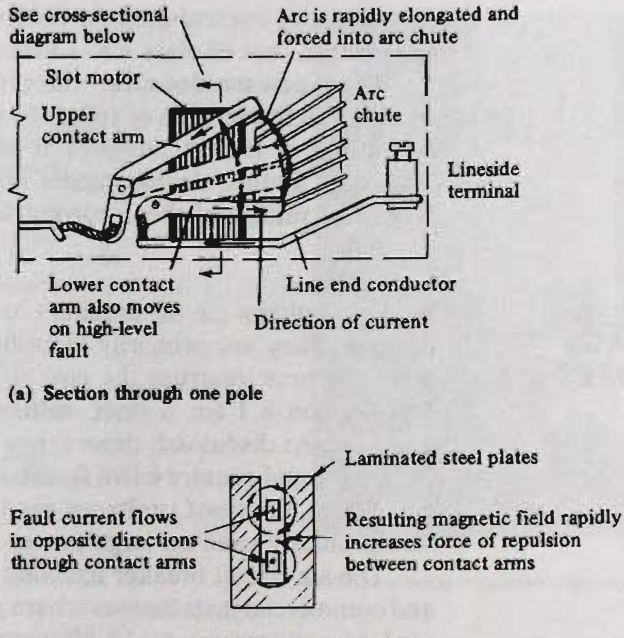


FIGURE 8.18

Operation of current-limiting circuit breaker

slot motor is a U-shaped block of laminated steel plates. The upper and lower contact arms rest within this slot motor, arranged so that in the closed position they are parallel with each other. On overloads and low-level faults where current limitation is not required, the breaker is tripped normally and the upper contact only moves to open the circuit. However, when a high-level fault occurs, the large current traveling in opposite directions through the contact arms creates a tremendous repulsion force that drives the contacts apart. The slot motor greatly enhances the strength of the magnetic field created by the current flow, which in turn increases this repulsion force. The force increases exponentially with the current. A fault current of 14,000 amperes develops a force some 17 times that produced by a current of 2000 amperes. This increased force is great enough to also move the lower contact, which increases the rate at which the contacts separate. The rapid elongation of the arc increases its resistance, which in itself provides a degree of current limitation. The elongated arc also breaks up faster when driven into the arc chute. On large fault currents, the contacts are driven apart so fast that the arc is extinguished before the first instantaneous peak current has been reached, thus reducing the peak let-through current and the thermal energy let-through values, similar to current-limiting fuses (see Section 7.3 and Figure 7.4). On 240 volt systems, the current-limiting ability of these slot motor breakers approaches that of class RK-1 fuses.

These new molded-case, current-limiting breakers are at present available in frame sizes of 100, 250, and 400 amperes, with interrupting ratings of 150,000 amperes at 480 volts and 200,000 amperes at 240 volts. Future developments are sure to expand the available types and ratings of these current-limiting breakers.

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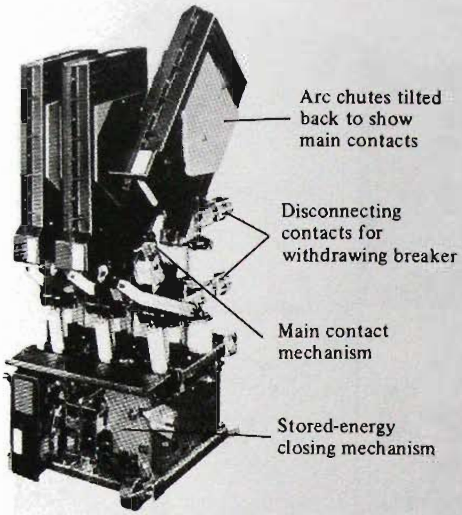
8.10 MEDIUM-VOLTAGE CIRCUIT BREAKERS

Medium-voltage circuit breakers are available in a wide variety of designs. They are primarily identified by the medium in which the main contacts interrupt the circuit: air, air blast, oil, or gas (SF_6). See Section 8.1 for a brief outline of the air blast, oil, and gas breakers. As discussed, these types of circuit breakers are relatively expensive and require extra facilities, such as complicated pressure equipment, fireproof vaults, or gas-tight enclosures. They are therefore primarily used on large power substations.

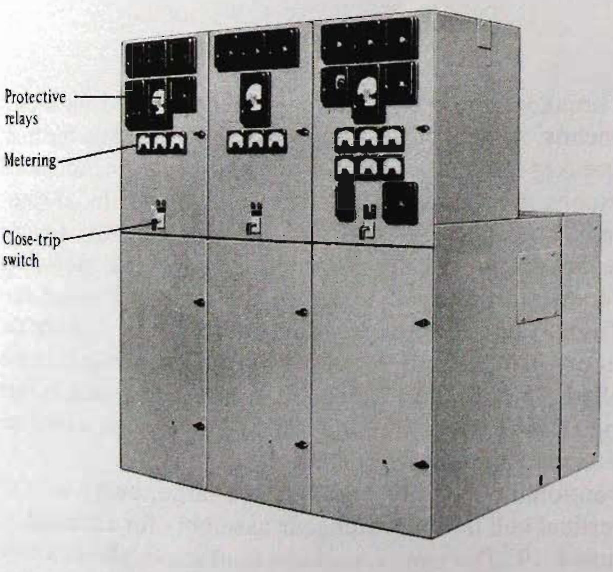
The air circuit breaker has long been the standard for industrial and commercial installations where power is received and/or distributed at voltages up to 15 kilovolts. Figure 8.19 shows a typical medium-voltage air circuit breaker, together with the type of metal-clad switchgear used to house the breakers. The medium-voltage air circuit breaker is basically an enlargement of the low-voltage power circuit breaker. They are naturally bulkier units, partly because of the larger insulators required for the higher voltages, but mostly because of the very large arc chutes required to handle the tremendous energy in the arcs during circuit interruption. Figure 8.19(a) shows the relative size of the arc chutes, which are the largest components of the breaker. These breakers are often referred to as magnetic air circuit breakers because of the importance of the magnetic field that drives the arc up into the arc chute. A blow-out coil is added to the center of the arc chute. During the circuit interruption, the arc current flows in series through this coil, materially increasing the magnetic field and thus rapidly forcing the arc further into the arc chute. Section 8.1 outlines the use of arcing contacts and arc chutes. Because of the higher inertia of the moving parts and the greater difficulty in extinguishing the arc at the higher voltages, the total time to fully interrupt the circuit can be as much as 5 cycles.

The breakers are mounted on wheels to permit them to be easily moved into and out of their switchgear cubicle [Figure 8.19(b)]. There are disconnecting contacts at the rear of the breaker by which electrical connections are made to the fixed plug-in contacts within the cubicle. The closing mechanism is the two-step, stored-energy, spring-powered type similar to that described for the low-voltage

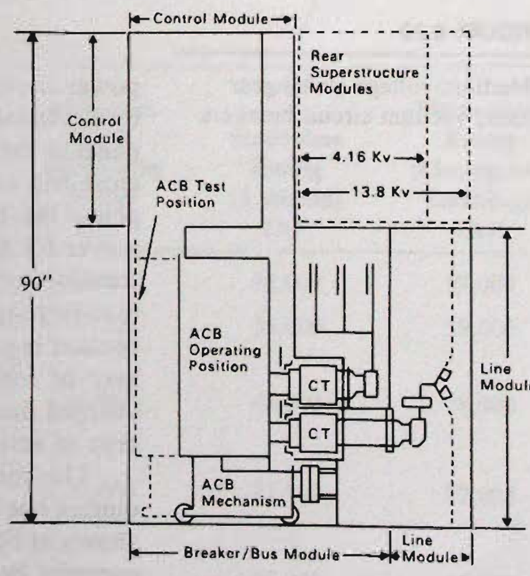


(a) Breaker shown with protective barriers removed

(b) Breaker being withdrawn from its cell



(c) Typical metalclad switchgear



(d) Section through one breaker cell

FIGURE 8.19

Medium-voltage air circuit breaker and switchgear assembly

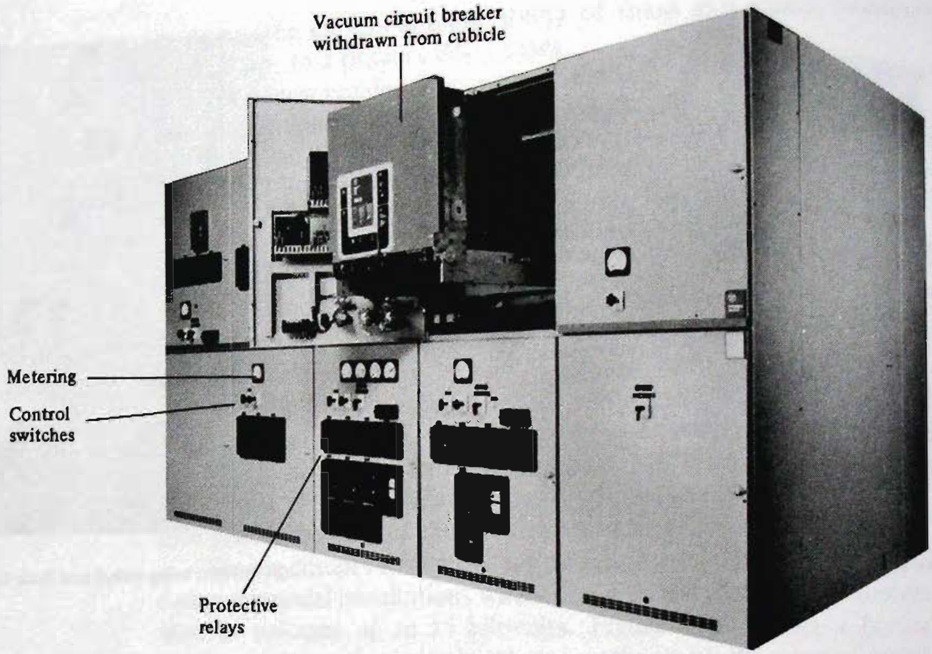


FIGURE 8.20

Medium-voltage switchgear using vacuum circuit breakers

power circuit breaker. The breakers are normally opened and closed by electrical means. A local close-trip switch is mounted on the front panel of the breaker cubicle, as shown in Figure 8.19(c). Additional close-trip switches can be added at remote locations. In an emergency the breakers can be opened and closed manually. Control power for the breaker is usually obtained from a small step-down transformer, connected to the lineside of the breaker through current-limiting fuses. For the critical power required to ensure that the breaker is properly tripped under fault conditions, separate batteries may be installed. If not, then a capacitor is used, which is kept charged during normal operation and which has enough stored energy to activate the shunt trip solenoid.

The conventional air circuit breakers are large, bulky units requiring one vertical cell in the switchgear assembly for each unit, as shown in Figure 8.19. The use of vacuum contactors allows a more compact breaker to be constructed. As mentioned in Section 8.1, there are problems with the interruption of currents in a vacuum. However, recent advances in the technology of vacuum circuit opening devices have overcome these problems. Medium-voltage vacuum circuit breakers up to 15 kilovolts are now available and are rapidly becoming the new standard for industrial and commercial installations in place of the magnetic air circuit breakers. Figure 8.20

shows a typical switchgear assembly using vacuum breakers. Note that two circuit breakers can be mounted in the one vertical section, allowing for more efficient use of space. The total floor space required for the installation of the switchgear can be reduced by as much as 50% compared to that required for conventional switchgear. This can be important in the restricted confines of a building.

Medium-voltage breakers are primarily circuit opening and closing devices. Unlike low-voltage breakers, they do not incorporate built-in automatic trip units. Separate protective relays are used to monitor the circuit conditions and then send an electrical signal to trip the breaker. The protective relays are normally mounted on the front panel of each circuit breaker cubicle, as shown in both Figures 8.19 and 8.20. Chapter 9 details the application of protective relays, together with the use of current and potential transformers.

Table 8.4 lists typical ratings for 5 and 15 kilovolt circuit breakers. Medium-voltage breakers are primarily rated by their nominal three-phase interrupting capacity in millions of volt–amperes (MVA). Because these breakers take 5 cycles to fully clear a fault, they must have a momentary rating that is a factor of 1.6 times their

TABLE 8.4 Typical Ratings for Medium-Voltage Air Circuit Breakers

Kilovolt Class	Nominal Three-Phase (MVA)	Rated Continuous Current (A)	System Voltage (kV)	Maximum Symm. Interrupting Rating (A)[a]	Short-time Rating (3 second) (A)[a]	Momentary Rating (Closing and Latching) (A)[a]
5 kV	75	1200	4.16	12,000	12,000	19,000
	250	1200 2000		36,000	36,000	58,000
	350	1200 2000 3000		49,000	49,000	78,000
15 kV	500	1200 2000 3000	13.8	23,000	23,000	37,000
	750	1200 2000 3000		36,000	36,000	58,000
	1000	1200 2000 3000		48,000	48,000	77,000

[a] rms values.

For a complete listing of all ratings, see ANSI standards.

rated short-circuit current (see Sections 6.5 and 6.6). These breakers have a 3 second short-time current-carrying capability, which allows for the tripping of the breaker on high fault currents to be delayed as necessary to ensure that all downstream devices closer to the fault operate first.

SUMMARY

The application of circuit breakers to system protection requires a detailed knowledge of their ratings, characteristics, and means of operation. Standard molded-case breakers are compact and relatively less expensive, but their generally lower interrupting ratings are a limiting factor in their application to large-capacity systems. Also, the fact that coordination between these breakers at high fault currents is not possible is a decided disadvantage. Power breakers are relatively more expensive and require more space, but they offer higher interrupting ratings and more flexibility in their operating characteristics. Also these breakers can be fully coordinated over the complete range of currents up to their interrupting ratings.

The following is a summary of the advantages and disadvantages of the standard circuit breakers as compared with fuses.

- Advantages

  - Can be safely opened under all load and fault currents up to their interrupting ratings
  - Can serve as both a means of protecting and of switching a circuit
  - Does not cause single phasing
  - Has repetitive operation, nothing to replace, no parts to stock
  - Are relatively tamper proof; operating characteristics cannot inadvertently be changed
  - Can be remotely operated
  - Undervoltage protection can be easily incorporated
  - Ground-fault protection can easily be incorporated

With the exception of the smaller molded-case breakers, further advantages are:

  - Tripping characteristics are not affected by the ambient temperature
  - Wide selection of operating characteristics and adjustments
  - UL listed for application at 100% of their designated current ratings

- Disadvantages

  - Higher initial cost
  - Larger and heavier, require much more space

— More complex, require maintenance
— Not basically a current limiting device; equipment being protected is subjected to higher thermal and mechanical stressing under fault conditions
— Not fail-safe; if the trip mechanism jams or the trip coil burns out, breaker can be left closed, creating a dangerous situation

QUESTIONS

1. Why is the use of a simple knife switch to interrupt large currents unreliable and unsafe?
2. What are three means by which circuit-opening devices can be made to safely interrupt large currents?
3. What is the purpose of an arc chute?
4. What is meant by a three-pole, gang-operated breaker?
5. When is electrical operation of breakers required?
6. Describe the stored-energy method of closing breakers.
7. What is meant by trip-free?
8. What breaker ratings are set by the frame size?
9. What is the significance of the trip rating of a breaker?
10. Describe how the series trip units operate to trip a breaker.
11. What physical characteristic differentiates the molded-case breaker from the standard power breaker?
12. Explain the thermal–magnetic trip unit as used on the standard molded-case breaker.
13. Describe the adjustable instantaneous trip unit as used on the larger molded-case breakers.
14. On breaker time–current characteristic curves such as Figure 8.7, why is it necessary to have a tolerance band as defined by the maximum and minimum lines?
15. How are frame sizes designated?
16. What is the major limitation to the use of standard molded-case breakers on large systems?
17. For a molded-case breaker with a 100 ampere trip unit, what is the maximum clearing time permitted at 200 amperes?
18. Why is a molded-case breaker tested at 600% of its normal current rating?
19. What is the definition of the low-voltage power circuit breaker?
20. What are the advantages of the drawout-type breaker?
21. How does a shunt trip coil operate to trip a breaker?
22. Why have the solid-state trip units largely replaced the mechanical dual-magnetic trip units on power circuit breakers?
23. What is the function of the sensors?
24. What does the pickup current represent?
25. Why does a power circuit breaker have a short-time rating?
26. With reference to Figure 8.14, why is there a lack of coordination between the two breakers above 2700 amperes?
27. Why were combination fused circuit breakers developed?
28. Which features does the encased circuit breaker incorporate from the molded-case and the power circuit breaker?
29. What advantages does the encased circuit breaker have over the power circuit breaker?
30. How does the molded-case current-limiting breaker provide the current-limiting feature?
31. Why are protective relays normally required to be used with medium-voltage breakers?
32. What is the major disadvantage of using oil circuit breakers for indoor installations?

PROBLEMS

1. Using Figure 8.7, for a breaker with a 150 A trip unit, determine the maximum and minimum tripping times for a current of 450 A.
2. Repeat Problem 2, except with a 50 A trip unit at 500 A.
3. Using Figure 8.8, for a breaker with a 300 A trip

unit, determine the maximum and minimum tripping times for a current of 1200 A?

4. Repeat Problem 3, except with a 400 A trip unit.
5. A 400 A frame breaker has a 200 A trip unit. The adjustable instantaneous unit is set at 10 times. Determine the current at which the breaker will be instantaneously tripped (ignoring tolerance allowance).
6. In Problem 5, with a tolerance allowance of ±10%, over what range of currents could the breaker actually be tripped instantaneously?
7. A 600 A frame power circuit breaker has a solid-state tripping unit with 400 A sensors. The long delay is set at 0.9 on the dial. Calculate the current at which the long delay timing will pickup.
8. Repeat Problem 7, except the breaker has a 2000 A frame, 1600 A sensors, and the dial is set at 1.0.

9 Instrument Transformers and Protective Relays

OBJECTIVES

After studying this chapter, you will be able to:

- Explain the use of instrument transformers to represent power circuit voltages and currents.
- List the accuracy classifications of instrument transformers.
- Recognize the effect of burden on the accuracy of instrument transformers.
- Outline the special operating features of current transformers.
- Recognize the forms of construction of current transformers.
- Detail the basic operation of the electromagnetic type of overcurrent relay.
- Determine the time delay and instantaneous response of overcurrent relays.
- Detail the sequence of operation of the trip circuit for the circuit breaker.
- Recognize the application of directional relays.
- Recognize the application of differential relays.

INTRODUCTION

Many breakers have no built-in intelligence; that is, they have no ability to directly monitor the system parameters and to initiate action when abnormal or dangerous conditions arise. The function of the protective relay then is to provide this intelligence. Normally, protective relays are required for medium- and high-voltage breakers as these types are usually just circuit opening and closing devices, as discussed in Section 8.10. On the other hand, low-voltage breakers normally have integral trip units, although they too can be used in conjunction with separate protective relays when special requirements must be met.

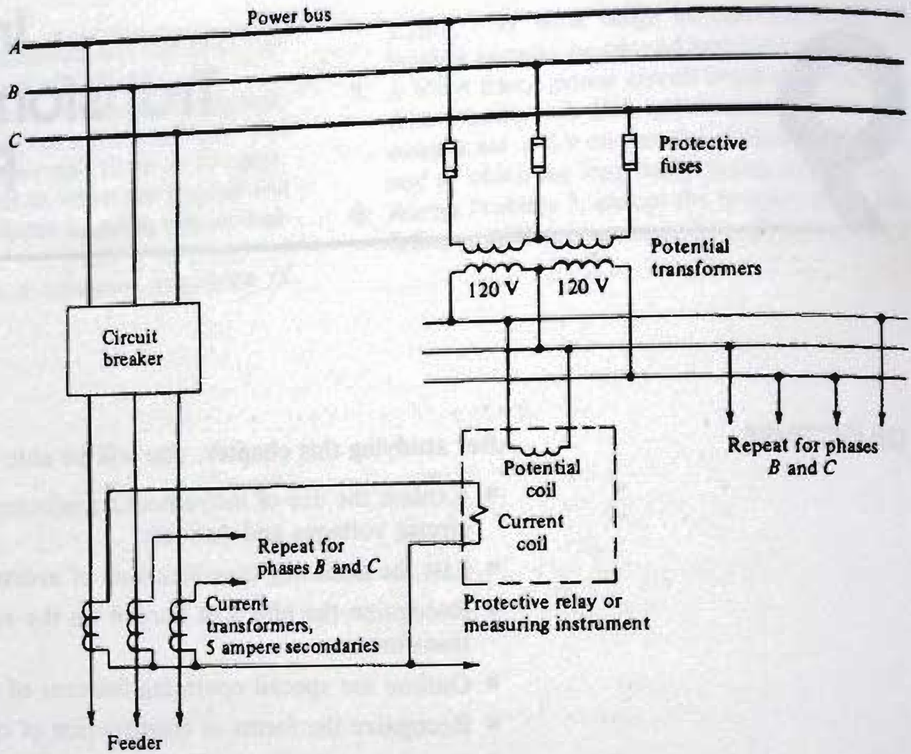


FIGURE 9.1

Typical instrument transformer connections to a power system

The protective relays themselves cannot be directly connected into the electrical power circuits. Separate sensors, in the form of *potential* and *current transformers*, are required to reduce the power circuit voltages and currents to levels that are compatible with the detection units of the protective relays and measuring instruments. Potential transformers (PTs) and current transformers (CTs) are classified as *instrument transformers* to differentiate them from power transformers. Figure 9.1 shows the typical interconnections when both the voltage and current parameters of a system are required for the operation of the protective relays and/or measuring instruments. The instrument transformers are discussed first, followed by the types and applications of protective relays.

There are literally hundreds of different types of protective relays. Some respond to current magnitude only, while others not only respond to the magnitude of the current but also to its direction (to the direction of power flow). Others operate on a differential principle (they compare values), while others operate on an impedance principle (distance to the fault location). Complex systems, which have many sources of power and different voltage levels, require sophisticated protection systems using many special types of relays.

The application of these more complex relays to such systems is beyond the scope of this book. The material presented in this chapter covers only the basic application of relays for the overcurrent protection of feeders, for monitoring the direction of power flow, and for the differential protection of equipment.

9.1 INSTRUMENT TRANSFORMERS

The purpose of instrument transformers is to represent, with acceptable accuracy, the primary (the power) circuit conditions of voltage, current, and phase position in the secondary circuits to the protective relays and measuring instruments. There are two types: potential transformers (PTs) and current transformers (CTs). They have two basic functions. The first is to transform the high voltages or high currents of the power circuit down to a common secondary base, generally 120 volts and 5 amperes. The second is to isolate the operating coils of the protective relays and measuring instruments from the high potentials of the power system. The use of the common base of 120 volts and 5 amperes allows the relays and meters to be standardized.

All transformers operate basically on the same principle as outlined in Section 1.7. The turns ratio of a transformer is the number of turns on the primary winding divided by the number of turns on the secondary winding. If there were no losses in the transformer, then the primary and secondary voltages would be exactly proportional to the turns ratio, and the primary and secondary currents would be exactly inversely proportional to the turns ratio. However, the transformer does have losses. There are heat losses caused by the flow of current through the windings and core losses caused by the alternating magnetic field in the iron core. Also, there is a magnetizing component of the primary current, which is required to create the magnetic flux, and there are voltage drops caused by the impedances of the windings. As a result of all these factors, the secondary voltage and current cannot exactly represent the primary voltage and current; that is, there are errors in the transformation. The amount by which the ratio of the primary voltage or current to the actual secondary voltage or current differs from the turns ratio (the nameplate ratio) is known as the *ratio error*. The amount in minutes (1 degree = 60 minutes) by which the phase angle of the voltage or current differs from its correct position is known as the *phase angle error*. Where instrument transformers are used for metering purposes, the errors must be small, that is, a maximum of 1.2% for the ratio error and a maximum of 60 minutes for the phase angle error. Where instrument transformers are used only for relaying purposes, the accuracy is not so critical. Ratio errors can be as high as 10% under certain conditions. This is discussed in more detail for each type of instrument transformer.

9.2 POTENTIAL TRANSFORMERS

Potential transformers are connected to the power system as shown in Figure 9.1. Their primary windings are normally protected by current-limiting power fuses (Section 7.8.2). The turns ratios are selected so that at rated primary voltage there is 120 volts at the secondary terminals. A typical potential transformer with the primary fuses mounted on the top is shown in Figure 9.2.

The operation of a potential transformer is the same as that of a power transformer except that the currents are much smaller. The secondary current and hence the primary current are set by the amount of load connected to the transformer. The loads are connected in parallel, and the secondary current increases as more load is connected. The primary and secondary voltages are relatively constant and are largely independent of the load. The loads connected to a potential transformer are the potential coils of protective relays and measuring instruments, such as voltmeters and wattmeters. To differentiate this load from that connected to the power circuit being measured, the potential transformer load is known as the *burden*. The burden is expressed in volt–amperes, that is, the voltage (usually 120 volts) times the total secondary current drawn by the relays and instruments. To keep the transformer ratio error to an acceptable value, the volt–ampere burden must be limited. Potential transformers are classified by their accuracy at specified levels of burden. Table 9.1 shows the standard accuracy classifications, together with the allowable burdens. These burdens are designated by letters that indicate the volt–amperes and minimum power factor. For example, a potential transformer classified as 0.3 Y has a maximum of 0.3% ratio error and 15-minute phase angle error with a

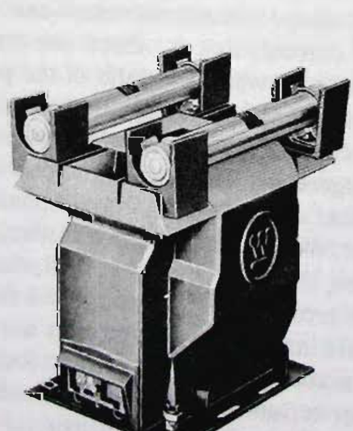


FIGURE 9.2

Potential transformer complete with primary fuses

TABLE 9.1 Standard Accuracy Classifications and Burdens for Potential Transformers

Accuracy Classifications

Maximum Percentage Ratio Errors	Maximum Phase Angle Error (min)
0.3	15
0.6	30
1.2	60

Standard Burdens

Letter Designation	Volt–Amperes at 120 Volts	Minimum Power Factor
W	12.5	0.10
X	25.0	0.70
Y	75.0	0.85
Z	200.0	0.85
ZZ	400.0	0.85

burden of 75 volt–amperes at 120 volts and a power factor of 0.85. The permissible burden for accuracy is much lower than that which the transformer can handle before overheating, which is its thermal rating. For example, this same transformer may have a thermal rating of 750 volts–amperes.

9.3 CURRENT TRANSFORMERS

The primary windings of current transformers (CTs) are connected in series with the circuit to be monitored as shown in Figure 9.1. The primary winding must be insulated for the higher voltage level of this circuit. The rated current of the primary winding should be from 110% to 125% of the full-load current of the circuit to prevent the CT from overheating in the event of minor overloading. The current transformer ratio (the turns ratio) is then selected to give a rated secondary current of 5 amperes. For example, a 1000/5 ampere CT produces a 5 ampere secondary current when the primary current is 1000 amperes. This CT has a turns ratio of 1000/5 or 200. It should be used with a circuit that has a full-load current in the range of 800 to 900 amperes.

A current transformer operates on the same principle as other transformers, that is, with regard to turns ratio, magnetizing current, and so on. However, the manner in which it is connected into the system causes it to display much different operating characteristics.

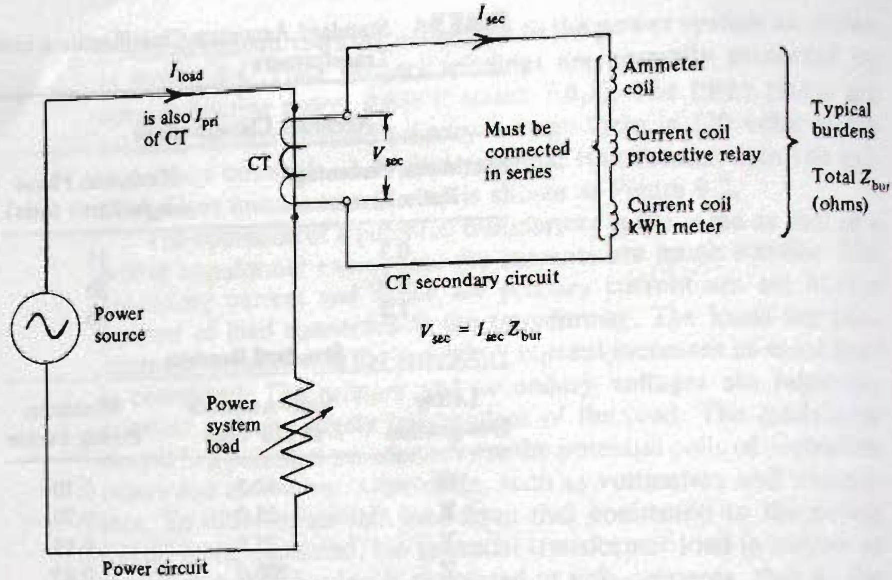


FIGURE 9.3

Simplified single-phase schematic diagram of the circuit connections for a current transformer

Figure 9.3 shows a simplified single-phase schematic diagram of the circuit connections of a CT. The loads connected to a CT are the current coils of protective relays and measuring instruments, such as ammeters, wattmeters, and the like. As shown in the diagram, these loads are connected in series since the same current must flow through each coil. Once again, to differentiate the CT load from that connected to the power circuit being monitored, the CT load is known as the *burden*. However, because of the series connection, the burden is expressed in total ohms of impedance at a specified power factor.

The operating characteristics of a current transformer differ significantly from those of power and potential transformers. First, the primary current of the CT is solely a function of the power circuit load and not of the secondary load (burden) as is normally the case with transformers. The secondary current is the reflected value of the primary current and, therefore, it too is independent of the burden on the secondary of the CT. Second, the CT voltages vary directly with the current, whereas with other transformers the voltages are largely independent of current. As shown in Figure 9.3, the CT secondary voltage is equal to the product of the secondary current and the burden in ohms. If this secondary voltage becomes excessive, the transformer will be driven into saturation, and the ratio error and phase angle error will increase very rapidly. Therefore, to keep these errors to acceptable values, the total burden permitted to be connected to a current transformer must be limited.

Similar to potential transformers, current transformers, when used for metering purposes, are classified by their accuracy at specified values of burden. Table 9.2 shows the standard accuracy classifications (which are the same as for PTs), together with the standard burdens in ohms at a minimum power factor. For example, a current transformer designated 0.3B-2.0 has a maximum of 0.3% ratio error with a burden of 2.0 ohms at 0.5 power factor. Manufacturers list the burdens of the current coils of their protective relays and meters. The total burden of all the current coils of the equipment to be connected in series to the one CT is first calculated. Then the proper classification of CT can be selected. If the total burden is excessive, two sets of CTs are required to split the burdens so that the required degree of accuracy can be obtained.

When a current transformer is used only for protective relaying service, the accuracy is not so critical. However, since the protective relay must respond properly well up into the short-circuit range, the errors with these high currents must not be too excessive. When a fault occurs on the power circuit, the secondary current should be the reflected value of the high primary current. With a fixed burden on the secondary and with this high secondary current, the secondary voltage must rise accordingly. If this high voltage drives the

TABLE 9.2 Standard Accuracy Classifications and Burdens for Current Transformers

Accuracy Classifications

Maximum Percentage Ratio Error	Maximum Phase Angle Error (min)
0.3	15
0.6	30
1.2	60

Standard Burdens

Burden Designation	Impedance (ohms)	Minimum Power Factor
B-0.1	0.1	0.9
B-0.2	0.2	0.9
B-0.5	0.5	0.9
B-0.9	0.9	0.9
B-1.0	1.0	0.5
B-2.0	2.0	0.5
B-4.0	4.0	0.5
B-8.0	8.0	0.5

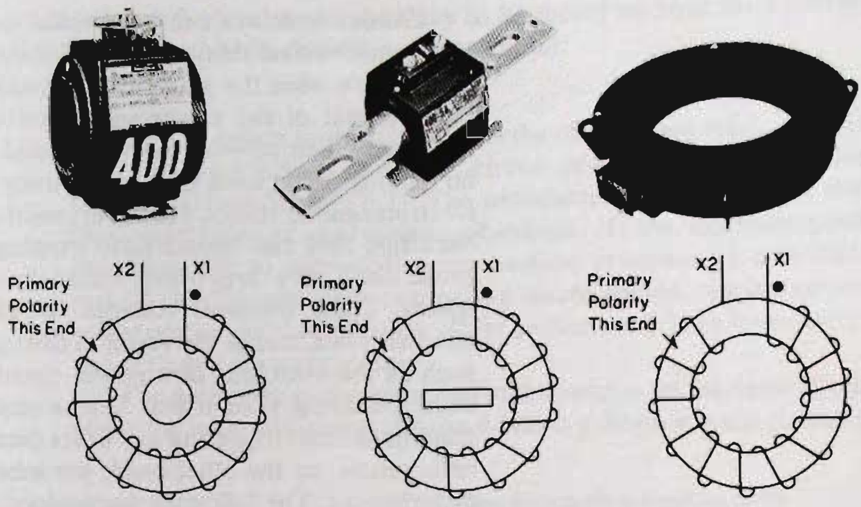
transformer too far into saturation, the ratio error becomes significant, and the actual CT secondary current no longer reasonably represents the primary (the short circuit) current. Therefore, the measure of the current transformer's ability to perform properly under high fault current conditions is the value of the highest secondary voltage that it can induce without severe saturation and consequent large errors.

There are two ratio accuracy standards, 2.5% and 10%. There are two performance classifications, H and L. For the H classification, the maximum stated voltage can be induced without exceeding the specified error at any secondary current from 5 to 20 times normal (25 to 100 amperes). For the L classification, the maximum stated voltage can be induced without exceeding the specified error at 20 times normal current only. The H classification is more generally used. The standard voltage ratings are 10, 20, 50, 100, 200, 400, and 800 volts.

As an example, a current transformer designated 2.5H100 has a maximum ratio error of 2.5% as long as it does not have to induce more than 100 volts at any secondary current between 5 and 20 times normal. Current transformers that are to be used for relaying applications are physically much larger than those used just for metering, as they must have much larger magnetic cores to prevent saturation at the higher voltages. A current transformer can have both a metering and a relaying classification. For example, a CT may be labeled 0.3B2.0 for metering and 2.5H100 for relaying.

The secondary circuit of a current transformer must never be open circuited when under load conditions. Refer again to Figure 9.3. If the secondary circuit is broken at any point (for example, at the drawout contacts of a protective relay), there can be no secondary current. However, current continues to flow through the primary winding of the CT, as this is the load current of the power circuit. With no secondary current, all the primary current becomes the magnetizing current, which drives the magnetic core of the transformer deep into saturation. This causes the secondary voltage to rise to dangerous values, which can result in flash-overs. This arcing would cause severe damage to the delicate components of the relays and meters. In addition, it creates a hazardous situation for maintenance personnel. Therefore, current transformers are equipped with a shorting bar that must be placed between the secondary terminals before any work is done on the secondary circuit and removed only when the circuit has been fully reconnected. Drawout protective relays have means of automatically shorting their current circuits before they can be withdrawn from their cases (see Section 9.4).

Current transformers have two basic types of construction: the through-type, which is the most common, and the wound primary.



(a) Window type (b) Bar type (c) Bushing type

FIGURE 9.4

Three forms of through-type current transformers

Figure 9.4 shows three forms of through-type construction. The window-type CT has the secondary winding permanently assembled on the transformer core. There is no fixed primary winding. The CT is installed with one phase of the feeder, either a cable or a bus bar, passing straight through the opening in the center of the transformer. This feeder conductor then becomes the primary winding, since it forms one turn by virtue of the complete return loop of the power circuit. The bar-type CT similarly has the secondary winding permanently assembled on the transformer core, but it also has a permanent primary winding in the form of an insulated bar passing directly through the center of the core. The bushing-type CT is similar to the window type, but it is specifically designed to be mounted as part of the insulated bushing used on equipment such as a circuit breaker or transformer. The conductor passing through the center of the bushing forms the primary winding of the CT. The wound primary type of current transformer has a primary winding of two or more turns. Both the primary and secondary windings are insulated and are permanently mounted on the transformer core.

9.4 PROTECTIVE RELAYS (GENERAL)

The *protective relay* is defined as *a device that causes an abrupt change in an electrical control circuit when the measured quantity to which it responds changes in a prescribed manner*. The electrical control circuit is usually the trip circuit of a circuit breaker, and the measured quantity is the power circuit current and/or voltage as represented by the instrument transformers.

Protective relays can be divided into two fundamental types: electromechanical relays and solid-state relays. Electromechanical relays have been the standard for many years and, in spite of the development of the newer solid-state units, are still widely used because of their proven reliability. Solid-state units, since they have no moving parts, have greater accuracy and faster reset times than electromagnetic relays. However, solid-state relays have the drawback that they can initiate false tripping of the circuit breakers because they may improperly react to spurious transient voltage spikes. These transient voltages, which may only last for a few microseconds, can be the result of disruptions on the power system, such as the switching of a power circuit. A solid-state relay must have a filtering system that blocks any chance of these transient conditions from triggering any of its detection circuits. Electromagnetic relays, on the other hand, are inherently immune to transient disturbances. The following discussions refer to electromagnetic relay types. Solid-state relays can offer the same operating characteristics and, in fact, usually use the same type of housing and terminal arrangements, so they are virtually interchangeable with electromagnetic units.

The typical protective relay is housed in a drawout type of case as shown in Figure 9.5. The case is designed for recessed mounting in a panel, such as shown in Figures 8.19 and 8.20. The external wiring from the instrument transformers and the breaker control circuit are connected to terminals on the rear of the relay case. Internal connections to the operating unit of the relay are made through sliding contacts so that the unit can be withdrawn without having to disconnect any wiring. As discussed in Section 9.3, the secondary connections of a current transformer should never be open circuited when they are energized. Therefore, as the relay unit is withdrawn, any CT connections to the relay are automatically shorted together, thus maintaining the CT secondary circuit. The

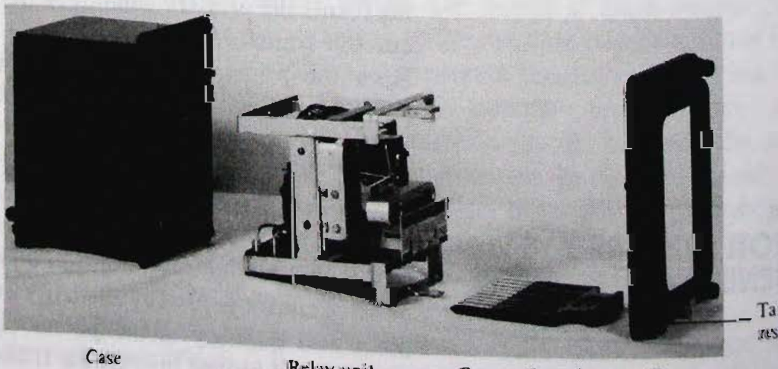


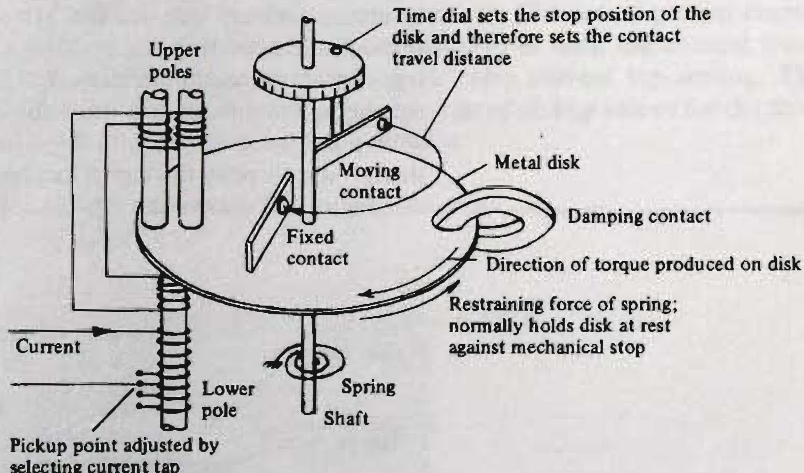
FIGURE 9.5

Exploded view of a protective relay showing the drawout feature drawout feature allows the relay to be tested without the necessity of having to shut down the power circuit.

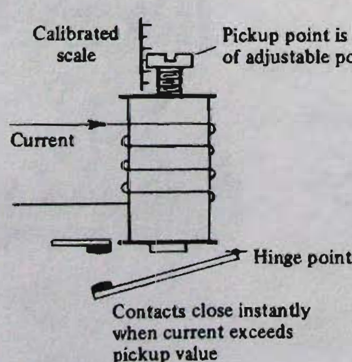
9.5 OVERCURRENT RELAYS

The most common protective relay is the overcurrent relay, which is used for the overload and short-circuit protection of feeders and equipment (see Section 6.1). The overcurrent relay normally uses two basic types of operating mechanisms, (1) the electromagnetic induction unit to provide the inverse-time response on overloads, and (2) the electromagnetic attraction unit to provide the instantaneous response on short circuits. Refer to Section 6.7 for inverse-time and instantaneous responses.

The electromagnetic induction unit operates on the same principle as the induction motor. Figure 9.6(a) is a diagrammatic represen-



(a) Electromagnetic induction unit



(b) Electromagnetic attraction unit

FIGURE 9.6

Diagrammatic representation of the operating units of an overcurrent relay tation of this type of unit. The moving element (the rotor) is simply a metal disk mounted on a vertical shaft. The operating current coils (the stator) create a magnetic field that induces eddy currents in the metal disk. These eddy currents interact with the magnetic field to produce a torque on the disk. The rotation of the disk is initially restrained by a spring until the torque is sufficient to overcome the spring tension. A damping magnet is used to stabilize the rotation of the disk after it starts moving. A contact is attached to the shaft of the disk, and when this contact eventually touches the fixed contact, the tripping sequence of the breaker is initiated (see Section 9.5.2). The timing function of the unit is a combination of the rate at which the disk rotates, which is dependent on the current, and the contact travel distance, which is set by the time dial.

The electromagnetic attraction unit is a simple solenoid that attracts a hinged armature, as shown in Figure 9.6(b). The operation is instantaneous; that is, the armature moves when the current through the operating coil reaches a prescribed value and snaps the trip contacts closed immediately. This is the same principle as used for the instantaneous trip units for the molded-case circuit breaker shown in Figure 8.5(b), with the difference that in the latter case the device acts directly through a mechanical linkage to trip the breaker.

Figure 9.7 shows the typical construction of an overcurrent re-

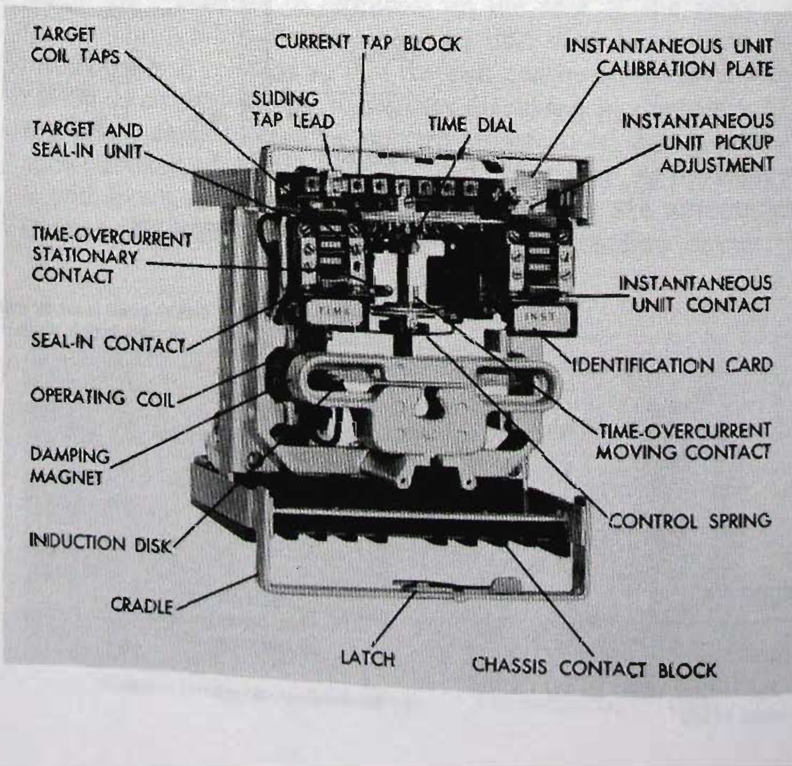


FIGURE 9.7

Induction disk overcurrent relay with instantaneous unit (relay withdrawn from its mounting case) lay. The settings and response characteristics of the relay are outlined in the next section.

9.5.1 Settings and Response Characteristics

The induction disk inverse-time unit of the overcurrent relay has two different adjustments, the current pickup setting and the time dial setting.

The current pickup adjustment is provided by a series of taps on the operating current coil, as shown in Figure 9.6(a). The term *pickup* refers to *the point at which the disk on the unit just starts to move and therefore to start its timing function*. Relays are available with three different ranges of taps: 0.5 to 2.0 amperes, 1.5 to 6.0 amperes, and 4 to 16 amperes. As an example, the 1.5 to 6.0 range has taps for 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, and 6.0 amperes. The current coil of the induction unit is connected to the secondary of the current transformer as shown in Figure 9.9 so that it responds to the magnitude of the power circuit current. The actual pickup current for the power circuit then is a function of both the current transformer ratio (Section 9.3) and the relay current tap setting. This allows for the selection of a wide range of pickup values for the time-delayed tripping of a circuit breaker.

EXAMPLE 9.1

The current transformer is rated 400/5 A. The tap on the relay is set at 4.0 A. Determine the current in the power circuit at which the inverse-time (induction) unit will pick up and begin its timing function.

Solution

— The ratio of the CT is 400/5 = 80.
— The circuit pickup current is 80 × 4 = 320 A.

The time dial setting on the induction unit controls the actual time at a specific current to close the trip contact. The adjustment is accomplished by varying the distance that the disk has to rotate from its normal stop position to the point where the contacts close. This is shown in Figure 9.6(a). The distance (and hence the time) is set by rotating the time dial on the shaft of the moving disk. The dial is marked in intervals numbered from 0 to 10. At the 0 setting, the time is zero as the contacts are already closed. The time increases as the dial is turned toward 10. Figure 9.8 shows the family of time–current curves for the typical overcurrent relay. Each curve represents the response of the unit for the indicated setting of the time dial. Note that the horizontal scale is the current in multiples of the relay tap setting.

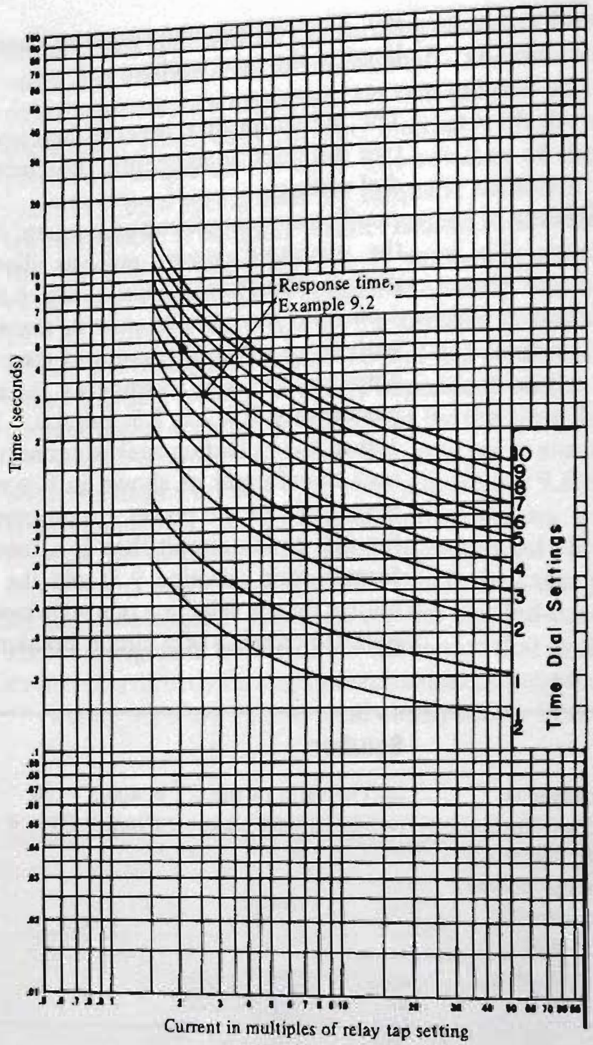


FIGURE 9.8

Overcurrent relay time–current curves (typical inverse characteristics)

■ EXAMPLE 9.2

Continuing with Example 9.1, the time dial on the relay is set at 5. Determine the response time of the inverse-time unit for a power circuit current of 800 A.

Solution

— The CT ratio is 80, as before.
— The CT secondary current is 800/80 = 10 A.
— The 10 A is 10/4 = 2.5 times the relay tap setting.
— From Figure 9.8, the time is 3 s.

Overcurrent relays can be made with different degrees of inverse time–current characteristics. The curves shown in Figure 9.8 are for the standard inverse-time relay. By modifying the design of the induction disk unit, the rate at which the time decreases with increases in current can be altered. For example, relays with very inverse and extremely inverse time–current characteristics have progressively steeper curves than those shown in Figure 9.8. The type of time–current characteristic is selected so that the relay can best coordinate with the other protective devices in the system.

The instantaneous unit of the overcurrent relay has only the one adjustment, that being for the pickup current. The timing function is instantaneous (no intentional time delay). The pickup current is set by adjusting the air gap on the electromagnetic unit as shown in Figure 9.6(b). Two ranges of settings are normally available: 10 to 40 amperes and 20 to 80 amperes. Similar to the induction unit, the actual pickup current for the power circuit is the current transformer ratio times the value of the current setting on the instantaneous unit of the relay.

EXAMPLE 9.3

Continuing with Example 9.1, the instantaneous unit is set at 30 A. Determine the current in the power circuit at which the instantaneous unit will pick up and trip the breaker.

Solution

— The CT ratio is 80, as before.
— The circuit pickup current is 80 × 30 = 2400 A.

9.5.2 Sequence of Operation for Tripping the Breaker

First, let us refer back to Section 8.2 and Figure 8.2 with regard to the operation of a circuit breaker. The breaker is tripped by energizing the shunt trip coil, which then mechanically releases the contact latching mechanism, allowing the breaker to open and interrupt the power circuit. For breakers controlled by protective relays, there would be no series trips.

Refer to Figure 9.9 for the schematic diagram of the current and trip circuits for the overcurrent relay. One current transformer and one relay are required for each phase of the power circuit being protected. The current coils (ID and IS) for each relay are connected in series with the output of the respective phase CT. Ground-fault protection can also be obtained by connecting the current coils of a fourth relay into the neutral return, as shown in the diagram. See Section 10.5 for ground-fault protection.

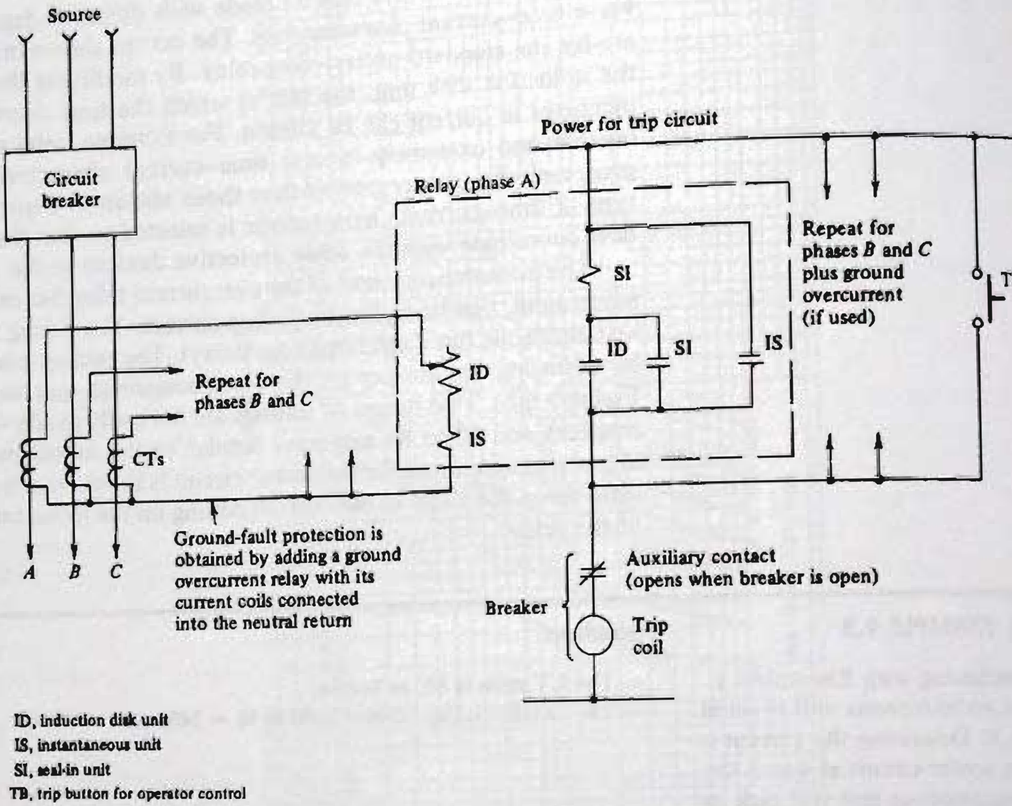


FIGURE 9.9

Schematic diagram of the current and trip circuits for the overcurrent relay

The trip circuit has some special features to ensure that the breaker is properly tripped once any one relay contact closes. As shown in the schematic diagram, each relay includes a seal-in unit, which is required to overcome the possibility of contact bounce on the induction disk unit. Once the current in the operating coil exceeds the pickup value, the induction disk starts to turn. If the overload current continues, as shown in Figure 9.6(a), the moving contact will eventually touch the fixed contact. This is shown as contact ID in the schematic diagram. As soon as contact ID closes, the circuit to the breaker trip coil is completed. The coil for the seal-in unit (SI), which is in series in the trip circuit, is immediately energized, closing contact SI. Contact SI is in parallel with contact ID and, therefore, even if contact ID were to bounce open after its initial contact, the trip circuit is now sealed in and the trip coil can be fully energized and can positively complete the tripping action of the breaker. When the breaker is fully opened, an auxiliary contact on the breaker snaps open, thus de-energizing the trip circuit. Note that the trip contacts of each phase relay, and the ground relay if used, are connected in parallel so that an overcurrent or ground fault on any phase will trip the breaker.

Reviewing the results of Examples 9.1, 9.2, and 9.3, the relays in Figure 9.9 (with the same CT ratios and relay settings) would protect the power circuit as follows. If the circuit current exceeds 320 amperes (there is an overload on the circuit), the induction disk unit picks up and, after the time interval associated with the curve for the time dial setting of 5, closes contact ID. The tripping sequence of the breaker is then completed as previously outlined.

At the same time, the operation of the seal-in unit mechanically releases its target, which then indicates that the breaker has been tripped on an overload. The target is a colored disk located on the front of the seal-in unit, as shown in Figure 9.7. If the circuit current exceeds 2400 amperes (there is a fault on the circuit), then the instantaneous unit picks up, closing contact IS (Figure 9.9), which bypasses the induction unit contact ID and immediately trips the breaker. At the same time, the operation of the instantaneous unit mechanically releases its target, which then indicates that the breaker has been tripped because of a fault on the power circuit.

As shown in Figure 9.9, a separate source of supply is normally used for the trip circuits. On large installations, where an extremely reliable source is desirable to ensure the proper tripping of the breakers regardless of the state of the main power system, batteries are used. On smaller systems, where the cost of separate batteries and associated charging equipment may not be warranted, special ac tripping units can be utilized. When the relay operates on an abnormal condition, this tripping unit transfers the current from the secondary of the current transformer into the trip circuit of the breaker. The CT then provides the momentary energy required to activate the trip coil and release the breaker.

9.6 DIRECTIONAL RELAYS

All the protective devices previously discussed (fuses, low-voltage circuit breakers, overcurrent relays) respond only to the magnitude of the current being monitored; that is, they are nondirectional. The directional relay has the ability to also respond to a change in the direction of the current, that is, to the change in direction of the power flow in a circuit. For this reason, the relays are often referred to as power directional relays.

The reversal of current in an ac system means the reversal of the instantaneous direction of the current with respect to the voltage. Therefore, for the relay to be able to detect the current direction, there must be a voltage reference. First, refer to Figure 9.6(a) for the induction unit. The flux created by both the upper and lower poles is a function of the current (the upper pole by induction). Therefore, the torque produced on the disk is a function of only the magnitude of the current and is always in the same direction, regardless of the direction of the current.

Refer now to Figure 9.10(a). The change for the directional relay is that the flux created by the upper pole is now a function of the system voltage. Through the use of phase shifting circuits within the relay, the torque produced on the induction disk is greatest when the system current is in phase with the system voltage (at unity power factor). By the proper selection of the current and potential transformer polarity connections, the torque is made to be counterclockwise when the power flow is in the desired direction, which then

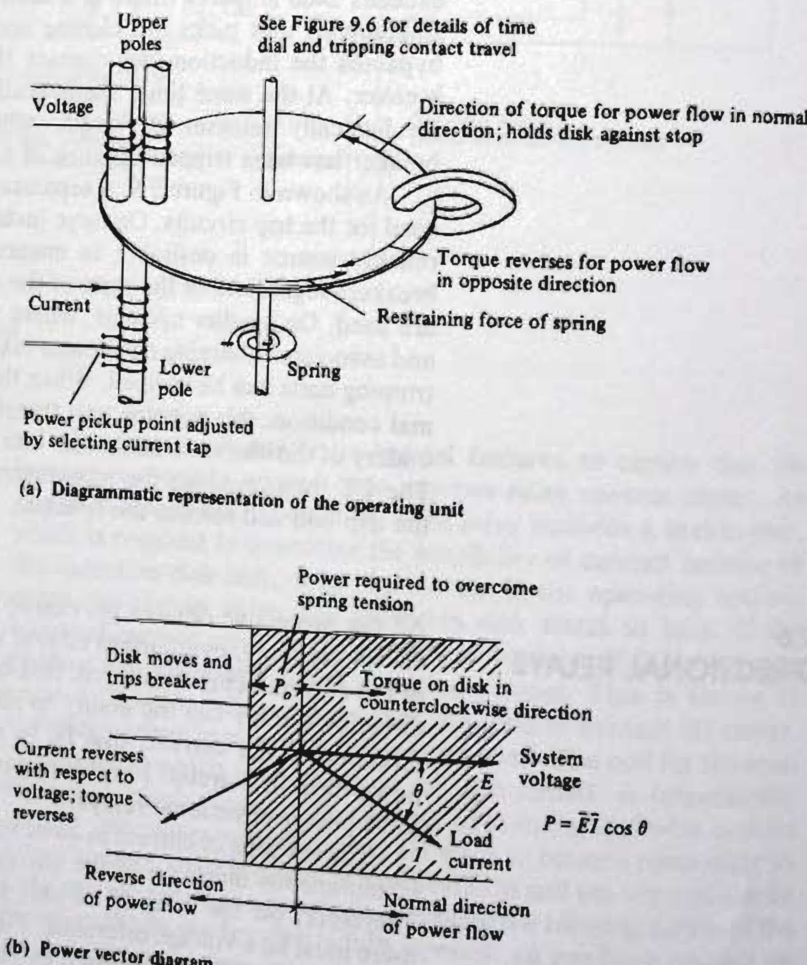


FIGURE 9.10

Method of operation of the directional relay holds the disk against the stop. The relay then ignores any power flow in that direction. However, if the current now reverses with respect to the voltage (that is, the power flow reverses direction), the torque on the disk also reverses and the disk moves in a clockwise direction. The relay then begins its timing function similar to the overcurrent relay. To prevent the relay from responding to very minor reversals of current, which could be the result of power surges on the system, a retarding spring is used. The spring tension prevents the disk from moving until there is a minimum amount of reverse power flow (P_o on diagram). This minimum power is adjusted by means of taps on the relay and is normally set to be a small percentage of the power that flows in the preferred direction. Figure 9.10(b) shows the power vector diagram for the operation of the directional relay.

There are many applications for the power directional relay. One example is an industrial plant that has an in-house generator to supply its own needs. There is also a normally closed feeder to a large electric utility system for the purpose of supplying any excess demand within the plant or to pick up the load if the in-house generator fails. However, if something abnormal happens on the utility system, power may suddenly be flowing out from plant and into the large load on the utility system. This could rapidly overload the in-house generator and shut it down. To prevent this shutdown, power directional relays are used to monitor the feeder connection to the utility. As soon as the set amount of power is detected flowing in the wrong direction (out of the plant), the breaker controlling this feeder is tripped, thus keeping the in-house system intact and operating.

Another example for the use of power directional relays is when there are two service feeders into a plant, each with its own transformer. The secondaries of the transformers are permanently connected in parallel so that failure of one service feeder or transformer does not disrupt any part of the load being fed. Figure 9.11 shows the one-line diagram for this arrangement. This type of connection, however, creates an unusual problem with regard to protecting the system. Assume that a fault occurs on the primary of transformer 2 (point × on the diagram). The primary fuses for transformer 2 would immediately blow, disconnecting feeder 2. However, the fault will be back-fed from the still energized secondary bus through transformer 1. To prevent this back-feed from continuing, the secondary breaker is equipped with directional relays that will immediately trip the breaker as soon as there is any reversal of current. Only then is the fault completely isolated. Both secondary breakers must be similarly equipped to cover faults on either transformer. Separate overcurrent relays are used for the protection of the system for normal power flows.

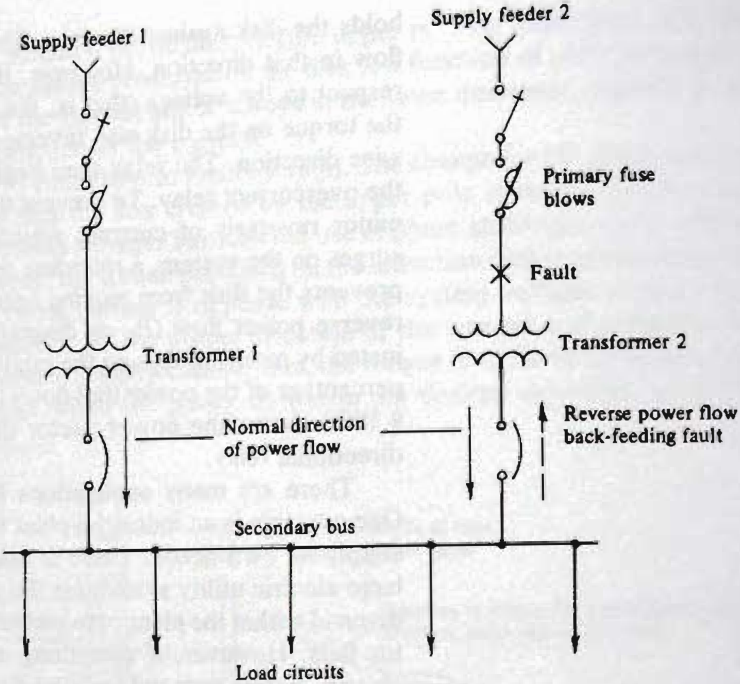


FIGURE 9.11

Parallel operation of two transformers

9.7 DIFFERENTIAL RELAYS

The differential relay responds to the difference between two measured values of current. If conditions are normal, the current flowing into a piece of equipment (a generator or motor) must equal the current leaving the equipment. If the input and output currents are not equal, this can only mean that there is an electrical fault within the equipment. It is the function of differential relays to monitor the two sets of currents. In the event that there is a set percentage difference between them, the relays operate to trip the necessary breakers and isolate the faulted piece of equipment.

Figure 9.12 shows the connections of the differential relays to the system through the current transformers. As long as currents I_1 and I_2 are balanced, there is no current through the operating coil. As soon as there is an unbalance, the difference between the two currents flows through the operating coil, thus causing the relay to operate.

Differential protection of equipment permits the detection of internal arcing faults as low as 10% of the normal load current and yet not cause needless shutdowns on minor overloads. Overcurrent relays are incapable of providing this degree of protection for internal arcing faults. Overcurrent relays are still needed to provide for protection against overloads and faults external to the equipment. Differential protection can also be applied to transformers. However, the difference between the normal primary and secondary cur-

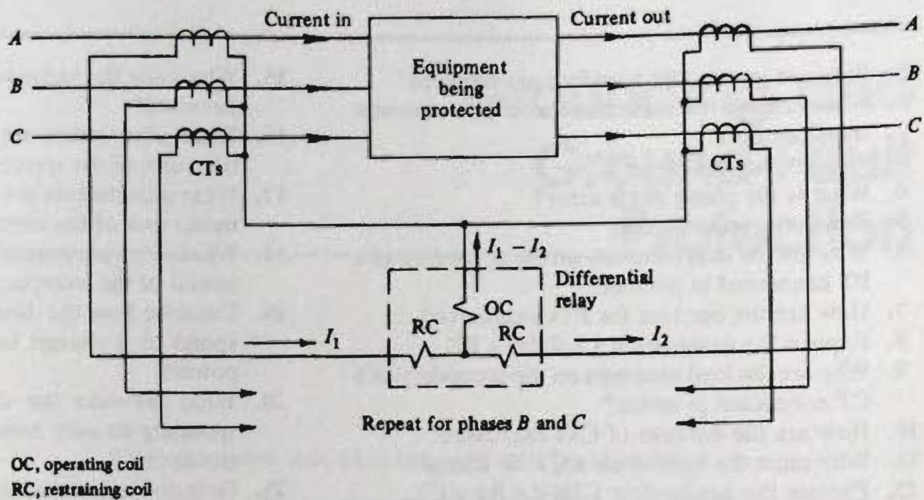


FIGURE 9.12

Schematic diagram of the connections for the differential relay compares current

rents due to the transformer turns ratio must be compensated for by the proper selection of the CT ratios so that their currents I_1 and I_2 are then matched.

SUMMARY

- The function of protective relays is to provide the intelligence for circuit breakers.
- Instrument transformers are required to provide protective relays and measuring instruments with scaled down representative values of the power system voltage and current.
- The accuracy of instrument transformers is dependent on the burden, that is, the amount of load connected to the transformers.
- Protective relays are usually of the drawout type so that they are readily accessible for testing and maintenance without the necessity of shutting down the power system.
- Overcurrent relays are widely used to provide protection to feeders and equipment.
- Overcurrent relays are available with a wide range of response characteristics.
- The pickup values and the timing of relays can be adjusted in the field.
- The trip circuit of the protective relay is arranged to provide positive tripping of the breaker.
- Directional relays can react to the incorrect direction of power flow in a system.
- Differential relays provide very close protection from internal faults in equipment.

QUESTIONS

1. Why are instrument transformers required?
2. What are the two basic functions of instrument transformers?
3. What is the ratio error?
4. What is the phase angle error?
5. Define the term burden.
6. Why are the load elements on the secondary of a PT connected in parallel?
7. How are the burdens for PTs expressed?
8. Explain the designation 1.2-Z for a PT.
9. Why are the load elements on the secondary of a CT connected in series?
10. How are the burdens of CTs expressed?
11. Why must the burden on a CT be limited?
12. Explain the designation 1.2B-4.0 for a CT.
13. Explain the designation 10H400 for a CT.
14. Why are there two separate methods of designating CTs?
15. Why must the secondary of a CT never be open circuited?
16. What adjustments are available on the inverse-time unit of the overcurrent relay?
17. What adjustments are available on the instantaneous unit of the overcurrent relay?
18. What is the purpose of the seal-in unit in the trip circuit of the overcurrent relay?
19. Describe how the directional relay is able to respond to a change in direction of the flow of power?
20. What prevents the directional relay from responding to very minor (transient) reversals of current?
21. Describe one application of the power directional relay.
22. How does the differential relay provide protection?

PROBLEMS

1. The current transformers for a power circuit are rated 1000/5 A. The tap on the inverse-time unit of the overcurrent relay is set at 6.0 A. Determine the current in the power circuit at which the relay will pick up and begin its timing function.
2. The time dial on the relay in Problem 1 is set at 10. Determine the response time of the relay for a power circuit current of 6000 A using Figure 9.8.
3. The instantaneous unit on the relay in Problem 1 is set at 40 A. Determine the current in the power circuit at which the instantaneous unit will pick up.
4. Repeat Problems 1, 2, and 3, except that (a) in Problem 1, the CTs are rated 500/5 A and the tap is set at 5.0 A; (b) in Problem 2, the time dial is set at 2 and power circuit current is 1000 A; and (c) in Problem 3, the instantaneous unit is set at 50 A.

10 Grounding and Ground-Fault Protection

OBJECTIVES

After studying this chapter, you will be able to:

- Discuss the importance of grounding.
- Recognize the difference between system and equipment grounding.
- Identify the advantages and disadvantages of ungrounded systems.
- Identify the advantages and disadvantages of grounded systems.
- Select the points for grounding systems.
- List the purposes of equipment grounding.
- Explain the effect of the equipment grounding circuit impedance.
- Select the size of the system and equipment grounding conductors.
- Identify the characteristics of arcing ground faults.
- Estimate the damage that can result from arcing ground faults.
- Explain the methods used for ground-fault protection.
- Discuss the merits of high-resistance grounding.

INTRODUCTION

The importance of proper grounding for electrical systems in buildings is often underestimated. Under normal conditions, an electrical system can continue to operate satisfactorily (that is, deliver power to the utilization equipment) even without proper grounding. It is not until an abnormal condition has occurred, and after either someone has been injured, equipment has been damaged, or a fire has been started, that it is realized that improper or faulty grounding was the reason. Therefore, a good understanding of the functions of grounding is essential for the proper design, installation, and mainte-

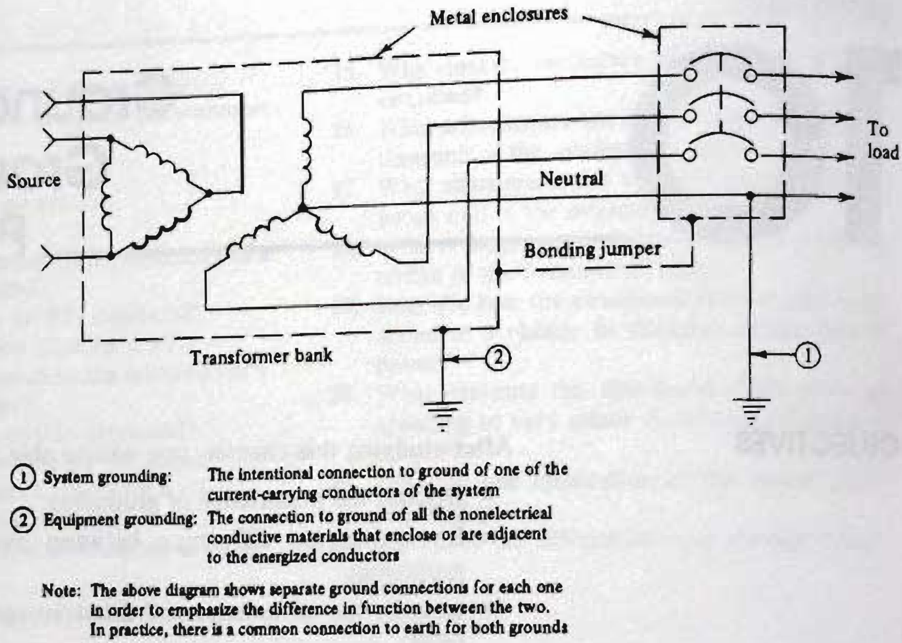


FIGURE 10.1

System and equipment grounding

nance of an electrical system. The mandatory requirements for grounding are covered in Article 250 of the *National Electrical Code* and in Section 1910.304(f) of the Occupational, Safety and Health Administration (OSHA) regulations. The *NEC* defines the term *grounded* as *connected to earth or to some conducting body that serves in place of earth*. In most cases, the connection is made by direct metallic contact with earth. The large mass of the earth then serves as a zero potential reference point.

The study of grounding must begin by identifying the different aspects of grounding: system grounding, equipment grounding, lightning protection grounding, and static electricity grounding. The protection of electrical systems and equipment against the effects of lightning and against the unsafe buildup of static electricity is involved and is beyond the scope of this textbook. The discussions in this chapter cover the very important aspects of system and equipment grounding and of ground-fault protection.

Figure 10.1 shows the basic difference between *system* grounding and *equipment* grounding. System grounding *is the intentional electrical connection to ground of one of the current-carrying conductors of the electrical system*. Equipment grounding *is the connection to ground of all the nonelectrical conductive materials that enclose or are adjacent to the energized conductors*. The electrical code requires that all equipment must be properly grounded, except in very rare special cases. However, the application of system grounding is not so universal. Certain types of systems, such as the 120/240 volt, single-phase, three-wire and the 208Y/120 volt, three-phase, four-wire systems used to supply lighting have always been grounded. On the other hand, the 480 and 600 volt, three-phase systems used to supply loads such as motors have until recently usually been operated ungrounded. To better understand the operating advantages of grounded systems, the ungrounded systems are discussed first.

10.1 UNGROUNDED SYSTEMS

An ungrounded system is one in which there is no intentional connection between any of the current-carrying conductors of the system and ground. The term intentional is included because there can always be an unintentional ground on the system due to breakdowns in the insulation or mechanical damage. Both the delta and wye systems (see Section 1.6) can be operated ungrounded, but it is usual that ungrounded systems are the delta configuration, as shown in Figure 10.2(a). Until the 1950s, most power systems in buildings (for motors as opposed to lighting) were operated as ungrounded delta systems. As will be shown, problems can arise with the operation of ungrounded systems, so the first question is why were they popular.

The principal reason for the selection of the ungrounded system is the fact that the first ground fault on the system does not require that any part of the system be shut down. As shown in Figure 10.2(b), this first ground fault merely puts that line of the system at ground potential. No fault current can flow because there is no other connection to ground on the system and hence no return path for the current to flow back to the source of supply. The very small charging current that does flow to ground can easily be tolerated on the system until it is convenient to shut the system down and make repairs.

A further reason for the use of the delta ungrounded system involves the connection of the transformer bank, as shown in Figure 10.3(a). When single-phase transformers are used and one transformer fails, it can be disconnected and the system can continue to operate with the two remaining transformers in open delta. The open-delta configuration can still provide three-phase power as shown in part (b), but at a reduced capacity (57% of normal). This allows the essential loads to be operated until the faulted single-phase transformer is repaired (or a new one obtained) and reconnected to the system.

While these two advantages are attractive when deciding whether to operate a system in the ungrounded mode, the following long-term operating disadvantages cannot be overlooked. In any system, there is a capacitive coupling between the system and

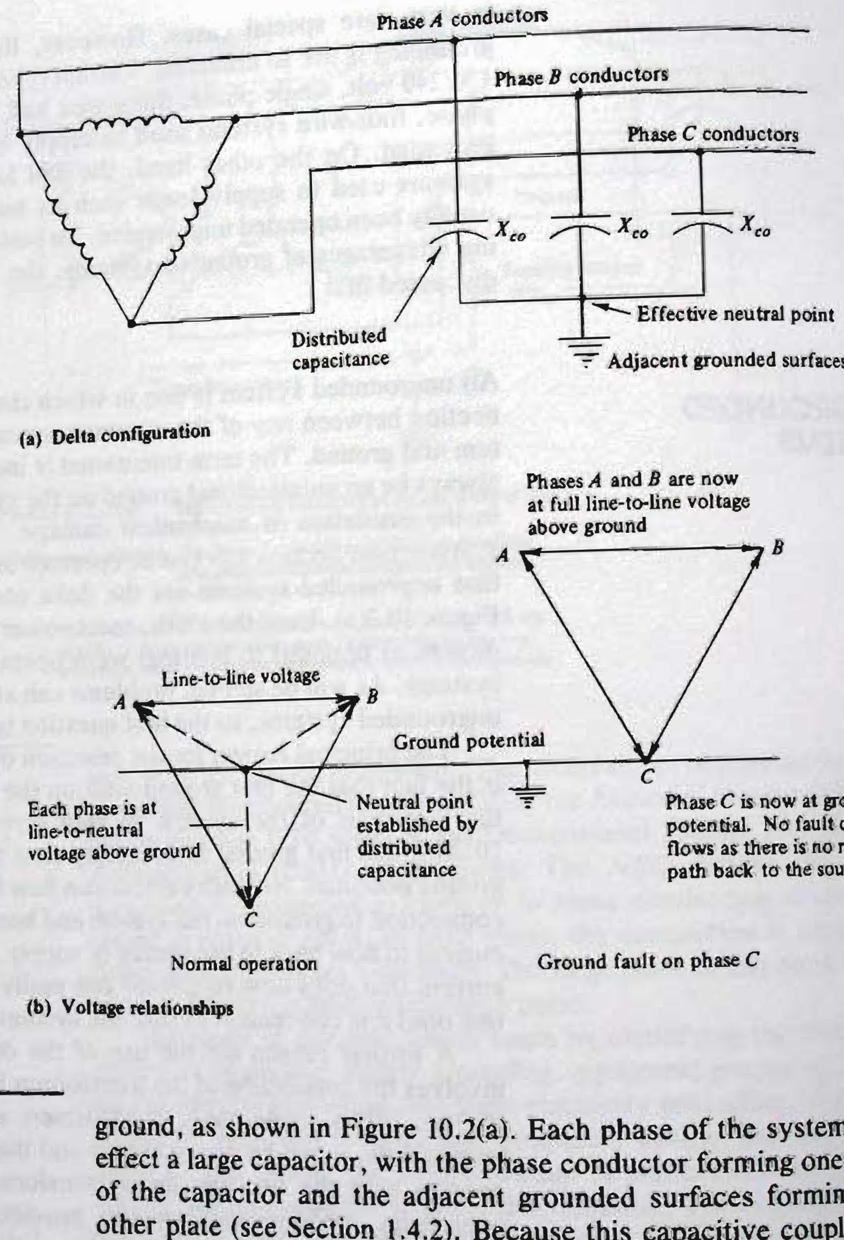


FIGURE 10.2

Ungrounded delta system

ground, as shown in Figure 10.2(a). Each phase of the system is in effect a large capacitor, with the phase conductor forming one plate of the capacitor and the adjacent grounded surfaces forming the other plate (see Section 1.4.2). Because this capacitive coupling is spread over the entire system, it is referred to as *distributed* capacitance. Under normal operating conditions, this distributed capacitance causes no problem and, in fact, is beneficial because it in effect establishes a neutral point for the system, as shown in Figure 10.2(b). Therefore, the phase conductors are stressed at only line-to-neutral voltage above ground. However, it is under abnormal conditions (when a ground fault has occurred) that serious problems can arise on the system, as discussed in the next section.

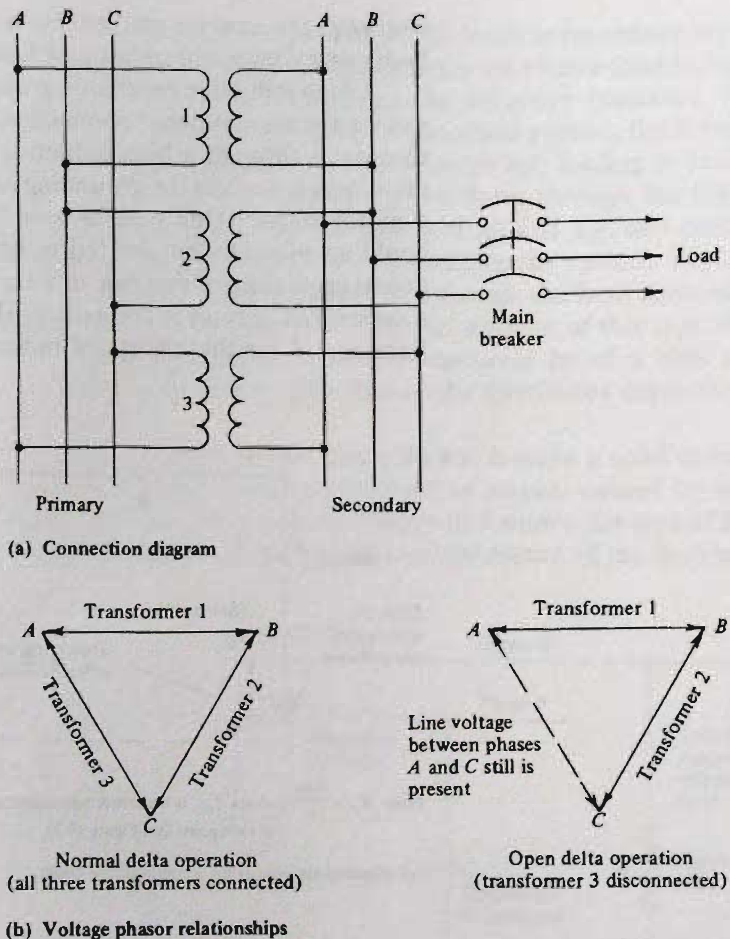


FIGURE 10.3

Bank of three single-phase transformers connected delta–delta.

10.1.1 Overvoltage Problems with Ungrounded Systems

The first ground fault on an ungrounded system, as previously discussed, does not shut the system down. However, the interaction between the faulted system and its distributed capacitance may cause destructive overvoltages to appear on the system. These overvoltages are between the system and ground and do not affect the line-to-line voltages. Therefore, the system can continue to operate and conditions can appear to be normal. The voltmeters, which read line-to-line volts, will not indicate that there is any problem. However, depending on the severity of the overvoltage, breakdowns of conductor and equipment insulation may soon start happening. There is a documented case involving an industrial plant in which upward of 50 motors failed during a 2-hour period before the offending ground fault was located and disconnected. These transient overvoltages can be caused by high inductive reactance ground faults or by intermittent ground faults.

A high inductive reactance ground fault is one in which the fault causes the unintentional connection of one of the phase conductors to ground through a high inductive reactance. This can happen in many ways, such as the grounding of one side of the operating coil of a motor starter. One control wire to a remote push-button station could accidentally be shorted to ground. Another way is the accidental grounding of one side of a transformer winding. In any event, a series *RLC* circuit is created, as shown in Figure 10.4(a). Refer to Section 1.4 for the effects of inductance (*L*) and capacitance (*C*).

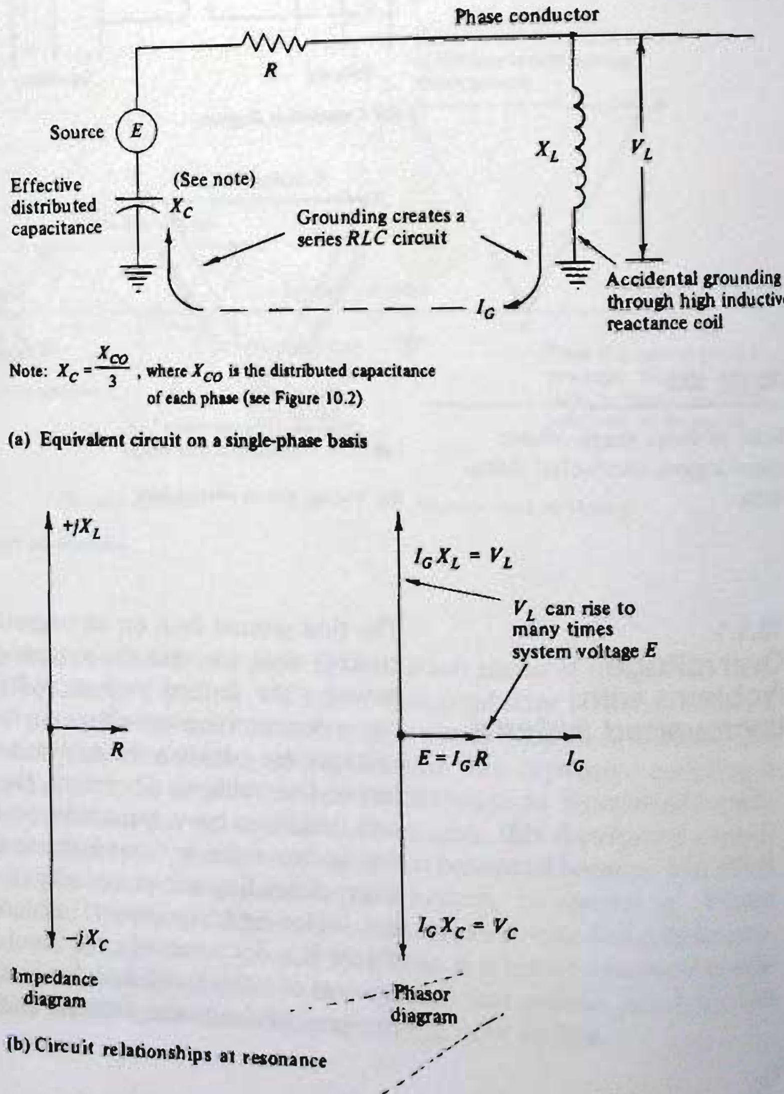
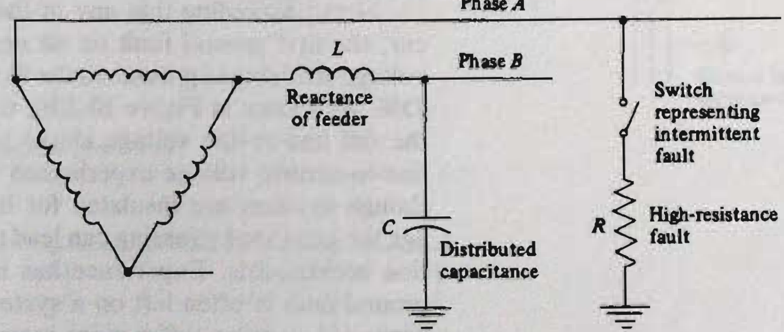


FIGURE 10.4

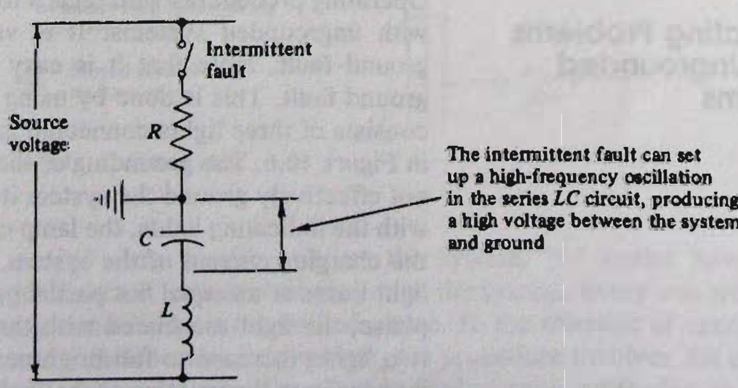
Unintentional grounding of an ungrounded delta system through a high inductive reactance

The relationships for a series *RLC* circuit at resonance are shown in Figure 10.4(b). A voltage many times the source (that is, the system) voltage can be induced across the inductive reactance. Since this voltage is between the affected phase and ground, the voltage stressing on the insulation is similarly increased, leading to early failures of equipment. The current I_G that flows through the fault is very small, because of the high values of X_L and X_C, and does not activate the overcurrent devices protecting the system. High transient overvoltages can still occur even though the fault does not operate exactly at resonance. The essential element of this type of destructive fault is that the inductive reactance be of a high value, approaching in ohmic value that of the distributed capacitance of the system.

Intermittent ground faults do not involve a solid connection to ground but are rather intermittent in nature, caused by such problems as vibration or arcing. Figure 10.5 shows this type of fault, with a switch representing the intermittent nature of the fault and with a



(a) Ground fault on phase *A*



(b) Equivalent circuit of the fault path

FIGURE 10.5

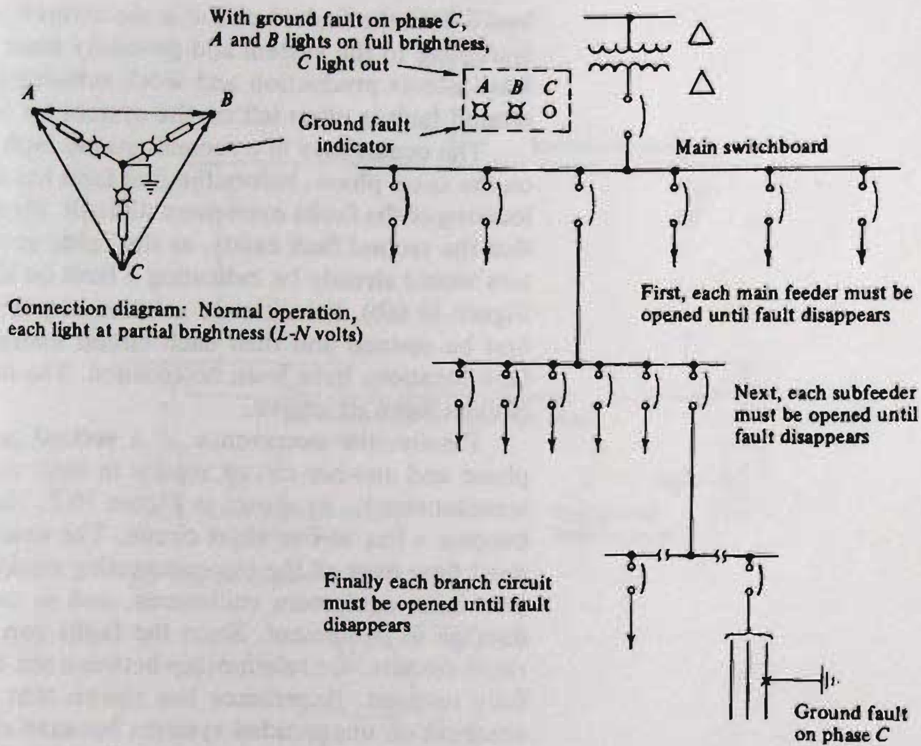
Intermittent high-resistance ground fault on an ungrounded delta system high resistance for the fault path to ground through an arc. Part (b) shows the equivalent circuit of the fault path, which in effect becomes an oscillator. A peculiar trait of an oscillator is that, regardless of the relative values of L and C, with an intermittent input the circuit will tend to operate at or near its resonant frequency. These high-frequency oscillations can produce a voltage as high as six times the system voltage. This voltage is induced between the system and ground, badly overstressing the insulation, which can lead to early breakdowns of equipment. In spite of the fact that this high voltage is induced, the high resistance of the fault connection means that only a small fault current flows, which does not activate the overcurrent devices protecting the system. The essential element of this type of destructive fault is that it be of an intermittent nature.

Other means of producing excessive line-to-ground voltages on ungrounded systems are more obvious, such as accidental contact with a higher-voltage system. These contacts can be as a result of the breakdown of insulation between the primary and secondary windings of a transformer or of high-voltage overhead wires falling down across lower-voltage circuits.

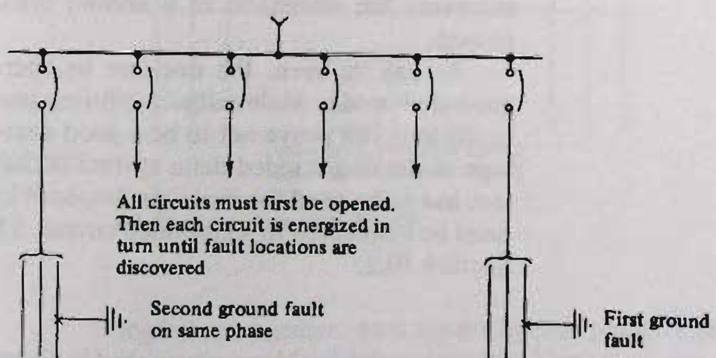
Notwithstanding that any of the preceding fault conditions occur, the first ground fault on an ungrounded system increases the voltage stressing to ground on the two remaining unfaulted phases by 73%. As shown in Figure 10.2(b), these two phases now operate at the full line-to-line voltage above ground, which is 1.73 times the line-to-neutral voltage experienced under normal conditions. Even though systems are insulated for line-to-line voltages, as systems age the increased stressing can lead to increased frequency of insulation breakdowns. Experience has indicated that, because the first ground fault is often left on a system for long periods of time, ungrounded systems suffer more ground faults than do grounded systems over their operating lifetime.

10.1.2 Operating Problems with Ungrounded Systems

Operating procedures with regard to ground faults are more difficult with ungrounded systems. It is very difficult to locate the first ground fault. Note that it is easy to detect the existence of the ground fault. This is done by using a ground-fault indicator, which consists of three lights connected in a wye configuration, as shown in Figure 10.6. The grounding of the wye point for these lights does not effectively ground the system itself. With the resistors in series with the indicating lights, the lamp currents are very small, less than the charging current of the system. Under normal conditions each light burns at an equal but partial brightness. With a ground on one phase, the light associated with that phase goes out and the other two lights increase to full brightness. However, these lights in no way indicate the location of the fault. Figure 10.6(a) shows a typical radial system that has a ground fault on a remote branch circuit on



(a) Locating first ground fault



(b) Second ground fault on same phase

FIGURE 10.6

Difficulty of locating ground faults on ungrounded systems

one of many panelboards on the system. No matter how many ground-fault indicators there are on the system, every one will show a ground fault on the faulted phase. In the absence of special and costly fault-locating equipment, the procedure involves the opening and closing in turn of each main feeder, each subfeeder on the affected feeder, and finally each branch circuit on the affected panelboard until the faulted circuit is discovered. Obviously, this is very disruptive to the system and generally must be done at a time that least affects production and work schedules. As a result, the first ground fault is often left on the system for long periods of time.

The occurrence of a second ground fault on another circuit, but on the same phase, before the first fault has been cleared makes the locating of the faults even more difficult. First, there is no indication that the second fault exists, as the lights on the ground fault indicators would already be indicating a fault on that phase. As shown in Figure 10.6(b), the ultimate solution requires that all circuits must first be opened and then each circuit energized in turn until both fault locations have been determined. The disruption to the system is even more extensive.

Finally, the occurrence of a second ground fault on another phase and another circuit results in both circuits being shut down simultaneously, as shown in Figure 10.7. The two faults effectively become a line-to-line short circuit. The resulting large fault current must flow over all the interconnecting equipment grounding circuit (conduits, equipment enclosures, and so on), which can result in damage to equipment. Since the faults can occur on widely separated circuits, the relationship between the two outages may not be fully realized. Experience has shown that double faults are very common on ungrounded systems because of the tendency to leave the first ground fault on the system. The 73% rise in the line-to-ground voltage on the unfaulted phases after the first ground fault increases the likelihood of a second breakdown on one of these phases.

As can be seen, the decision to operate a system in the ungrounded mode, while initially offering important advantages, may in the long run prove not to be a good decision. One final disadvantage of the ungrounded delta system is the fact that a separate system has to be used for those single-phase loads such as lighting that must be connected to a grounded circuit. This is discussed further in Section 10.2.

10.2 GROUNDED SYSTEMS

Now that the problems associated with ungrounded systems have been pointed out, the merits of grounded systems can be discussed. First, return to Figure 10.1 and review what constitutes system grounding; that is, the intentional connection to ground of one of the current-carrying conductors of the system. Delta systems can be operated as grounded systems by either grounding one corner of the delta or by grounding the midpoint of one of the phases. However, this is not the usual method. The majority of grounded systems use the wye configuration with the neutral grounded. This is the most

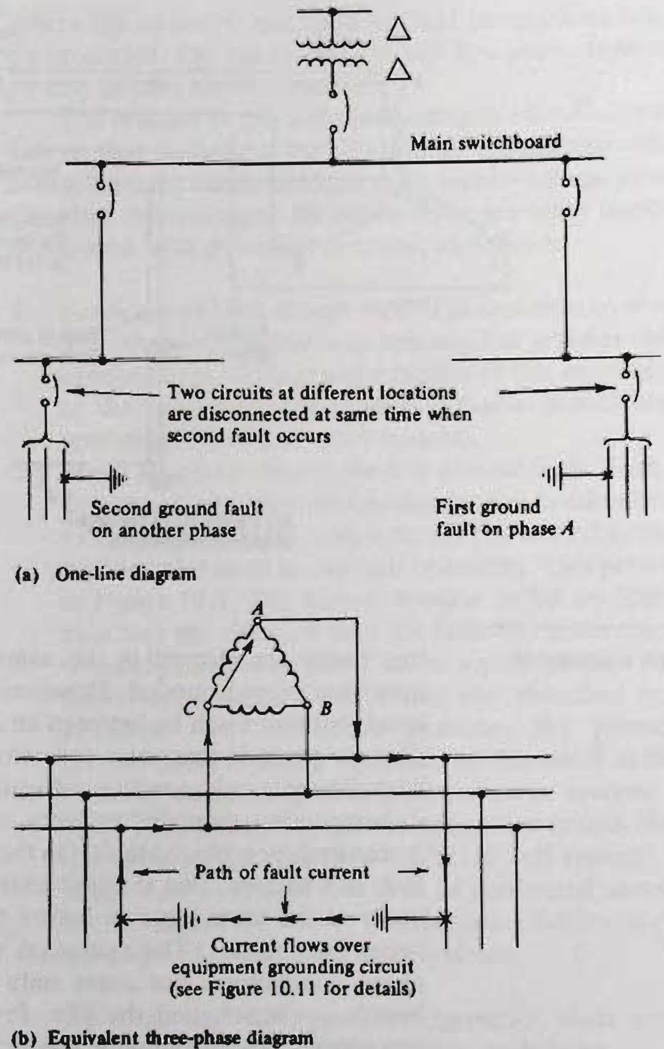


FIGURE 10.7

Problem with second ground fault on another phase

logical arrangement as it results in each phase of the system being at the same potential above ground. Therefore, the remaining discussions in this chapter are on the basis of wye-connected systems.

The most significant difference in operating characteristics between the grounded and ungrounded systems is what happens when the first ground fault occurs. With the grounded system, there is a path for the fault current to flow when the first ground fault occurs, as shown in Figure 10.8. The overcurrent devices are now activated by the resulting fault current. It must be emphasized that the difference between the two systems involves ground faults only. Line-to-

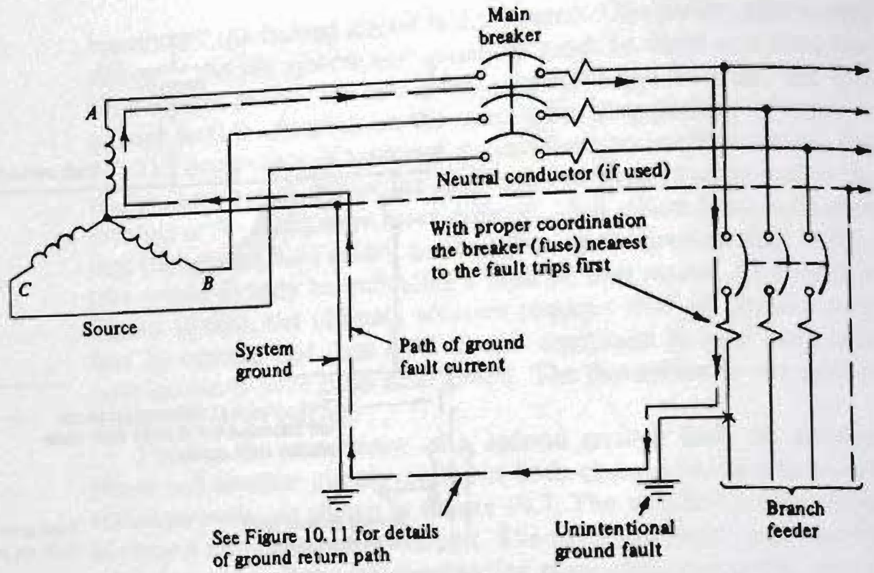


FIGURE 10.8

Ground fault on a grounded wye system

line faults are cleared in the same manner whether a system is grounded or ungrounded. However, there is a much greater likelihood that faults will be between an energized conductor and ground (line to ground) than between two energized conductors (line to line). There is only one layer of insulation between a conductor and its surrounding grounded surfaces, and only one point of breakdown is required for a ground fault. On the other hand, before a line-to-line fault can happen, two simultaneous breakdowns of insulation must occur at the same location before there is a fault path directly between two phases. The exception would be at locations with bare phase conductors, but these only occur at switchboards, panelboards, switches, and the like. Proper design and testing of this equipment should minimize the possibility of line-to-line faults at these locations. Therefore, line-to-ground faults are far more likely to occur on a system than line-to-line faults.

The *National Electrical Code*, Article 250, Parts B and C, covers system grounding. Section 250-5(b) covers alternating current systems, 50 to 1000 volts, that must be grounded, specifically where the system can be so grounded that the maximum voltage to ground on the ungrounded conductors does not exceed 150 volts, and for any system where the neutral is to be used as a circuit conductor. Thus, 120/240 volt single-phase, three-wire, and 208Y/120 volt three-phase, four-wire systems must be grounded. Those 480Y/277 volt three-phase, four-wire systems where the neutral is used as a circuit conductor (that is, for single-phase fluorescent lighting loads) must also be grounded. The 480 and 600 volt three-phase systems where the neutral is not used for load connections may or may not be grounded. The trend over the last few years, however, has been to also ground these systems.

The primary purpose for grounding an electrical system is one of safety, that is, to limit the potential to ground that otherwise could occur from accidental contact with higher-voltage systems or from transient overvoltages. However, there are other important benefits associated with grounded systems, as follows:

1. *Service reliability is improved:* The transient overvoltage conditions that are possible with ungrounded systems (Section 10.1.1) cannot occur. With the elimination of this overvoltage stressing of the insulation, fewer ground faults should occur over the operating life of grounded systems.
2. *Much simpler to locate the first ground fault:* With proper coordination, the overcurrent device (circuit breaker or fuse) nearest to the fault operates to disconnect the faulted circuit, thus leaving the balance of the system operating. This principle is shown in Figure 10.8. The tripped breaker or blown fuse immediately indicates the circuit where the fault has occurred.
3. *Ground-fault protection can be easily added:* Arcing ground faults can be difficult to detect and therefore require special attention. With grounded systems, the protection against ground faults is easily obtained, as discussed in Section 10.5.
4. *Provides two voltage levels on the same system:* Single-phase loads such as lighting can be connected across the line-to-neutral voltage (120 volts on a 208Y/120 volt system). Three-phase loads such as motors can then be connected across the line-to-line voltages (208 volts). See Section 1.6.1 for the voltage relationships of three-phase wye systems.

As is the case with most arrangements, there are some drawbacks to the use of grounded systems, as follows:

1. The first ground fault results in the immediate shutdown of part of the system.
2. There can be very high ground-fault currents on bolted-type faults. These large currents must flow over the equipment grounding circuit (see Section 10.3).

10.2.1 Selection of System Grounding Points

Once the decision has been made to ground an electrical system, the following should govern the selection of the system grounding points. These comments are based on the system being *separately derived,* that is, *a system whose power is derived from generator, transformer or converter windings and that has no direct electrical*

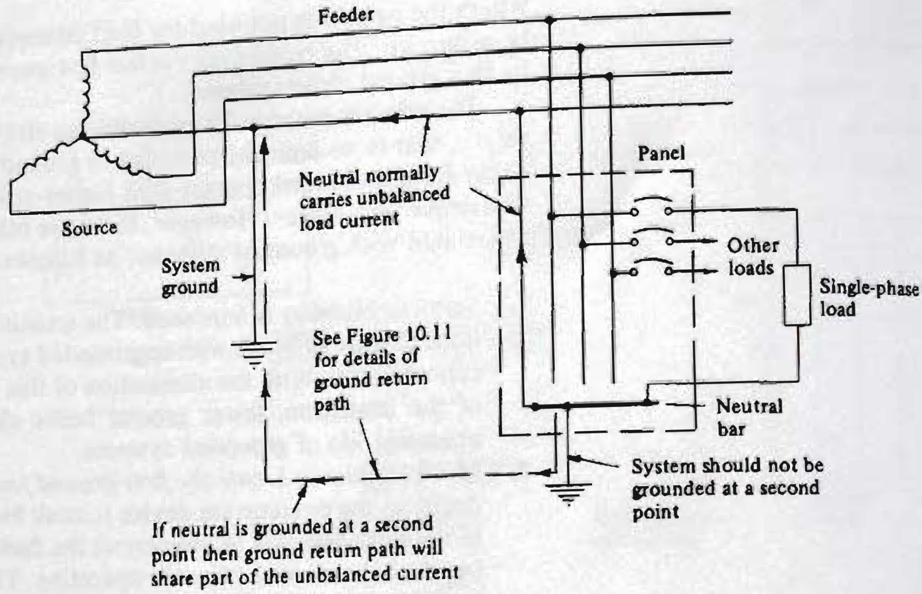


FIGURE 10.9

Each separately derived system should be grounded at one point only

connection, including a solidly connected grounded circuit conductor, to supply conductors originating in another system. In a typical separately derived system, the main transformer is on the customer's premises and is used solely to supply power to those premises. In contrast, a system that is not separately derived is fed from a common utility transformer bank external to the premises and which also supplies other customers in separate premises.

The following points should govern the grounding of separately derived systems:

1. *Ground each system at one point only.* Figure 10.9 shows what would happen if, for instance, the neutral bar of a panel is grounded in addition to the system neutral being grounded at the source. The second ground connection at the panel then puts the ground return path (the equipment grounding circuit) in parallel with the neutral conductor of the feeder. Therefore, the equipment grounding circuit will share part of the unbalanced current that flows when the single-phase loads are not equal over the three phases. Thus, under normal conditions, the equipment grounding circuit is carrying current, which is not a desirable condition. Section 250-21 of the *NEC* states in part that *The grounding of electrical systems . . . and conductive noncurrent-carrying materials and equipment shall be installed and arranged in a manner that will prevent an objectionable flow of current over the grounding conductors or grounding path*. Furthermore, if the neutral conductor were acci-

dently broken or disconnected, then, with the second ground connection, the equipment grounding circuit would carry all the unbalanced neutral current. Finally, the second ground connection would interfere with the proper operation of the ground-fault protection (see Section 10.5). For these reasons, the neutral of the system must be grounded at one point only, and the neutral conductor (including the neutral bars in panels) must be insulated for its entire length to prevent any further unintentional grounds.

2. *The system grounding point must be as close to the source as possible.* Refer to Figure 10.10(a). Suppose the system is grounded at one of the loads (for example, the neutral point of a motor winding). If a ground fault occurs on another branch feeder, the distance of the return path for the fault current is unnecessarily long, creating problems with the proper operation of the overcurrent protective

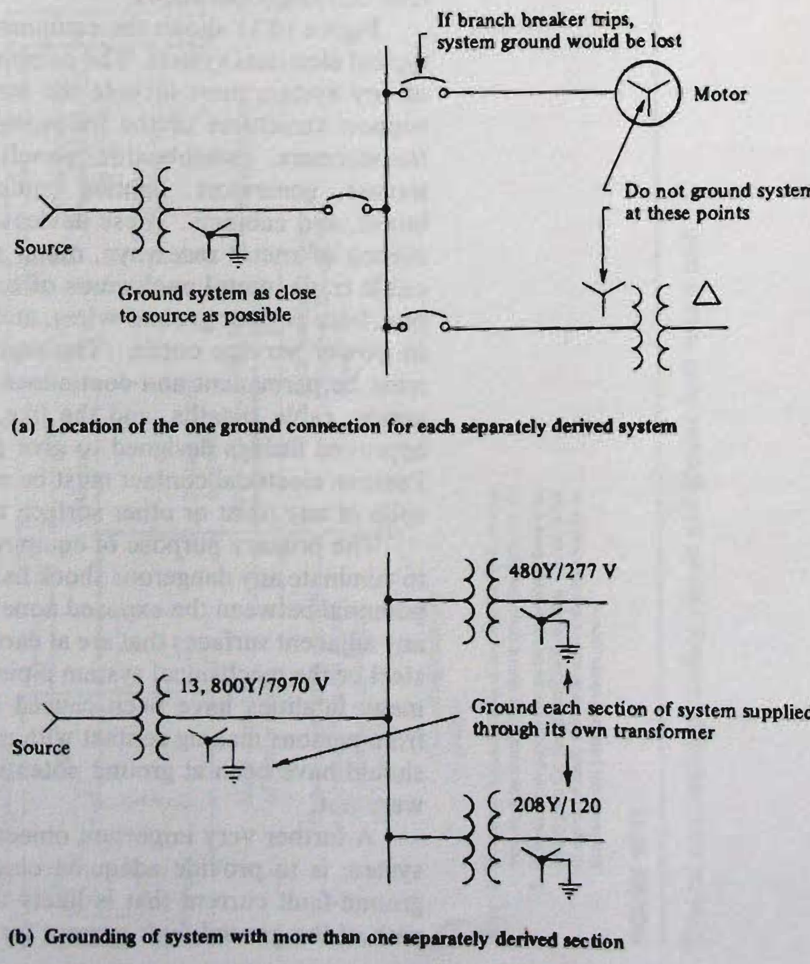


FIGURE 10.10

Location of system ground connections

devices. Furthermore, if the branch breaker feeding the motor is opened, the system grounding is lost. Therefore, the system ground connection should be made as close to the source as possible, that is, on the line side of the first disconnecting means for the system.

3. *Ground each separately derived section of the system.* It is necessary to reestablish the system ground on the secondary side of each of the power transformers, as shown in Figure 10.10(b).

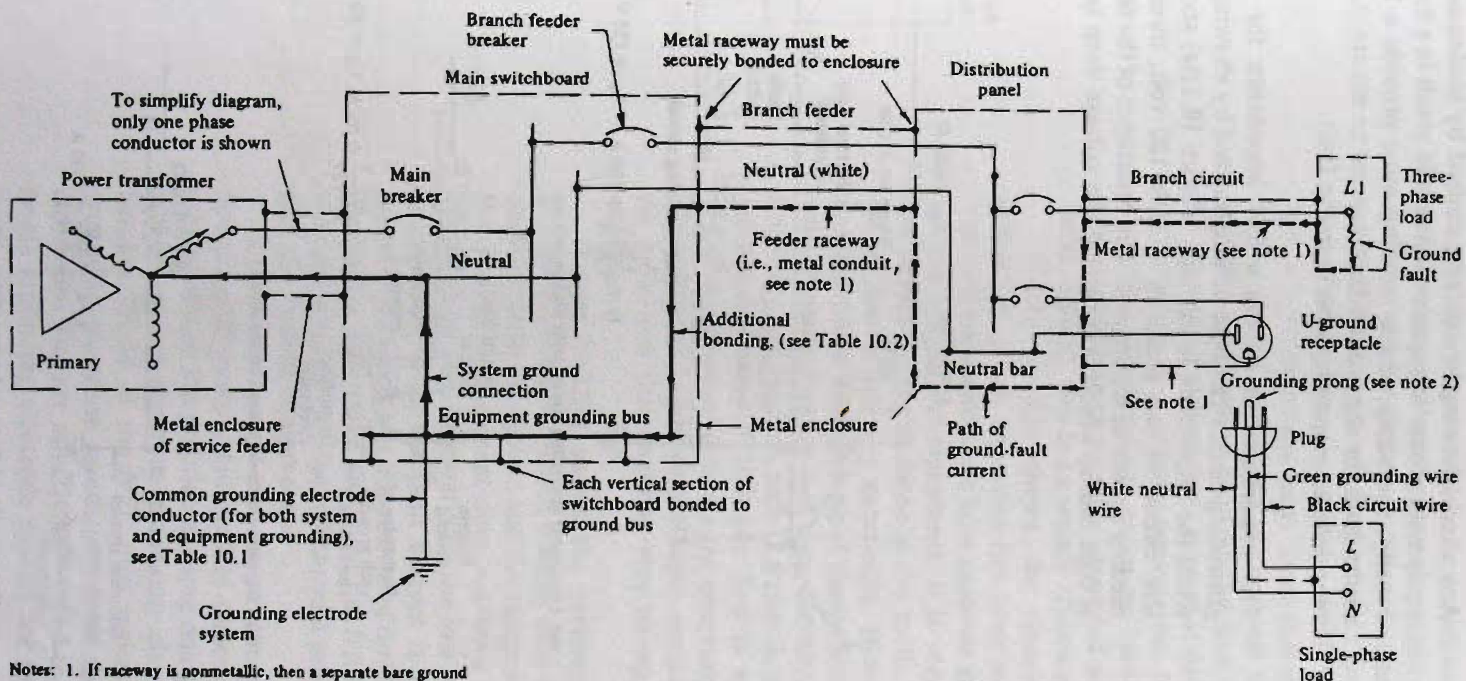
10.3 EQUIPMENT GROUNDING

Equipment grounding is concerned with the interconnecting of all the nonelectrical conductive materials that enclose or are adjacent to the energized conductors of the system and their connection to ground. The term *nonelectrical* means *those metal parts of the system that do not carry current under normal conditions* (that is, when there are no faults on the system) and are referred to as the *noncurrent-carrying conductors*.

Figure 10.11 shows the equipment grounding arrangement for a typical electrical system. The complete equipment grounding circuit of any system must include the metal enclosures, frames, and/or support structures of the following: service entrance equipment, transformers, switchboards, panels, switches, motor controllers, motors, generators, lighting equipment, outlet boxes, junction boxes, and cabinets. These devices are then all interconnected by means of metal raceways, metal sheaths, and armors of cables, cable trays, metal enclosures of bus ducts, equipment grounding bus, bare copper ground wires, and the green insulated conductor in power service cords. The equipment grounding circuit path must be permanent and continuous. Where metal raceways, cable armor, cable sheaths, and the like, are terminated at enclosures, approved fittings designed to give positive bonding must be used. Positive electrical contact must be made between the metal parts in spite of any paint or other surface coating on the enclosure.

The primary purpose of equipment grounding is safety, that is, to eliminate any dangerous shock hazard to personnel by limiting the potential between the exposed nonelectrical parts of the system and any adjacent surfaces that are at earth potential, such as the building steel or the mechanical system piping. Accident statistics show that many fatalities have been caused by electric shock that resulted from persons making contact with metallic enclosures that normally should have been at ground potential but, due to faulty grounding, were not.

A further very important objective of the equipment grounding system is to provide adequate current-carrying capability for any ground-fault current that is likely to flow. Figure 10.11 shows the path of the ground-fault current for a fault at the three-phase load.



Notes: 1. If raceway is nonmetallic, then a separate bare ground wire must be installed in the raceway (see Table 10.2)

2. If equipment ground connection is broken, there is no return path for the ground fault current. In the event of a ground fault, the metal case of the load will be at line-to-neutral potential above ground

FIGURE 10.11

Typical equipment grounding circuit and ground-fault return path

Any excess heating or sparking caused by inadequate or improper equipment grounding connections could result in a fire or explosion. Finally, the equipment grounding must provide a low-impedance return path for the ground-fault current to ensure that the overcurrent devices respond properly to the fault.

10.3.1 Impedance of Equipment Grounding Circuit

The importance of having a low impedance for the equipment grounding circuit can best be emphasized by showing what happens when the impedance is too high. Figure 10.12(a) shows the equivalent circuit of one phase of a 208Y/120 volt, three-phase system feeding a piece of equipment. The resistance of the feeder conductor is 0.02 ohms, which is typical if the voltage drop is to be approxi-

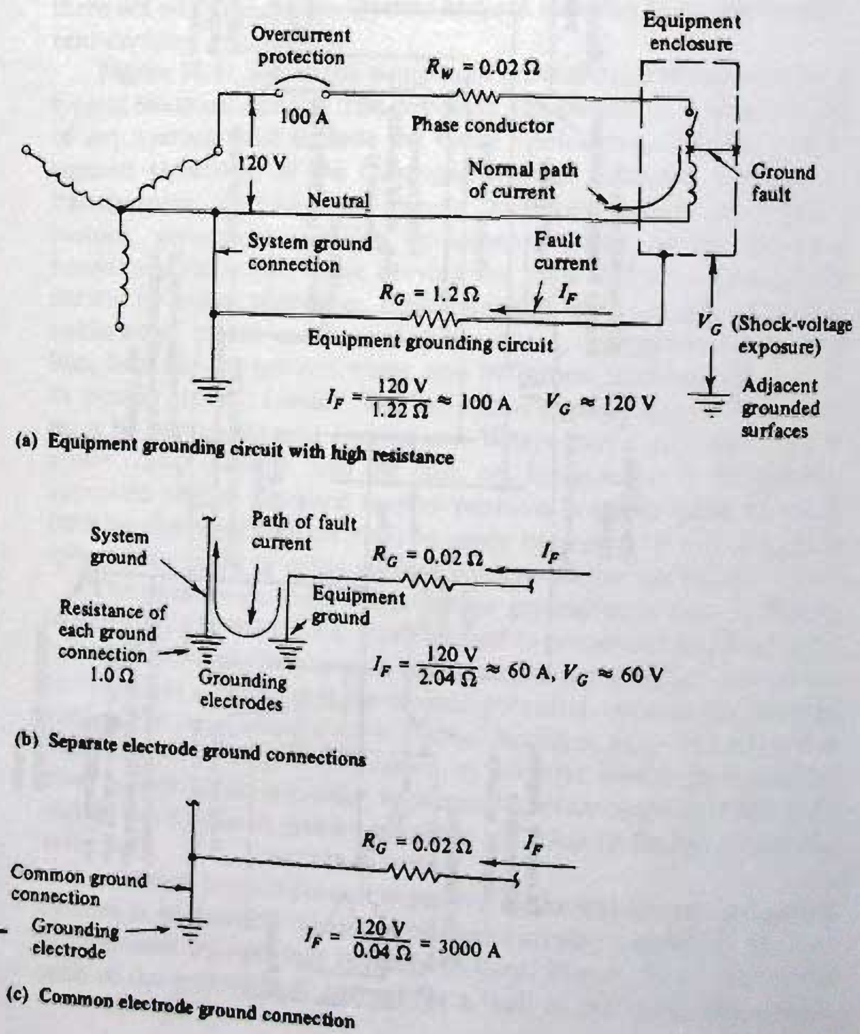


FIGURE 10.12

Effects of impedance in the ground-fault return path mately 2% under normal load conditions. A ground fault is assumed to have occurred between the energized conductor in the equipment and its grounded enclosure. The resistance of the equipment grounding circuit through which the fault current must flow back to the source is indicated as 1.2 ohms. While this 1.2 ohms in itself seems low, it is nevertheless many times that of the feeder conductor and, in fact, is the major part of the total fault circuit impedance. As indicated, even with a solid ground fault to the equipment enclosure, the maximum ground fault current is only 100 amperes. This is not high enough to positively activate the 100 ampere overcurrent device. The shock-voltage exposure between the metal case of the equipment and any adjacent grounded surface is approximately 120 volts. Clearly, this is an unsafe situation.

Figure 10.12(b) shows the situation where the equipment grounding circuit resistance has been reduced to that of the phase conductor, but there are now separate grounding electrodes for the system and for the equipment. It is very difficult to establish very low resistance connections to the earth, and therefore the 1.0 ohm values shown are very acceptable. However, the ground-fault current must flow through both of these electrode connections in series, with the consequence that they constitute the majority of the total impedance of the fault path (2.0 ohms). As indicated, the maximum ground-fault current that can flow is approximately 60 amperes, which would never activate the overcurrent protective device. The shock-voltage exposure of 60 volts would persist and there would be no indication that anything was wrong. Again, this is an unsafe situation.

Figure 10.12(c) shows the preferred method of making the ground connection, that is, making only one common connection to earth for both the system and the equipment grounding. In this way, the ground-fault current does not have to pass through any earth connections and, together with the low resistance of the equipment grounding circuit, the fault current is now on the order of 3000 amperes (ignoring any impedance of the power source, which will be low). This high value (30 times the full-load current of the feeder) will instantly activate the overcurrent protective device and de-energize the faulted equipment.

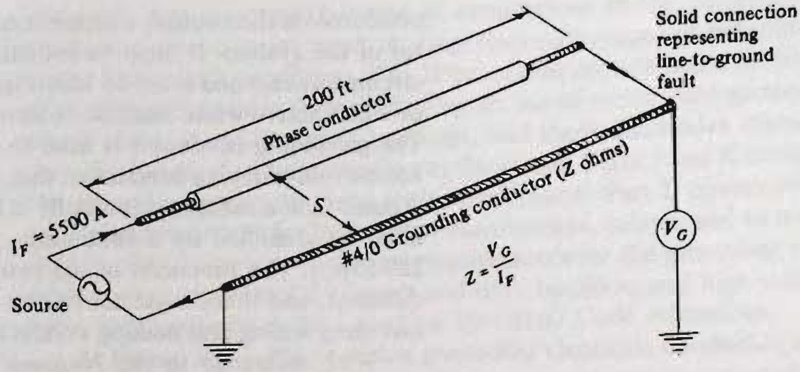
In the past, many cases were uncovered where the improper operation of overcurrent devices under ground faults was directly attributable to the practice of using one grounding electrode for the system and a separate grounding electrode for the equipment. Section 250-54 of the *NEC* now makes the use of one common grounding electrode mandatory. Note that two or more grounding electrodes that are effectively bonded together are considered as a single grounding electrode system for the purpose of this requirement.

10.3.2 Inductive Reactance of Equipment Grounding Circuit

The examples shown in Figure 10.12 and discussed in the previous section considered only the resistance of the ground-fault circuit path for simplification. However, on ac systems with feeders rated at more than 50 amperes, the inductive reactance (X_L) of the ground fault return path (the equipment grounding circuit) becomes an important parameter of the total impedance of the circuit ($Z = R + jX_L$; see Section 1.4.3).

Three factors affect the inductive reactance of the equipment grounding circuit: (1) the location of the grounding circuit with respect to the phase conductors, (2) the configuration of the grounding circuit, and (3) the material used (whether magnetic or nonmagnetic). Comprehensive testing has been done to show the effects of these factors. Figure 10.13 shows the arrangements used for the test circuits and lists a few of the test results. For each test the source voltage was adjusted so that the fault current flowing in the circuit was 5500 amperes. In part (a), the equipment grounding circuit consists of a No. 4/0 grounding conductor run parallel to the phase conductor at a fixed spacing for the entire 200 foot length of the feeder. The test results show that the location of the grounding conductor is critical. The inductive reactance is reduced by more than one-half when the spacing is decreased from 30 inches to 2 inches. Therefore, when a conductor is used for equipment grounding, it must be run as close as possible to the phase conductors of the feeder supplying the equipment. The test results also show that the use of the building steel as the return path for ground faults is not a good practice. The remote location of the ground return path through the steel with respect to the phase conductors would create a very high inductive reactance and therefore severely limit the flow of fault current. This could result in unsatisfactory operation of the overcurrent protective devices.

In Figure 10.13(b), the grounding conductor is replaced by an enclosing metal raceway that is connected to form the fault return path. The test results with this arrangement show that the impedance of the return path through the raceway (as measured by the voltage V_G with the same I_F) are even much lower than when using a closely spaced grounding conductor. As shown in the cross section through the raceway, the returning fault current in the shell of the raceway completely surrounds the current flowing outward in the phase conductor. Therefore, there is a complete cancellation of the magnetic flux, and the inductive reactance of the circuit approaches zero. As expected, the higher conductivity of the aluminum raceway provides the lowest impedance of all. Thus metallic raceways as used for the support and mechanical protection of the insulated feeder and circuit conductors (see Section 11.5) also serve very effectively as part of the equipment grounding system when properly installed and solidly connected at all joints.



Spacing S (in.)	Voltage V_G	Grounding Conductor		
		R	X	Z
30	143.5	0.013	0.023	0.026
2	89.5	0.013	0.010	0.016

(a) Tests using a copper ground conductor

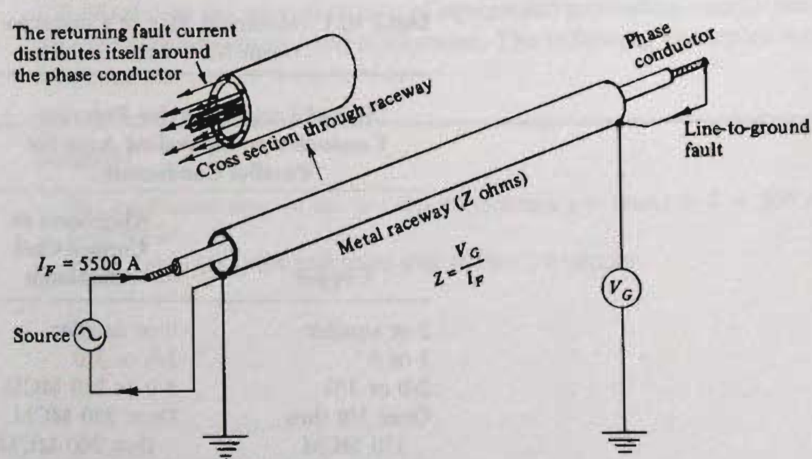


FIGURE 10.13

Equipment grounding circuit impedance as a function of its location and configuration

Raceway	Voltage, V_G
Rigid steel conduit	11.0
Rigid aluminum conduit	6.7

(b) Tests using a metal raceway as the ground conductor

10.3.3 Summary of National Electrical Code Requirements

As shown in the previous examples, a well-planned equipment grounding system must be provided for every electrical system to minimize shock and fire hazards and to ensure proper operation of the protective devices. The total impedance of the equipment grounding circuit must be kept as low as possible. It would be well at this time to reemphasize the difference between a grounded conductor and a grounding conductor. Refer to Figure 10.11. The grounded conductor is the neutral, which is a normal current-carrying conductor of the system. It must be insulated (except in very rare special circumstances) and must be identified by either a white outer finish or a distinctive white mark at its termination (see *NEC* Article 200). The grounding conductor is used to ground the equipment and is a noncurrent-carrying conductor; that is, it carries current only under ground-fault conditions. It usually is bare, but where it is insulated it must be identified by a continuous green color [see *NEC* Section 250-57(b)]. The functions of the two types of conductors are quite different, and there must not be any confusion between them when installing wiring and making connections.

With reference to the *National Electrical Code*, Article 250, Parts D and E, covers the specific requirements for enclosure and equipment grounding. Part F covers methods of grounding, Part G covers bonding, which is the permanent joining of metallic parts to form an electrically conductive path that will assure electrical continuity and the capacity to conduct safely any current likely to be

TABLE 10.1 Minimum Size of Conductors for Grounding AC Systems (from *NEC* Table 250-94)

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	**Aluminum or Copper-Clad Aluminum**	**Copper**	**[a]Aluminum or Copper-Clad Aluminum**
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

[a] See installation restrictions in Section 250-92(a).

See Section 250-23(b).

Where there are no service-entrance conductors, the grounding electrode conductor size shall be determined by the equivalent size of the largest service-entrance conductor required for the load to be served.

imposed. Any improper bonding at connections in the equipment grounding circuit could result in dangerous differences of potential under heavy fault conditions. Part H covers the requirements for the grounding electrode system, including the use of metal underground water pipes, metal frames of buildings, and made electrodes (those specifically installed for grounding to the earth). Parts J and K cover the grounding conductors and their connections. Part L covers the special requirements for instrument transformers, relays, and so on. Finally, Part M covers additional requirements for the grounding of systems and circuits of 1 kilovolt and over (medium and high voltage). See Appendix A for Canadian Electrical Code references.

In Figure 10.11, the common grounding electrode conductor as required by *NEC* Section 250-54 is shown connected to the equipment grounding bus. This is permitted by Section 250-23(a), Exception No. 5, and in fact is the preferred arrangement for the application of ground-fault protection as shown in Figure 10.15.

Table 10.1 in this text (*NEC* Table 250-94) shows the minimum size of conductors for grounding ac systems. Table 10.2 (*NEC* Table 250-95) shows the minimum size of equipment grounding conductors for grounding raceways and equipment. The following examples will illustrate the use of these tables.

■ EXAMPLE 10.1

Refer to Figure 10.11. The main secondary feeder from the transformer to the main breaker (the service feeder) consists of two parallel runs of 500 MCM XHHW copper conductors per phase. Determine the size of the common grounding electrode conductor.

Solution

— The equivalent area of the parallel conductors per phase is 2 × 500 = 1000 MCM.

— From Table 10.1, the minimum size is No. 2/0 copper.

■ EXAMPLE 10.2

Refer to Figure 10.11. The trip unit for the branch feeder breaker is rated for 350 A, and the branch feeder to the distribution panel is enclosed in a nonmetallic raceway. Determine the size of the bare conductor that has to be run in the raceway for grounding the equipment.

Solution

From Table 10.2, the minimum size is No. 3 copper.

TABLE 10.2 Minimum Size of Equipment Grounding Conductors for Grounding Raceways and Equipment (from *NEC* Table 250-95)

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size	
	Copper Wire No.	Aluminum or Copper-Clad Aluminum Wire No.[a]
15	14	12
20	12	10
30	10	8
40	10	8
60	10	8
100	8	6
200	6	4
300	4	2
400	3	1
500	2	1/0
600	1	2/0
800	0	3/0
1000	2/0	4/0
1200	3/0	250 MCM
1600	4/0	350 MCM
2000	250 MCM	400 MCM
2500	350 MCM	600 MCM
3000	400 MCM	600 MCM
4000	500 MCM	800 MCM
5000	700 MCM	1200 MCM
6000	800 MCM	1200 MCM

[a] See installation restrictions in Section 250-92(a).

10.4 ARCING GROUND FAULTS

As previously discussed in Section 6.3, there are two types of faults: bolted type and arcing type. Bolted-type ground faults are rare. If they do occur, the fault currents are large (with proper equipment grounding), and the overcurrent devices should respond very rapidly, thus minimizing any damage. Ground faults are more likely to be of the arcing types. Because of the relatively higher resistance of the arc and its intermittent nature, the resulting fault currents are much smaller than those for bolted faults and are therefore harder to detect. In recent years, especially as the size of low-voltage systems increased in capacity, in a number of instances extensive damage has been done by arcing faults that were improperly handled. Arcing ground faults have the following characteristics:

1. Arcs have a negative volt–ampere relationship; as the arc current increases, the resistance of the arc decreases. As a result, the voltage drop across an arcing fault is relatively constant (that is, it is independent of the current). Tests have shown that arc voltages fluctuate between 60 and 140 volts, with the average being around 100 volts.
2. Most of the fault energy is concentrated at the arc itself as most of the voltage drop is at the arc. This energy, being confined to a small area, can therefore cause a lot of damage.
3. The arc can travel from its point of origin and can rapidly extend the area of damage.
4. All arcs are extinguished at each current zero point (at each point where the ac current reverses direction) and require a voltage much higher than the arcing voltage drop to restrike. This restrike voltage is approximately 375 volts.
5. Arcs under 200 amperes are unstable and are generally self-extinguishing.

Because of the high restrike voltage, most arcing ground faults extinguish themselves on 208Y/120 volt systems as the peak line-to-ground voltage is only 170 volts (see Figure 1.7). However, on 480Y/277 volt systems (and above), the arcs can be sustained as the peak voltage is 390 volts ($\sqrt{2} \times 277$).

It is difficult to express the amount of damage that can be caused by an arcing fault in absolute terms. After the fact, the amount of damage can of course be indicated in terms of the number of sections of switchgear destroyed, the amount of cable damaged, the number of motors destroyed, and so on. The extent of the damage has some relationship to the amount of electrical energy dissipated in the arc, but equal amounts of energy can cause different amounts of damage in different circumstances. However, notwithstanding these difficulties, Table 10.3 is an attempt to quantify the levels of damage that might be expected. The amount of energy involved in the arc is expressed in kilowatt-cycles (rather than kilowatt-hours) because the elapsed time is relatively short. To demonstrate the amount of damage that can be caused by arcing faults, refer to the two cases shown in Figure 10.14.

In case 1, a 1600 ampere feeder is protected by a low-voltage power circuit breaker that has the older type of electromechanical

TABLE 10.3 Estimated Levels of Damage Caused by Arcing Faults

Fault Energy (kW-cycles)	Estimated Level of Damage
100	Location of fault identifiable only by observation. Some spit and smoke marks.
2,000	Little damage; likely no hardware to replace. Equipment can be restored by cleaning smoke marks and repairing punctured insulation. This is recommended maximum level of let-through fault energy.
10,000	Fault will probably be contained by a metal enclosure.
20,000	Fault will probably burn through a single-thickness enclosure and spread to other sections of the equipment.
Above 20,000	Considerable destruction to equipment in proportion to the let-through fault energy.

series trip units, which respond only to overcurrents (see Section 8.3.2). The typical time–current curve for a breaker with these types of trip units is shown in the diagram. There is inverse time-delayed tripping up to 10 times the rating of the trip unit (that is, its pickup point) and instantaneous tripping above that point (see Section 6.7). Assume that an arcing fault has occurred from one phase of the feeder to ground, which has an rms value of 4000 amperes. This value is only 2.5 times the rating of the trip unit and therefore falls within the range of time-delayed tripping. The breaker with only the series-type trips cannot in fact discriminate between a 4000 ampere overload on the feeder and this arcing fault and therefore takes 80 seconds to disconnect the feeder and extinguish the arc. The 80 seconds amounts to 80 × 60 or 4800 cycles at 60 hertz. Assuming the voltage drop across the arc is 100 volts (the average value), the amount of arcing fault energy is calculated to be 1,920,000 kilowatt-cycles. Reference to Table 10.3 indicates that the amount of damage could be extensive.

On the other hand, if the fault in case 1 is a bolted type with the resulting large current, then the breaker will be tripped instantaneously. Assume a fault current of 32,000 amperes or 20 times the trip rating. The breaker would trip in 0.03 second or approximately 2 cycles, and even though there would be a higher current, the reduction in the elapsed time from 4800 to 2 cycles reduces the amount of fault energy to the point where no permanent damage should be done.

In case 2, a 600 ampere feeder is protected by current-limiting fuses (see Section 7.3). The arcing ground-fault current is assumed

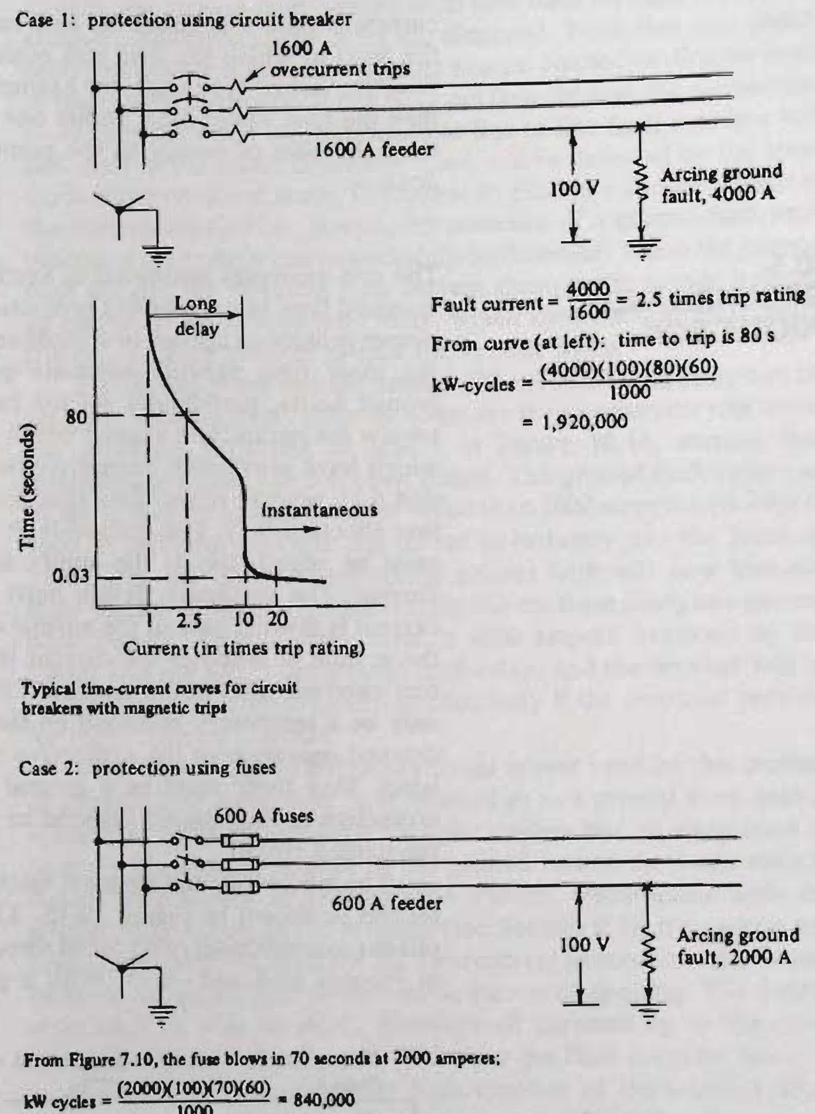


FIGURE 10.14

Effects of arcing ground faults on feeders with only overcurrent protection

to be 2000 amperes rms. Referring to Figure 7.10, which shows the typical response curves for UL class RK-5 current-limiting fuses, the blowing time for a 600 ampere fuse at 2000 amperes is 70 seconds ($70 \times 60 = 4200$ cycles). Assuming 100 volts across the arc, the fault energy is calculated as 840,000 kilowatt-cycles. Again, at this level of energy, a great deal of damage could be done. Similar to the breaker in case 1, the fuse is incapable of discriminating between an overload current and an arcing fault current. The 2000 ampere fault current is only 3.33 times the fuse rating and therefore well below the level at which the fuse will begin to current limit. If the fault were the bolted type with, for example, a value of 30,000 amperes, then the fuse would blow within one half-cycle and reduce the let-through value of energy to the point where no damage would be done.

10.5 GROUND-FAULT PROTECTION

The two examples presented in Section 10.4 clearly show that the standard type of overcurrent protection, while capable of providing proper protection against overloads and bolted-type faults, cannot at the same time provide adequate protection against arcing-type ground faults, particularly on the larger-capacity feeders. Let us review the parameters against which systems can be protected and which have previously been discussed, that is, overcurrents (Section 6.1), reverse power flow (Section 9.6), and differential protection (Section 9.7). For ground-fault protection, a new parameter must be added; this is the ability to detect the path of the fault current. The protective device must be able to detect whether the current is flowing only in the normal current-carrying conductors of the system or whether the current is flowing partly in the noncurrent-carrying parts of the system. If it is the former, then there may only be a temporary overload on the system, in which case time-delayed operation of the protective device is desirable. If it is the latter, then there must be a ground fault on the system, and the protective device should respond as fast as possible to disconnect the faulted circuit.

The most basic and simplest method of adding ground-fault protection is shown in Figure 10.15. This diagram shows the single-phase representation of a typical three-phase system, such as shown in Figures 10.8 and 10.11. With a ground fault anywhere on the

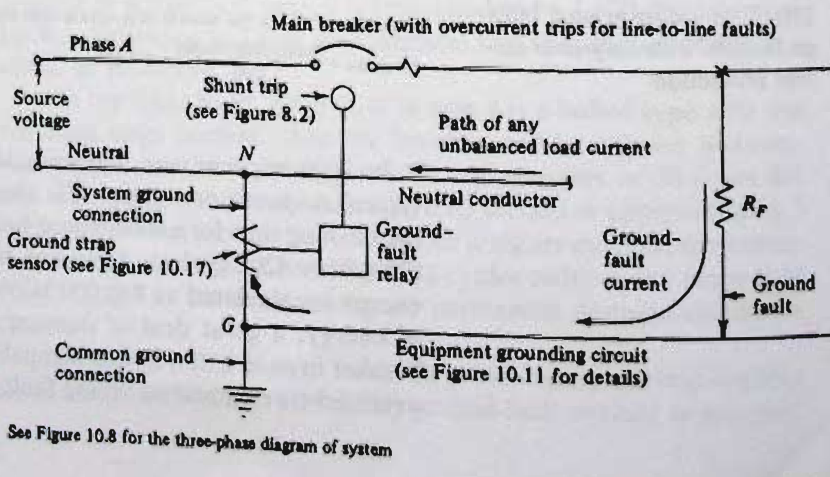


FIGURE 10.15

Basic method of adding ground-fault protection to a system

system, the ground-fault current must flow back through the system ground connection (G to N on the diagram). Note that any unbalanced load current flows through the neutral conductor directly back to the system neutral point and does not flow through the connection G–N. Furthermore, any overloads or line-to-line fault currents will flow only in the phase conductors and will be detected by the standard overcurrent trip units. Therefore, by placing a current sensor in the connection G–N as shown, the presence of a ground fault anywhere on the system can immediately be detected. When the ground fault occurs, the resulting fault current through the sensor induces an output to the ground-fault relay, which then energizes the shunt trip on the main breaker to shut the system down.

The pickup point and the timing of the ground-fault relay can be set quite independently from those set for the overcurrent trip units. For example, returning to case 1 in Figure 10.14, assume that ground-fault protection has been added. The ground-fault relay can be set to pick up at a much lower value than 1600 amperes (at 20% of 1600 or 320 amperes) and can be set to instantly trip the breaker. Therefore, the 4000 ampere arcing ground fault will now immediately trip the breaker, thus preventing the arc from doing any permanent damage. On the other hand, a 4000 ampere overload on the feeder will not affect the ground-fault relay, and the breaker will be opened by the series overcurrent trips only if the overload persists for more than 80 seconds.

Figure 10.17 shows a typical current sensor used for this method of ground-fault protection. It is referred to as a ground strap sensor since it is normally installed over the copper bar or strap used to connect the system neutral to the ground bus at the main switchboard. The sensor is essentially a current transformer with the ground strap acting as the primary (see Section 9.3). If a switch and fuse combination is used for the overcurrent protection, the switch must be equipped with an automatic means of opening. The switch must also be able to safely interrupt all currents up to the point where the fuses will take over and clear the fault currents first.

Because of the unusually high number of burn-downs from arcing ground faults that were occurring on 480Y/277 volt systems, the *National Electrical Code*, Section 230-95, now requires that

> Ground-fault protection of equipment shall be provided for solidly grounded wye electrical services of more than 150 volts to ground, but not exceeding 600 volts phase-to-phase for each service disconnecting means rated 1000 amperes or more. The ground-fault protection system shall operate to cause the service disconnecting means to open all ungrounded conductors of the faulted circuit. The maximum setting of the ground-fault protection shall be 1200 amperes and the maximum time delay shall be one second for ground-fault currents equal to or greater than 3000 amperes.

Section 230-95 also carries a note to the effect that *ground-fault protection may be desirable for service disconnecting means rated less than 1000 amperes*. Case 2 in Figure 10.14 shows that ground-fault protection should definitely be considered for services less than 1000 amperes.

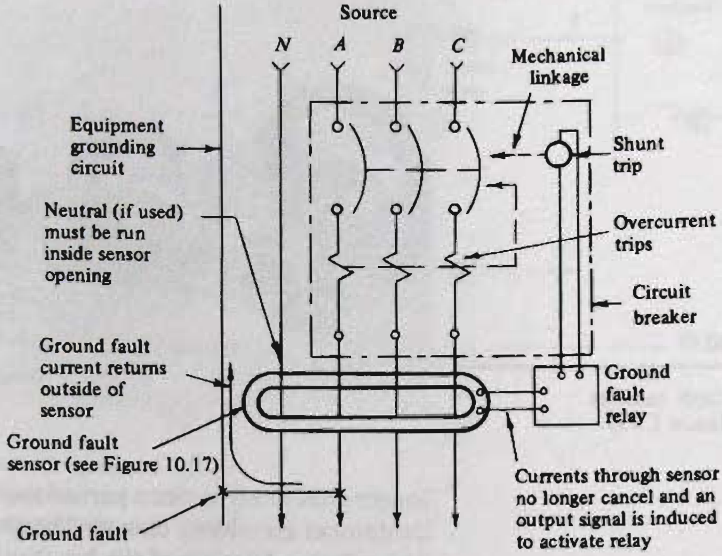
The foregoing method of ground-fault protection is relatively inexpensive to add to a system and it fully meets the code requirements. However, it has one major disadvantage: a ground fault anywhere on the system in excess of the pickup point of the ground-fault relay shuts down the entire system. This could prove to be inconvenient and costly in the long run because of the loss of work time and production. To overcome this disadvantage, ground-fault protection with selective coordination can be used.

10.5.1 Selective Coordination of Ground-Fault Protection

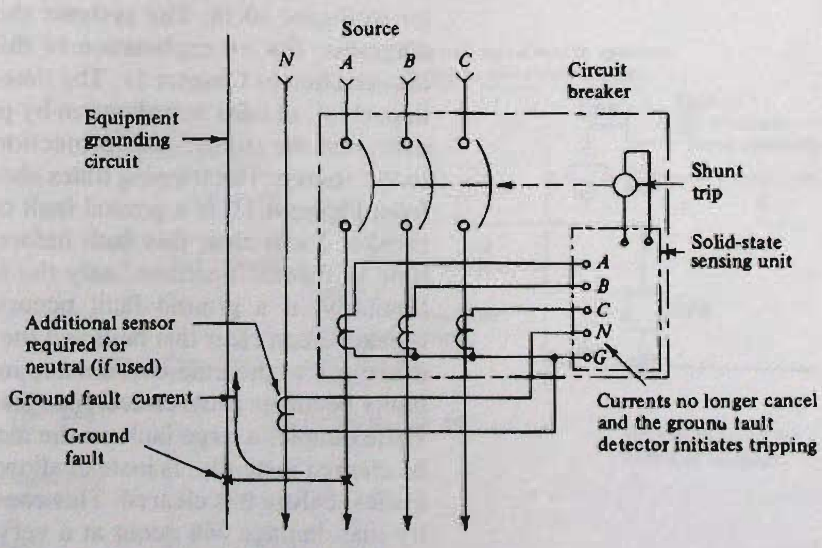
Selective coordination requires that only the actual circuit that is faulted be shut down. The desirability of having coordination of the protective devices is discussed in the introduction to Chapter 6. To obtain coordination, each branch feeder must be provided with its own ground-fault protection system.

Circuit breakers that use thermal–magnetic series overcurrent trip units, such as the standard molded-case breakers (Section 8.4.1) and the older type of low-voltage power circuit breakers that use magnetic series trip units, must have ground-fault protection added as shown in Figure 10.16(a). A ground-fault sensor is located on the loadside of the breaker through which all the feeder current-carrying conductors (phase conductors and the neutral when used) must be run. As long as the feeder currents flow only in these conductors, the instantaneous values of all the currents add up to zero, and there is no output from the sensor (see Section 1.6 for the current relationships in three-phase systems). However, when a ground fault occurs on any of the phases, part of the current returns outside the sensor through the equipment grounding circuit, and the currents flowing through the sensor no longer sum to zero. The resulting magnetic field induces an output from the sensor, which activates the ground-fault relay, which in turn energizes the shunt trip to open the breaker. Depending on the type and size of the breaker, an external source of control power may be needed to operate the system. The sensors come in two basic shapes, as shown in Figure 10.17. The toroidal shape is used when the sensor is to enclose cables, and the rectangular shape is used when the sensor is to enclose rigid copper or aluminum bus bars. These sensors are also referred to as *zero-sequence*, or preferably *core balance* current transformers.

The larger frame sizes of molded-case circuit breakers and the newer versions of the low-voltage power circuit breakers with solid-state trip units (Section 8.5.1) have the ground-fault protection in-



(a) Breakers with thermal and/or magnetic overcurrent trip units



(b) Breakers with solid-state trip units

FIGURE 10.16

Methods of providing ground-fault protection using circuit breakers

corporated directly into the system, as shown in Figure 10.16(b). An additional sensor is required for the neutral conductor when used in the feeder. As long as the current outputs from the sensors sum to zero, the input to the ground-fault detector (*N–G*) is zero. However, when a ground fault occurs, the current outputs from the sensors no

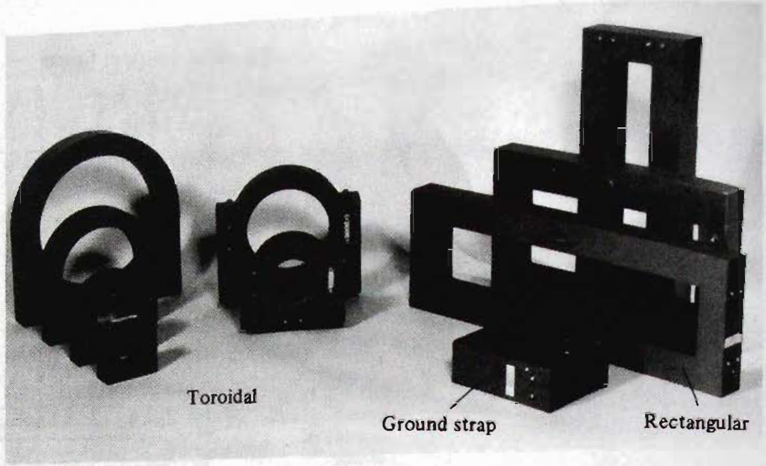


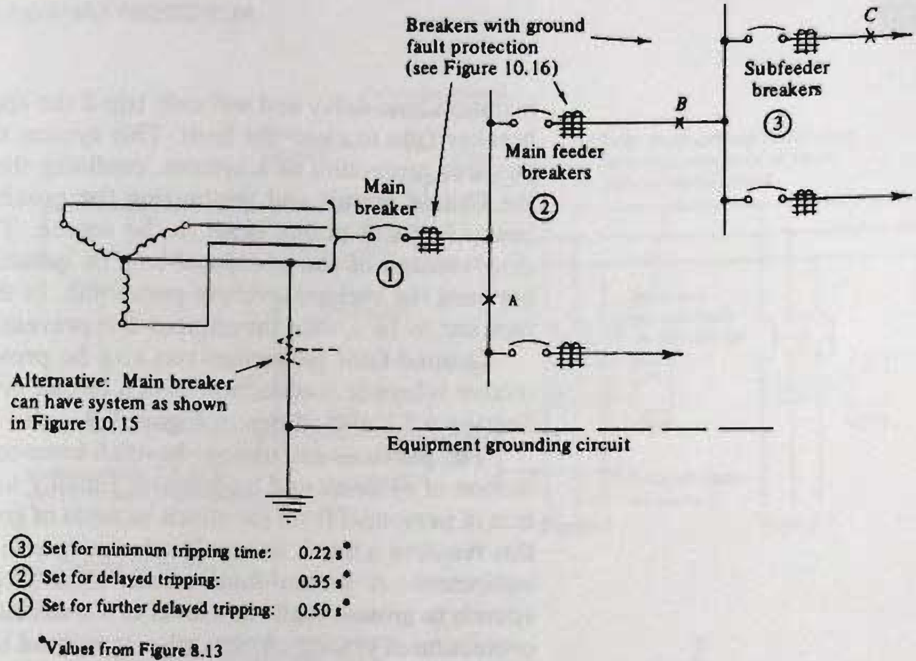
FIGURE 10.17

Ground-fault sensors (core-balance CTs)

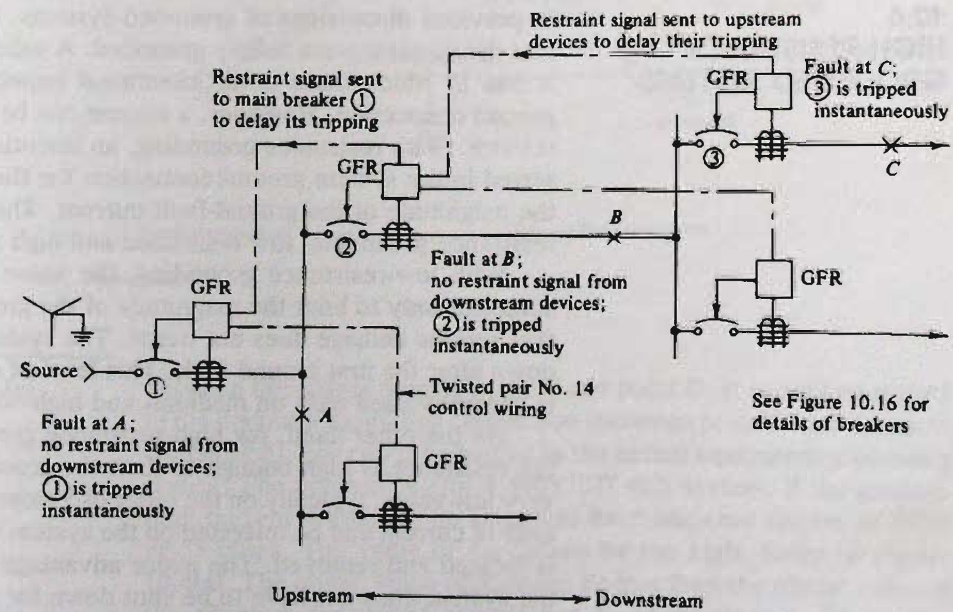
longer sum to zero, since part of the current is returning through the equipment grounding circuit. The ground-fault detector is activated and initiates tripping of the breaker.

Selective coordination can be achieved in two ways, the time-coordinated method and the zone-selective interlocking method. Refer to Figure 10.18. The systems shown are in the form of one-line diagrams. For an explanation of this type of diagram, refer to the introduction to Chapter 11. The time-coordinated method, as shown in part (a), obtains coordination by progressively setting longer time delays on the ground-fault protection system for the breakers closer to the source. The tripping times shown on the diagram are obtained from Figure 8.13. If a ground fault occurs on a subfeeder (point *C*), breaker 3 can clear this fault before the main feeder breaker 2 has time to react. Therefore, only the faulted subfeeder is shut down. Similarly, if a ground fault occurs on a main feeder (point *B*), breaker 2 can clear this fault and the main breaker stays closed. The drawback to the time-coordinated method is that the duration of the faults becomes progressively longer with more levels of selectivity. For example, a large fault on the main bus at point *A*, which should be cleared instantly, is instead allowed to persist for 0.50 second (30 cycles) before it is cleared. This considerably increases the probability that damage will occur at a very vital section of the system.

The zone-selective interlocking method overcomes this disadvantage of the time-coordinated method. As shown in Figure 10.18(b), control wiring is run between the breakers at each level of protection. With the addition of special circuitry within the ground-fault relays to provide appropriate restraint signals, each level of breaker is then able to discriminate between a fault in its own zone and one in a zone further downstream. Thus a breaker instantly clears a fault in its own zone. If the fault is in a downstream zone, it



(a) Time-coordinated selective method



(b) Zone-selective interlocking method

FIGURE 10.18 Ground-fault protection with selective coordination is put on time delay and will only trip if the appropriate downstream breaker fails to clear the fault. This system then provides the best possible protection to a system, confining the area of shutdown to the faulted circuit and minimizing the possibility of damage from heavy faults at points close to the source. There is, however, the disadvantage of the additional cost of installing the control wiring between the various levels of protection. In the long run, this could turn out to be a wise investment if it prevents costly shutdowns.

Ground-fault protection can also be provided when using protective relays in conjunction with a circuit breaker, as discussed in Section 9.5.2 and shown in Figure 9.9.

The previous discussions have all been concerned with the protection of systems and equipment. Equally important is the protection of personnel from the shock hazards of ground faults. However, this requires a much keener level of response than that required for equipment. A ground-fault circuit interrupter (GFCI), which responds to ground faults at a level of 5.0 milliamperes, is used for the protection of branch circuits where required by the code. The use of GFCIs is covered in Section 12.10.

10.6 HIGH-RESISTANCE GROUNDED SYSTEMS

In previous discussions of grounded systems, it has been assumed that the systems were solidly grounded. A solidly grounded system is one in which there is no intentional impedance in the system ground connection. However, a system can be grounded through a resistor. With resistance grounding, an intentional resistance is inserted in the system ground connection for the purpose of limiting the magnitude of the ground-fault current. There are two levels of resistance grounding, low resistance and high resistance.

With low-resistance grounding, the value of the resistance is sufficient only to limit the magnitude of the ground-fault current so that serious damage does not occur. The system must still be shut down after the first ground fault. This level of resistance grounding is generally used only on medium- and high-voltage systems.

On the other hand, for high-resistance grounding, the value of the resistance is high enough to limit the ground-fault current to a very low value, typically on the order of 5 amperes. This low magnitude of current can be tolerated on the system until the ground fault is located and removed. The major advantage then is the fact that the system does not have to be shut down for the first ground fault that occurs on the system. This is the same advantage enjoyed with the ungrounded system, but it is obtained without many of the disadvantages of the ungrounded system.

Figure 10.19 shows a system with high-resistance grounding. Note the position of the grounding resistor R_N. It must be placed

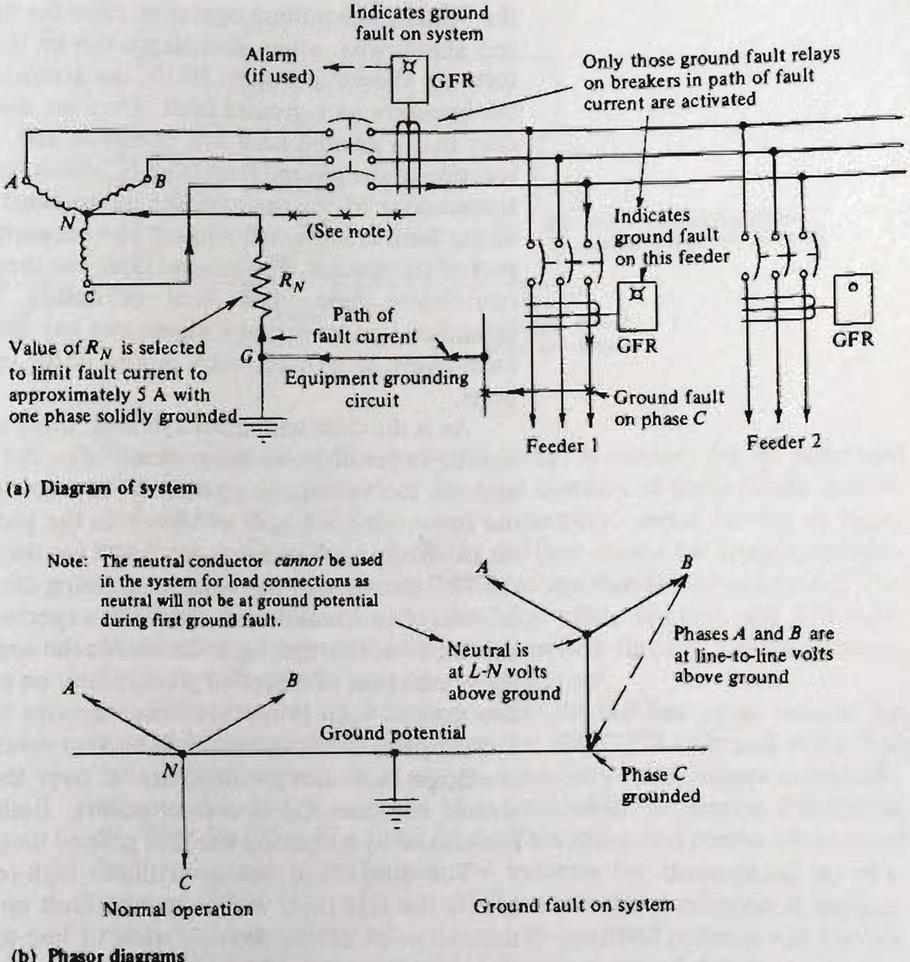


FIGURE 10.19

High-resistance grounded system

between the source neutral point N and point G. It cannot be placed in the common grounding connection (between point G and the earth connection), nor can it be placed in the actual equipment grounding circuit. The value of R_N for a 480Y/277 volt system, if the ground-fault current is going to be limited to the 5 amperes shown, is 277/5 or 55 ohms. The value of R_N cannot be too high. Refer to Figure 10.4(a). The ohmic value of R_N must be less than the ohmic value of the effective distributed capacitance X_C of the system. Otherwise, the transient overvoltage conditions, as is possible with ungrounded systems, can occur. In other words, if the value of R_N is too high, the system will start to behave like an ungrounded system.

With high-resistance grounded systems, in addition to allowing the system to continue operating after the first ground fault without any shutdowns, other advantages can be incorporated into the system. As shown in Figure 10.19, the ground-fault relays do not trip the breakers on a ground fault. They are used instead, first, to indicate that a ground fault has occurred and, second, to indicate the location of the ground fault (that is, which feeder is faulted). This is a tremendous advantage over the ungrounded system, as the location of the fault is indicated without the necessity of shutting down any part of the system. The ground fault can then be removed at the first convenient time. The final advantage of the high-resistance grounded system is that it eliminates any dangerous and destructive flash-overs to ground, such as can occur on solidly grounded systems.

As is the case with most systems, there are some disadvantages. Similar to the ungrounded systems, after the first ground fault on the system, the voltage to ground of the two unfaulted phases rises to the line-to-line voltage, as shown in the phasor diagrams in Figure 10.19. While each phase is insulated for the full line-to-line voltage, the 73% increase in the voltage stressing can increase the likelihood of insulation breakdowns over the expected life of the system. A second disadvantage, again similar to the ungrounded system, is that the occurrence of a second ground fault on another phase before the first ground fault is removed then creates a line-to-line fault. Both faulted parts of the system will be shut down simultaneously. Also, the large fault current must travel over the equipment grounding circuit between the two fault points. Both disadvantages can be minimized by removing the first ground fault as quickly as possible.

The third disadvantage with the high-resistance grounded system is the fact that, with a ground fault on one of the phases, the neutral point of the system rises to line-to-neutral voltage above ground, as shown in Figure 10.19 (b). Therefore, the neutral cannot be used in the system for load connections, as the neutral when used as a circuit conductor must remain at ground potential at all times. This precludes such single-phase loads as fluorescent lighting, which is normally connected line-to-neutral, from being directly connected to the system. Instead, these loads must be fed through separate transformers, with the neutral of the secondaries of these transformers solidly grounded. High-intensity discharge (HID) light sources are an exception to this problem. Two-winding transformers can be used for the ballasts of each lamp, as shown in Figure 10.20. The primary of the ballast can be connected line to line to the high-resistance grounded system and the secondary, which is electrically isolated from the primary, can then be grounded as shown.

In conclusion, the high-resistance grounded system is not a good choice for a commercial building where a significant part of the

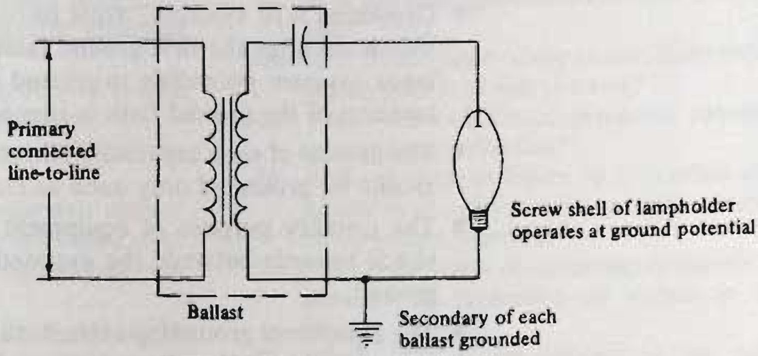


FIGURE 10.20

Two-winding ballast for HID lamps

load is likely to be fluorescent lighting. However, for an industrial plant where the majority of the load consists of three-phase motors and where the HID light source (mercury, metal halide, or high-pressure sodium lamp) is usually the best choice for large area lighting, the high-resistance grounded system should be considered. The small amount of power required for office lighting and 120 volt, single-phase loads can easily be supplied through separate transformers with solidly grounded secondaries.

There has been a definite trend in the last few years toward the use of high-resistance grounding for 480Y/277 volt and 600Y/347 volt systems in industrial plants, especially those where continuity of power is vital. Exception 5 has been added to Section 250-5(b) in the 1987 *National Electrical Code*. This exception permits the use of high-resistance grounded neutral systems for three-phase ac systems of 480 to 1000 volts provided that (1) the conditions of maintenance and supervision assure that only qualified persons will service the installation, (2) continuity of power is required, (3) ground detectors are installed on the system, and (4) line-to-neutral loads are not served. Section 250-27 has also been added to cover the requirements for high-impedance grounded neutral system connections.

SUMMARY

- System grounding is the intentional electrical connection to ground of one of the current-carrying conductors of the electrical system.
- Equipment grounding is the connection to ground of all the nonelectrical conductive materials that enclose or are adjacent to the energized conductors.
- Ungrounded delta systems, while offering some advantages, have many operating disadvantages. High transient overvoltages can occur that are not immediately evident. Ground faults are difficult to locate.

- Grounded wye systems, while having the disadvantage of a partial shutdown after the first ground fault, have many important advantages. System potentials to ground are limited to safe values. The location of the ground fault is immediately indicated.
- The neutral of each separately derived system or section of a system should be grounded only once as close to the source as possible.
- The primary purpose of equipment grounding is to eliminate any shock hazards between the exposed enclosures of the system and ground.
- The equipment grounding system must have adequate current-carrying capability to handle any ground-fault current without creating any shock, fire, or explosion hazards.
- The impedance of the equipment grounding circuit must be kept as low as possible to ensure proper operation of protective devices and to minimize any dangerous differences of potential under fault conditions.
- There must be only one common connection to earth for both the system and equipment grounding.
- The metallic raceways used to carry circuit conductors offer a very low impedance return path for ground-fault currents when properly installed as part of the equipment grounding system.
- Arcing ground faults, if not properly handled, can do a great deal of damage on systems that operate at more than 150 volts to ground.
- Ground-fault protection is required by code on all solidly grounded systems that exceed 150 volts to ground and are rated at 1000 amperes or more.
- Selective coordination of the ground-fault protection confines any power shutdown to the faulted circuit.
- High-resistance grounding of systems, where practical, offers some important operating advantages. No part of the system has to be shut down after the first ground fault. The location of the ground fault can easily be determined without disrupting the operation of the system.

QUESTIONS

1. What is the difference between system grounding and equipment grounding?
2. What is an ungrounded system?
3. What is the principal reason for operating a system ungrounded?
4. What is the advantage of using three single-phase transformers connected in delta?
5. List four disadvantages of ungrounded systems.
6. What is the most significant operating characteristic of the grounded system?
7. Which low-voltage systems are required by the electrical code to be grounded?
8. What is the primary purpose for grounding an electrical system?

9. List all other benefits of a grounded system.
10. What are the two disadvantages of grounded systems?
11. What differentiates a separately derived system from one that is not separately derived?
12. List three points governing the grounding of separately derived systems.
13. Explain why the neutral of a separately derived system should be grounded at one location only.
14. What are the noncurrent-carrying conductors of a system?
15. List the components that can form part of the equipment grounding circuit of a system.
16. What are the three objectives of the equipment grounding system?
17. What operating problems arise if the impedance of the equipment grounding circuit is too high?
18. Why does the electrical code call for one common grounding electrode for both the system and equipment grounding?
19. Why is it necessary to keep an equipment grounding circuit conductor as close as possible to the feeder phase conductors?
20. Does a metal raceway used to carry the feeder conductors serve as a good equipment grounding conductor? Explain.
21. Why are arcing ground faults hard to detect with the standard overcurrent devices?
22. Why can arcing ground faults cause a lot of damage?
23. Why do sustained arcing ground faults rarely occur on 208Y/120 volt systems?
24. What is the additional parameter required for ground-fault protection?
25. With reference to Figure 10.15, explain why the ground-fault relay sensor must be located between points *N* and *G*.
26. What is the major disadvantage of the method of ground-fault protection as shown in Figure 10.15?
27. Which systems are required by the electrical code to have ground-fault protection?
28. What is the major disadvantage of the time-coordinated method of ground-fault protection?
29. What is the major improvement offered by the zone-selective interlocking method of ground-fault protection?
30. What is the purpose of high resistance as used for grounding a system?
31. What is the major advantage of the high-resistance grounded system?
32. With reference to Figure 10.19, explain why the grounding resistor R_N must be connected between points *N* and *G*.
33. For a high-resistance grounded system, why is the neutral not permitted to be used as a circuit conductor to connect to loads?

PROBLEMS

1. The service entrance feeder conductors for a system are 300 MCM THW copper. Determine the minimum size of the common grounding electrode conductor (copper).
2. The service entrance feeder conductors for a system are No. 1 aluminum. Determine the minimum size of the common grounding electrode conductor (aluminum).
3. A feeder is protected by a 1600 A frame breaker with a 1200 A trip unit. Determine the minimum size of the equipment grounding conductor (copper).
4. A feeder is protected by a 600 A fuse. Determine the minimum size of the equipment grounding conductor (copper).
5. Determine the estimated level of damage if a 1000 rms ampere arcing ground fault occurs on a feeder protected by 400 A UL class RK-5 fuses (Figure 7.10).

11 Design of Feeders

OBJECTIVES

After studying this chapter, you will be able to:

- Identify the factors that affect ampacity ratings of conductors.
- Determine the ampacity ratings of conductors.
- Determine the short-circuit rating of conductors.
- Determine the voltage drop of a feeder.
- Identify types of cables.
- Recognize the uses of raceways.
- Select conduit sizes.
- Design feeders.
- Recognize the purpose for using cable trays and busways.

INTRODUCTION

We have now reached the point where we can begin to discuss the actual design of the electrical system itself. All electrical systems have the common purpose of providing electrical energy to the utilization equipment as safely and reliably as economically possible. The system must be adequate to deliver to the location of each piece of equipment the necessary energy on a continuous basis, without any component overheating or causing unacceptable voltage drops.

The initial planning of a system involves the preparation of a one-line diagram showing all the interconnections and basic components, such as shown in Figure 11.1. The one-line format uses simplified symbols and a single line to represent a feeder or circuit, rather than using a line to represent each phase or conductor of the system. For further explanation of the one-line concept, refer to Figure 13.1.

An important part of any electrical system is the electrical wiring that connects all the components. The connecting wiring can be divided into three sections, as shown in Figure 11.1:

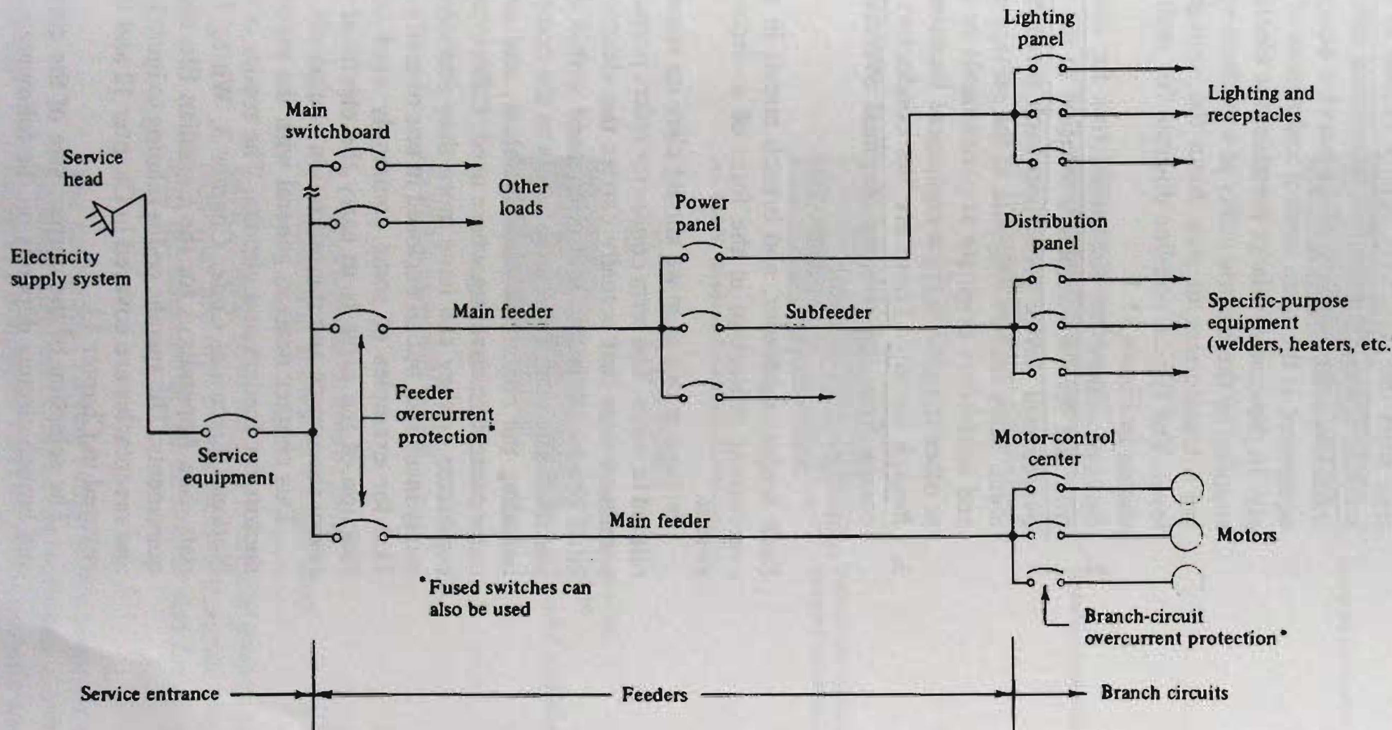


FIGURE 11.1

One-line diagram showing basic system components

1. *Service entrance:* These are the conductors for delivering energy from the electricity supply system to the premises being served. The conductors are terminated near their point of entrance into the building in the service equipment. The service equipment is the main control and means of cutoff for the supply. In the case of a large premise, the electric power is usually supplied by the electric utility at a medium-voltage level, requiring a transformer to step down the voltage to the utilization level. The typical one-line diagram for such an arrangement is shown in Figure 15.1.
2. *Feeders:* These are the conductors for delivering the energy from the service equipment location to the final branch-circuit overcurrent device protecting each piece of utilization equipment. Main feeders originate at the service equipment location, and subfeeders originate at panelboards or distribution centers at other than the service equipment location.
3. *Branch circuits:* These are the conductors for delivering the energy from the point of the final overcurrent device to the utilization equipment.

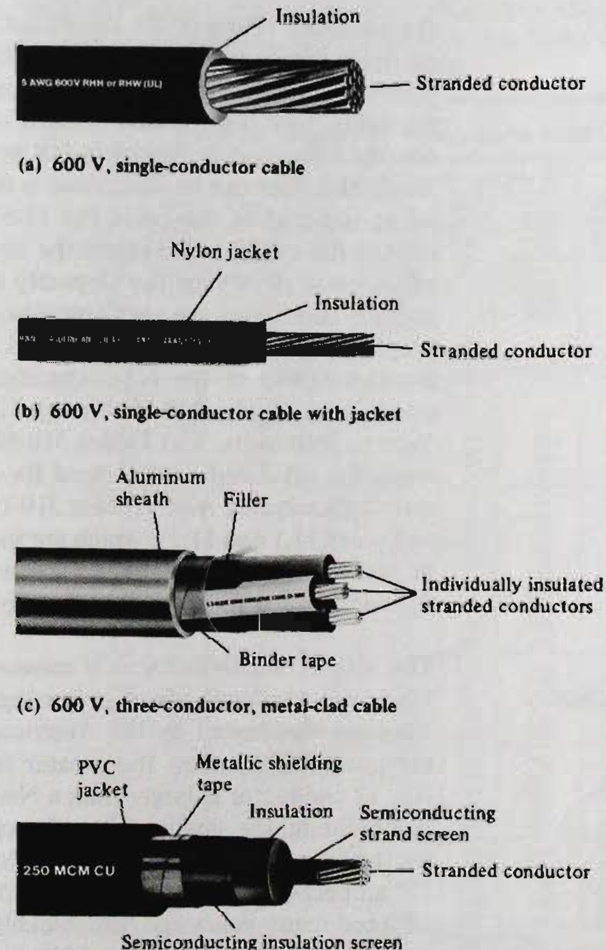
Each feeder, subfeeder, and branch circuit in turn needs its own overcurrent protection in the form of a circuit breaker or fused switch.

Perhaps at this time we should clear up some basic terminology related to *wires*. The term *conductor* refers properly to the copper or aluminum wire that actually carries the electric current. An insulated conductor is one that is encased within electrical insulation material. The term *cable* then refers to the complete wire assembly including the conductor, the insulation, and any shielding and/or outer protective covering where used. Cables can have just a single conductor or they can have more than one conductor, each separately insulated, but all enclosed in one overall covering. See Figure 11.2 for examples of some commonly used cables. The primary function of the cable is to carry the electrical energy reliably between the source and the utilization equipment.

This chapter deals in general with the proper selection of conductors for feeders and circuits. The reader is also referred to the *National Electrical Code*, Chapter 3, Wiring Methods and Materials. See Appendix A for the Canadian Electrical Code (CEC) requirements. The specific codes relating to branch circuits for lighting and receptacles are covered in Chapter 12 and those for motors are covered in Chapter 13.

The selection of the correct size of the conductors for feeders and branch circuits depends on the following:

1. Continuous current rating



(a) 600 V, single-conductor cable

(b) 600 V, single-conductor cable with jacket

(c) 600 V, three-conductor, metal-clad cable

(d) 5000 V, single-conductor cable

FIGURE 11.2

Examples of commonly used cables

2. Short-circuit current rating
3. Maximum allowable voltage drop

Each of these requirements is initially dealt with separately. Design examples are then presented that integrate the three requirements into the selection of the conductor size for a particular feeder.

11.1 CONTINUOUS CURRENT RATING OF CONDUCTORS

The continuous current rating of a conductor is referred to in the *National Electrical Code* as *ampacity* and is defined as *the current in amperes a conductor can carry continuously under the conditions of use without exceeding its temperature rating*. The physical characteristics of a cable obviously play an important part in determining the ampacity rating of the conductor. However, equally important, as indicated in the foregoing definition, are the *conditions of use* under which the cable operates. As current flows in the conductor of the cable, heat is generated because of the resistance of the conductor (the heat is proportional to I^2R as per Section 1.1.4). The rate at which this heat can be dissipated is not only dependent on the insulating material of the cable but also on the environment that surrounds the cable, for example the air temperature. The precise calculations to determine the ampacity of a conductor operating under specific conditions are very complex. Fortunately, tables have been prepared that allow us to obtain this ampacity rating fairly quickly. Section 310-15 of the *NEC* specifically covers the ampacities of conductors. Tables 310-16 through 310-31 apply to conductors rated for 0 to 2000 volts, and Tables 310-69 through 310-84 apply to solid dielectric insulated cables rated for 2001 to 35,000 volts. We will start by analyzing *NEC* Tables 310-16 and 310-27 (reproduced here as Tables 11.1 and 11.2), which are the two most applicable to wiring in and adjacent to buildings. The ampacity rating of a conductor depends on the following characteristics and conditions.

11.1.1 Size of Conductor

The size of a conductor is a measure of its cross-sectional area. There are two methods of indicating conductor sizes. The smaller sizes are designated by the American Wire Gage (AWG) number; the lower the number, the greater the cross-sectional area (thus a No. 12 conductor is larger than a No. 14). For general power wiring in a building, the smallest size of copper conductor that can be used for the low-voltage wiring is No. 14 (rated for a maximum loading of 15 amperes). Unfortunately, when the AWG designation was adopted many years ago, presumably it was not foreseen that conductors larger than No. 1 would be in common use. For the next size larger the designation 0 was adopted. Then in an attempt to carry on with this system the next three larger sizes were designated as 00, 000, and 0000, respectively. However, as shown in Tables 11.1 and 11.2, it is common practice to identify these conductor sizes as 1/0, 2/0, 3/0, and 4/0 (pronounced one-aught, two-aught, and so on).

For conductors larger than 4/0, the cross-sectional area in thousands of circular mils (MCM) is used to designate their size. Thus the next size above 4/0 (211.6 MCM) is 250 MCM. Note that M is used here to designate 1000. This is not consistent with the SI system, which uses k for 1000. Thus MCM should be more properly designated kcmil. A circular mil is the area of a circle that is 1 mil or 1/1000th of an inch in diameter. The circular mil area of a conductor is then equal to its diameter in mils squared. Thus a solid conductor, 1 inch (1000 mils) in diameter, has a circular mil area of 1000 times 1000 or 1,000,000, which is designated 1000 MCM. Its area in square

TABLE 11.1 Ampacities of Not More Than Three Single Insulated Conductors, Rated 0 through 2000 Volts, in Raceway in Free Air (from *NEC* Table 310-16)

Based on Ambient Air Temperature of 30°C (86°F).

Size	Temperature Rating of Conductor. See Table 310-13.								Size
	60°C (140°F)	75°C (167°F)	85°C (185°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	85°C (185°F)	90°C (194°F)	
AWG MCM	TYPES †TW, †UF	TYPES †FEPW, †RH, †RHW, †THW, †THWN, †XHHW, †USE, †ZW	TYPE V	TYPES TA, TBS, SA, AVB, SIS, †FEP, †FEPB, †RHH, †THHN, †XHHW*	TYPES †TW, †UF	TYPES †RH, †RHW, †THW, †THWN, †XHHW †USE	TYPE V	TYPES TA, TBS, SA, AVB, SIS, †RHH, †THHN, †XHHW*	AWG MCM
	COPPER				ALUMINUM OR COPPER-CLAD ALUMINUM				
18	....	....	....	14	....	....	....	....	....
16	....	....	18	18	....	....	....	....	....
14	20†	20†	25	25†	....	....	....	....	....
12	25†	25†	30	30†	20†	20†	25	25†	12
10	30	35†	40	40†	25	30†	30	35†	10
8	40	50	55	55	30	40	40	45	8
6	55	65	70	75	40	50	55	60	6
4	70	85	95	95	55	65	75	75	4
3	85	100	110	110	65	75	85	85	3
2	95	115	125	130	75	90	100	100	2
1	110	130	145	150	85	100	110	115	1
1/0	125	150	165	170	100	120	130	135	1/0
2/0	145	175	190	195	115	135	145	150	2/0
3/0	165	200	215	225	130	155	170	175	3/0
4/0	195	230	250	260	150	180	195	205	4/0
250	215	255	275	290	170	205	220	230	250
300	240	285	310	320	190	230	250	255	300
350	260	310	340	350	210	250	270	280	350
400	280	335	365	380	225	270	295	305	400
500	320	380	415	430	260	310	335	350	500
600	355	420	460	475	285	340	370	385	600
700	385	460	500	520	310	375	405	420	700
750	400	475	515	535	320	385	420	435	750
800	410	490	535	555	330	395	430	450	800
900	435	520	565	585	355	425	465	480	900
1000	455	545	590	615	375	445	485	500	1000
1250	495	590	640	665	405	485	525	545	1250
1500	520	625	680	705	435	520	565	585	1500
1750	545	650	705	735	455	545	595	615	1750
2000	560	665	725	750	470	560	610	630	2000

AMPACITY CORRECTION FACTORS

Ambient Temp. °C	For ambient temperatures other than 30°C (86°F), multiply the ampacities shown above by the appropriate factor shown below.								Ambient Temp. °F
21-25	1.08	1.05	1.04	1.04	1.08	1.05	1.04	1.04	70-77
26-30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	79-86
31-35	.91	.94	.95	.96	.91	.94	.95	.96	88-95
36-40	.82	.88	.90	.91	.82	.88	.90	.91	97-104
41-45	.71	.82	.85	.87	.71	.82	.85	.87	106-113
46-50	.58	.75	.80	.82	.58	.75	.80	.82	115-122
51-55	.41	.67	.74	.76	.41	.67	74	.76	124-131
56-60	....	.58	.67	.71	....	.58	.67	.71	133-140
61-70	....	.33	.52	.58	....	.33	.52	.58	142-158
71-80	....	....	.30	.41	....	....	.30	.41	160-176

† Unless otherwise specifically permitted elsewhere in this Code, the overcurrent protection for conductor types marked with an obelisk (†) shall not exceed 15 amperes for 14 AWG, 20 amperes for 12 AWG, and 30 amperes for 10 AWG copper; or 15 amperes for 12 AWG and 25 amperes for 10 AWG aluminum and copper-clad aluminum after any correction factors for ambient temperature and number of conductors have been applied.

* For dry and damp locations only. See 75°C column for wet locations.

TABLE 11.2 Ampacities of Three Single Insulated Conductors, Rated 0 through 2000 Volts, in Underground Electrical Ducts (from *NEC* Table 310-27)

Table 310-27. Ampacities of Three Single Insulated Conductors, Rated 0 through 2000 Volts, in Underground Electrical Ducts (Three Conductors per Electrical Duct) Based on Ambient Earth Temperature of 20°C (68°F), Electrical Duct Arrangement per Figure 310-1, 100 Percent Load Factor, Thermal Resistance (RHO) of 90, Conductor Temperature 75°C (167°F)

Size AWG MCM	1 Electrical Duct (Fig. 310-1 Detail 1)	3 Electrical Ducts (Fig. 310-1 Detail 2)	6 Electrical Ducts (Fig. 310-1 Detail 3)	1 Electrical Duct (Fig. 310-1 Detail 1)	3 Electrical Ducts (Fig. 310-1 Detail 2)	6 Electrical Ducts (Fig. 310-1 Detail 3)	Size AWG MCM
	TYPES †RHW, †THW, †THWN, †XHHW, †USE	TYPES †RHW, †THW, †THWN, †XHHW, †USE	TYPES †RHW, †THW, †THWN, †XHHW, †USE	TYPES †RHW, †THW, †THWN, †XHHW, †USE	TYPES †RHW, †THW, †THWN, †XHHW, †USE	TYPES †RHW, †THW, †THWN, †XHHW, †USE	
	COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM			
14	24†	22†	16†	....	....	....	14
12	36†	31†	24†	28†	22†	18†	12
10	46†	41†	32†	36†	31†	25†	10
8	58	51	44	45	40	34	8
6	77	67	56	60	52	44	6
4	100	86	73	78	67	57	4
3	116	99	83	91	77	65	3
2	132	112	93	103	87	73	2
1	153	128	106	119	100	83	1
1/0	175	146	121	136	114	94	1/0
2/0	200	166	136	156	130	106	2/0
3/0	228	189	154	178	147	121	3/0
4/0	263	215	175	205	168	137	4/0
250	290	236	192	227	185	150	250
300	321	260	210	252	204	165	300
350	351	283	228	276	222	179	350
400	376	302	243	297	238	191	400
500	427	341	273	338	270	216	500
600	468	371	296	373	296	236	600
700	509	402	319	408	321	255	700
750	529	417	330	425	334	265	750
800	544	428	338	439	344	273	800
900	575	450	355	466	365	288	900
1000	605	472	372	494	385	304	1000

Ambient Temp. °C	For ambient temperatures other than 20°C (68°F) multiply the ampacities shown above by the appropriate factor shown below.						Ambient Temp. °F
6-10	1.09	1.09	1.09	1.09	1.09	1.09	43-50
11-15	1.04	1.04	1.04	1.04	1.04	1.04	52-59
16-20	1.00	1.00	1.00	1.00	1.00	1.00	61-68
21-25	.95	.95	.95	.95	.95	.95	70-77
26-30	.90	.90	.90	.90	.90	.90	79-86

†Unless otherwise specifically permitted elsewhere in this Code, the overcurrent protection for conductor types marked with an obelisk (†) shall not exceed 15 amperes for 14 AWG, 20 amperes for 12 AWG and 30 amperes for 10 AWG copper; or 15 amperes for 12 AWG and 25 amperes for 10 AWG aluminum and copper-clad aluminum.

inches is $\pi D2/4 = \pi/4 = 0.785$ square inches. It is not practical to use solid conductors for the larger sizes as they would be very difficult to bend. Therefore, smaller strands of wire are twisted together to form one large conductor (see Figure 11.2). The wire size designation then gives the total actual cross-sectional area of all the individual strands added together.

If we refer to Tables 11.1 and 11.2, the conductor sizes in either AWG or MCM are listed in the left column and are repeated for convenience on the right side. Naturally, the larger the cross-sectional area (the size) of the conductor, the greater its ampacity rating. However, the ampacity rating is not a linear function of size. For example, in Table 11.1 the rating of a 250 MCM copper conductor with 60°C insulation (column 2) is 215 amperes, whereas the rating of a 500 MCM copper conductor (twice the size) is 320 amperes, only 1.5 times as much. With alternating current circuits, the current-carrying capacity per circular mil of conductor area decreases with size because of the skin effect, plus the fact that it is harder to dissipate the heat within large conductors. Therefore, it is often preferable to parallel smaller conductors for each phase of a feeder rather than use one large conductor. Paralleling of conductors is discussed in Section 11.6.

11.1.2 Conductor Material

The two conductor materials in common use are copper and aluminum. Copper has historically been used for conductors of insulated cables because of its desirable electrical and mechanical properties. Aluminum has had restricted use but is considered where its ampacity rating to weight ratio and its relative cost are favorable. The use of aluminum requires a larger conductor size in order to have the same ampacity rating as copper. For example, refer to Table 11.1. A No. 1 AWG copper conductor with 90°C temperature rating (column 5) has a rating of 150 amperes. An aluminum conductor with the same temperature rating (column 9) has to be size 2/0 (two sizes larger) to have the same rating of 150 amperes.

Unlike copper, aluminum has a few undesirable properties when used as the conductor material. An oxide film forms on the surface of aluminum. This aluminum oxide is essentially an insulating film, causing poor electrical contact at connections. To help overcome this problem, the aluminum must be cleaned immediately prior to being connected. On the other hand, the oxide film that forms on copper is a relatively good conductor, causing no real problem at connections. Aluminum conductors can break after bending much more readily than copper conductors and therefore aluminum conductors must be handled very carefully during installation. Aluminum deforms at a lower pressure than copper and can become loose at connections after a period of time. The resulting poor electrical contact can cause excessive heat buildup, leading to the ultimate failure of the insulation. The terminals of equipment, unless otherwise marked, are approved for use with copper conductors only.

11.1.3 Maximum Allowable Operating Temperature

The maximum continuous current that a conductor can carry is ultimately determined by the temperature at which it is allowed to operate for prolonged periods of time. This maximum allowable temperature is set by the type of insulating material that surrounds the conductor and is selected so that a reasonable working life (years) is obtained. If this operating temperature is exceeded for long periods of time, the insulation ages much more rapidly, becoming hard and brittle and subject to failure. The temperature rating classifications for building wires are 60°C, 75°C, and 90°C, as shown in Table 11.1 (note that 85°C is also shown, but this classification only applies to one very special type of cable).

A higher allowable operating temperature increases the ampacity rating for a particular conductor size. For example, from Table 11.1, a No. 2 AWG copper conductor, with 60°C insulation (column 2), has an ampacity of 95 amperes, whereas, with 90°C insulation (column 5), its ampacity is increased to 130 amperes. The higher permissible operating temperature means that there is a greater temperature difference between the conductor and the surrounding medium, resulting in a more rapid dissipation of the heat generated in the conductor. The higher temperature rated insulation may cost a bit more, but if its use results in a smaller size conductor being required for a given feeder, then the overall cost may be less (see Examples 11.15 and 11.16). An exception to the foregoing is with regard to conductor sizes Nos. 14, 12, and 10. See the note at the foot of Tables 11.1 and 11.2. The setting of the overcurrent protection for the conductors indicated cannot exceed the values quoted in the note regardless of the temperature classification of the insulation. The application of this restriction is discussed further in Section 12.1. Also refer to Section 11.1.7 for limitations imposed by conductor terminations.

11.1.4 Ambient Temperature

The ambient temperature refers to the temperature of the medium through which the wiring is to be run (air or earth). As the ambient temperature increases, there is less temperature differential between the conductor and the surrounding medium, and the rate at which the heat is dissipated from the conductor decreases. This means that the conductor can carry less current before it reaches its maximum operating temperature.

Table 11.1 is based on an ambient air temperature of 30°C (86°F), as noted in the heading. There can be areas within a building where the ambient temperature exceeds 30°C, such as in enclosed ceiling areas adjacent to heating pipes and in rooms with heating equipment. For wiring installed in areas with ambient temperatures higher than 30°C, the ampacity of the conductors must be reduced. Conversely, if the ambient temperature is lower than 30°C, the ampacity can be increased. Table 11.2 is based on an earth ambient temperature of 20°C. The appropriate correction factors are shown at the bottom of the ampacity tables. For example, from Table 11.1 for a conductor with 90°C insulation (columns 5 and 9) operating in an ambient temperature of 40°C, the correction factor is 0.91. Thus a No. 6 copper conductor, 90°C, has an ampacity rating of 75 amperes at 30°C and only a rating of 0.91 times 75 or 68 amperes at 40°C. Further examples are shown in Section 11.1.6.

11.1.5 Conductors Installed in Raceways

The most common method of installing wiring in a building is to run the conductors in a raceway, as shown in Figure 11.3. The use of raceways is discussed in Section 11.5. Note the heading of Table 11.1, which states *not more than three single insulated conductors, rated 0 to 2000 volts, in raceway*. The raceway enclosure impedes the dissipation of the heat from the conductors. This fact requires the derating of a conductor as compared to its ampacity rating when run by itself in air (its free air rating). As an example, if we refer to Table 310-17 in the *NEC*, the free air rating of a No. 1/0 copper conductor, 90°C, is 260 amperes, whereas when three No. 1/0 copper conductors, 90°C, are installed in a raceway, the ampacity of each conductor is only 170 amperes (Table 11.1).

Note that Table 11.1 applies to conductors in raceways installed in free air. However, this table can also be applied where conduits are installed in walls and structural floor slabs that are above grade level. Where conduits are run adjacent to each other, sufficient spacing must be maintained between them to permit proper cooling. Table 11.2, on the other hand, applies to 75°C rated conductors installed in underground electrical ducts. The ampacities are based

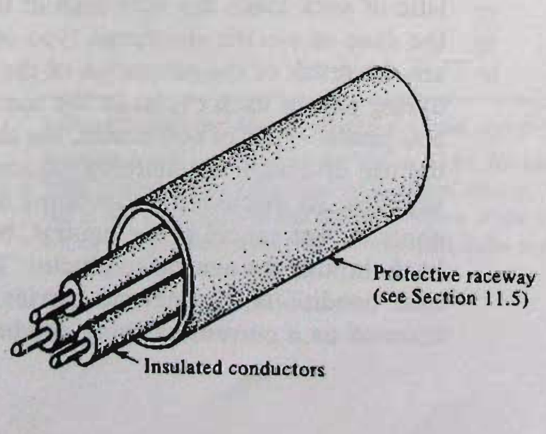


FIGURE 11.3

Conductors installed in a raceway

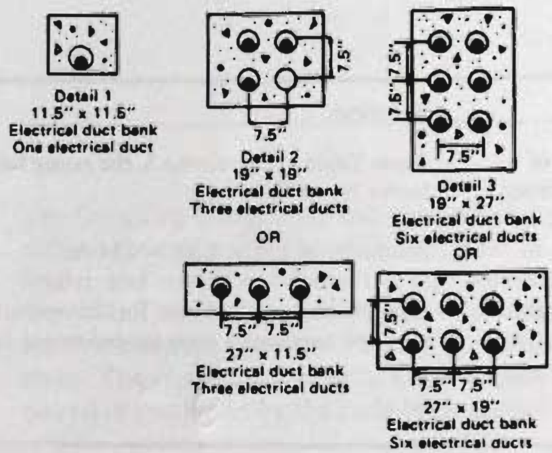
on an ambient earth temperature of 20°C (68°F). Ratings are shown for arrangements where from 1 to 6 electrical ducts are run in the same duct bank. The duct arrangements and accompanying notes are shown in Table 11.3(a).

The ratings in Tables 11.1 and 11.2 apply when not more than three conductors are installed in the one raceway or electrical duct. When more than three conductors are installed, their ampacity rating must be decreased to compensate for the added conductors. Adjacent conductors have the dual effect of raising the temperature within the raceway and of impeding the heat dissipated from the raceway. Table 11.3(b) shows the percentages that must be applied to the values listed in Tables 11.1 and 11.2. For example, as previously indicated, three No. 1/0 copper conductors, 90°C, installed in a raceway in free air have an ampacity of 170 amperes. If six No. 1/0 copper conductors, 90°C, are installed in one raceway, then the rating of each conductor is reduced to 80% of 170, or 136 amperes. Note that for more than nine conductors in one raceway the percentage values are based on a load diversity of 50% between the circuits involved.

The interpretation of the number of conductors in a raceway for the purpose of establishing their ampacity rating is actually based on the number of current-carrying conductors. In the case of a three-phase, four-wire system employing a neutral conductor (see Section 1.6.1), it must be determined whether the neutral has to be considered as a current-carrying conductor. This is covered in Note No. 10 that accompanies *NEC* Tables 310-16 through 310-31. Normally, the neutral conductor of a three-phase, four-wire system does not have to be counted when applying the percentages listed in Table 11.3(b), as the neutral current is zero under balanced conditions. A major exception to this is the case where the majority (more than 50%) of the load on a feeder or circuit consists of electric discharge type of lighting (see Section 4.2), electronic data processing systems, or other similar types of equipment. The current waveforms characteristic of such loads are very high in third-harmonic components. In the case of electric discharge type of lighting, the third harmonics are the result of the saturation of the magnetic cores of the ballasts during part of each cycle. In the case of electronic data processing and similar types of equipment, the third harmonics are the result of the use of diodes for charging capacitors on the input of the power supplies. As discussed in Section 1.6.4, the third-harmonic components do not cancel at the neutral, but in fact add together to flow back through the neutral conductor. Therefore, even under balanced load conditions, the neutral carries a large current and must be counted as a current-carrying conductor (see example 11.2). Note

TABLE 11.3 Details and Adjustment Factors for Tables 11.1 and 11.2

(a) Electrical duct details for use with Table 11.2 (from *NEC* Figure 310-1 and Notes to Tables 310-25 through 310-27).



(i) For cables installed in two electrical ducts in one horizontal row, 7.5-inch center-to-center spacing, multiply ampacity shown for 1 electrical duct by 0.88.

(ii) For cables installed in four electrical ducts in one horizontal row, 7.5-inch center-to-center spacing, multiply ampacity shown for 3 electrical ducts by 0.94.

(b) Ampacity adjustment factors for more than three conductors in a raceway or cable [from *NEC* Notes to Tables 310-16 through 310-31, No. 8(a)].

Number of Conductors	Percent of Values in Tables 11.1 and 11.2
4–6	80
7–9	70
10–24[a]	70
25–42[a]	60
43 and above[a]	50

[a] These factors include the effects of a load diversity of 50%.

that grounding or bonding conductors do not have to be counted when applying the percentages listed in Table 11.3(b).

11.1.6 Determining the Ampacity of Conductors

The following examples illustrate the use of the ampacity tables and derating factors as discussed in the previous sections. (See Appendix A for application of CEC rules.)

■ EXAMPLE 11.1

Determine the ampacity of a three-phase, four-wire feeder using 250 MCM copper conductors, 75°C insulation, installed in a raceway in free air, 40°C ambient temperature, and feeding an incandescent lighting load.

Solution

From Table 11.1, column 3, the rating for 250 MCM is 255 A. The correction factor for 40°C is 0.88:

$$\text{Ampacity} = 255 \times 0.88 = 224 \text{ A}$$

There is no need to derate for the neutral (the fourth wire) because there are no third harmonics with incandescent lighting.

■ EXAMPLE 11.2

Determine the ampacity of a three-phase, four-wire feeder using 400 MCM copper conductors, 90°C insulation, installed in a raceway in free air, 30°C ambient temperature, and feeding a fluorescent lighting load.

Solution

From Table 11.1, column 5, the rating for 400 MCM is 380 A. The neutral must be counted as the fourth current-carrying conductor because of the fluorescent lighting (which is an electric discharge type). From Table 11.3(b), the ampacity adjustment factor for four conductors is 0.80:

$$\text{Ampacity} = 380 \times 0.80 = 304 \text{ A}$$

■ EXAMPLE 11.3

Determine the ampacity of No. 6 aluminum conductors, 75°C insulation, eight current-carrying conductors in a raceway in free air, 45°C ambient temperature.

Solution

From Table 11.1, column 7, the rating for No. 6 is 50 A. The correction factor for 45°C is 0.82. From Table 11.3(b), the ampacity adjustment factor for eight conductors is 0.70:

$$\text{Ampacity} = 50 \times 0.82 \times 0.70 = 28.7 \text{ A}$$

■ **EXAMPLE 11.4**

Determine the ampacity of a three-phase, three-wire feeder using 4/0 copper conductors, 75°C insulation, installed in an underground electrical duct, ambient earth temperature of 20°C. There is a second feeder installed in the same duct bank.

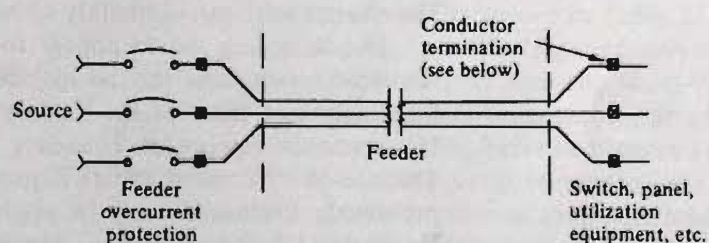
Solution

From Table 11.2, column 2, the rating for No. 4/0 is 263 A. From Table 11.3(a), the multiplying factor for two ducts is 0.88:

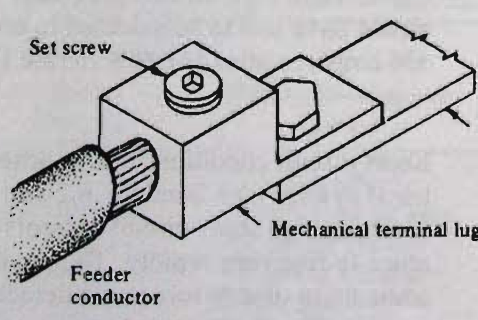
Ampacity = 263 × 0.88 = 231 A

11.1.7 Ampacity Limitations Imposed by Conductor Terminations

The foregoing discussions and examples have not taken into consideration the ampacity limitations imposed by the terminations of the feeder and circuit conductors at equipment terminals. Refer to Figure 11.4. The maximum allowable operating temperature permitted for the terminals is covered by the approvals granted for the equipment. The *National Electrical Code* requires that all equipment required or permitted by the code be approved by a qualified electrical



(a) Typical feeder connections



(b) Typical conductor termination

FIGURE 11.4

Feeder terminations

testing laboratory and that this equipment be used or installed in accordance with any instructions included in the testing or labeling of the equipment. A major electrical testing laboratory is the Underwriters Laboratories, Inc. (UL). A basic statement in the *UL Electrical Construction Materials Directory* notes that

> The termination provisions of the approved equipment are based on the use of 60°C insulated conductors in circuits rated 100 amperes or less and the use of 75°C insulated conductors in higher rated circuits. The 60°C ampacities for circuits rated 100 amperes or less and the 75°C ampacities for circuits rated over 100 amperes shall be based on Table 310-16 of the *National Electrical Code* [Table 11.1]. Conductors having a temperature rating higher than specified may be used if the size of the conductor is based on the 60°C ampacity for circuits 100 amperes and less and the 75°C ampacity for circuits over 100 amperes.

These temperature limitations are required to protect electrical equipment. A cable rated for 90°C, when loaded to its full ampacity rating, operates at a temperature of 90°C. If this cable is connected to an equipment terminal rated for 75°C, then the higher conductor temperature can eventually overheat the terminal, even though the load current does not exceed the rated current of the equipment. The excess heat can ultimately damage the equipment.

The foregoing would appear to eliminate the use of the 90°C insulated conductors for the majority of the feeders installed in a building, since most of the feeders and circuits are terminated in UL-approved equipment. However, this is not necessarily the case. The use of 90°C rated cables is justified where derating factors as previously discussed must be applied. To explain this, return to Example 11.2. Since the final ampacity of 304 amperes is less than the listed 75°C ampacity of 335 amperes for 400 MCM, there will be no problem at the terminations of this feeder. If 75°C rated conductors were to be used for this feeder, then one size larger (500 MCM) would have had to be selected to obtain the same ampacity rating of 304 amperes after the 80% derate factor is applied.

11.2 SHORT-CIRCUIT CURRENT RATING OF CONDUCTORS

Short-circuit conditions can impose tremendous stresses on an electrical system (see Sections 6.2 and 6.3). In the case of feeders, the resulting high short-circuit currents can cause the conductor temperature to rise very rapidly. The device protecting the feeder requires some finite time before it can detect and then fully interrupt the fault current. The feeder conductors must be sized large enough to carry the fault current for this time interval without reaching a temperature that will permanently damage the insulation (see Section 6.4). The maximum allowable short-circuit transient temperature rating of a cable is much higher than its maximum allowable operating temperature rating because the short circuit is of such short duration. The maximum short-circuit temperature rating depends on the type of insulation material used for the cable.

At this point we must return to Section 6.5 on asymmetrical fault currents and in particular to Figure 6.4. With an asymmetrical fault current, the heating of the conductors is greater than it would be if the fault current were symmetrical. Therefore, allowance must be made for this increased heating in selecting the correct size of conductor. The ratio between the asymmetrical and the symmetrical current is dependent on the rate of decay of the dc component after the fault occurs. If we let K_0 represent this ratio, then

$$I_{ASY} = K_0 \times I_{SYM} \tag{11.1}$$

where I_{ASY} = asymmetrical short-circuit current used to size the conductor
I_{SYM} = available short-circuit symmetrical current

The value of K_0 depends on the system voltage and type of overcurrent device used for the feeder, as shown in Table 11.4. This table also shows the total clearing times for the overcurrent devices.

The precise calculation to determine the short-circuit current rating of a cable is very complex. Fortunately, graphs have been prepared that simplify the process. Refer to Figures 11.5, 11.6, and 11.7. These graphs show short-circuit current on the vertical axis and the conductor size on the horizontal axis, with a series of diagonal lines indicating the duration of the fault (the total clearing time of

TABLE 11.4 Clearing Times and K_0 Factors

System Voltage	Feeder Overcurrent Device	Total Clearing Time (cycles)	K_0 Factor
Up to 1000 V	Circuit breaker[a]	2	1.3
	Current-limiting fuse	½	1.4
Above 1000 V	Air circuit breaker	5	1.15
	Oil circuit breaker	8	1.1
	Power fuse	1	1.6
	Current-limiting fuse	½	1.6

[a] Noncurrent-limiting type.

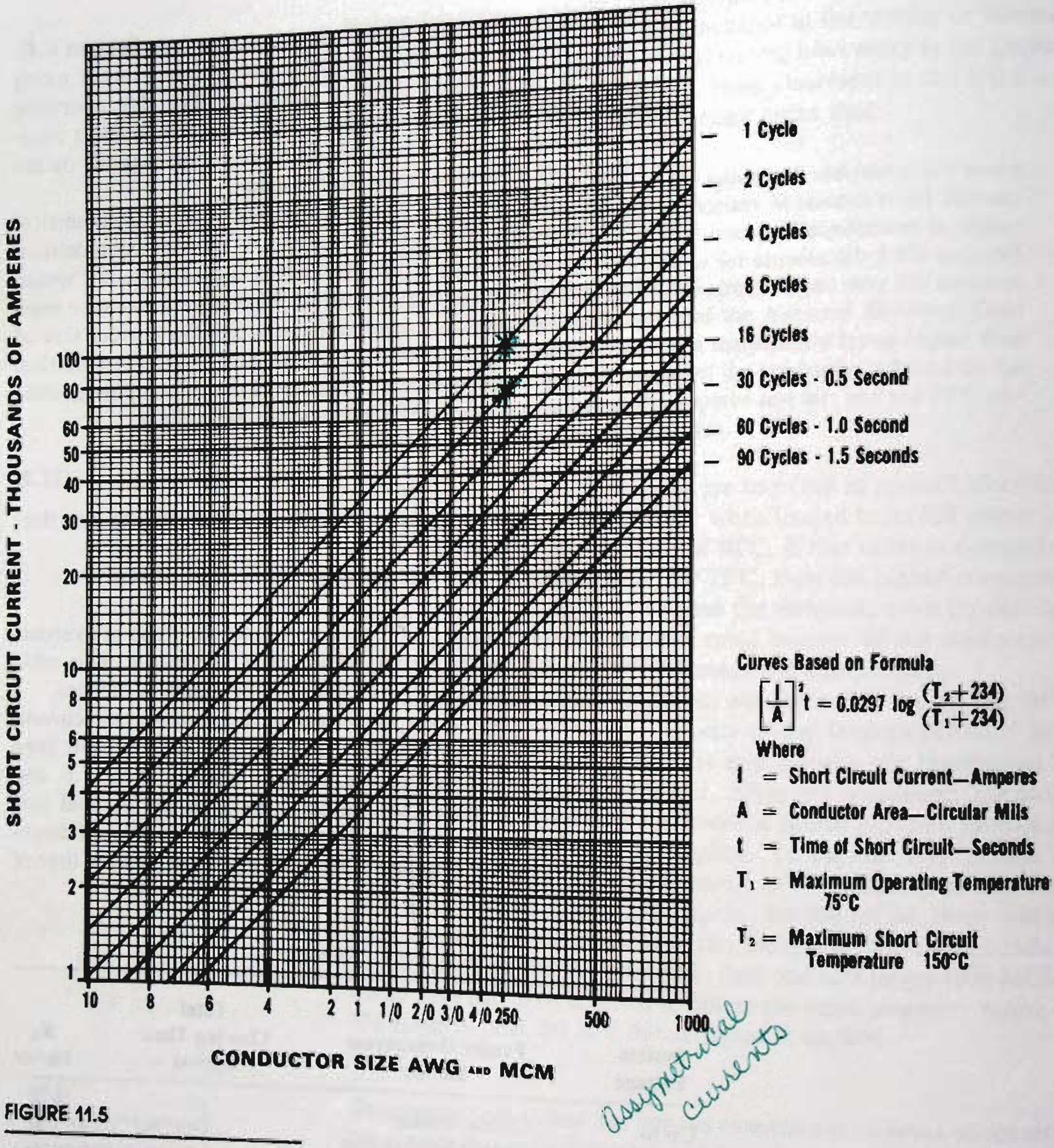


FIGURE 11.5

Allowable short-circuit currents for *copper* conductors with thermoplastic insulation (*NEC* type THW, CSA type TW75)

the overcurrent device protecting the conductors). Note the descriptions for the different graphs. Figure 11.5 applies to copper conductors with thermoplastic insulation, which has a maximum operating temperature of 75°C and a maximum short-circuit temperature of 150°C. Figure 11.6 applies to copper conductors with cross-linked

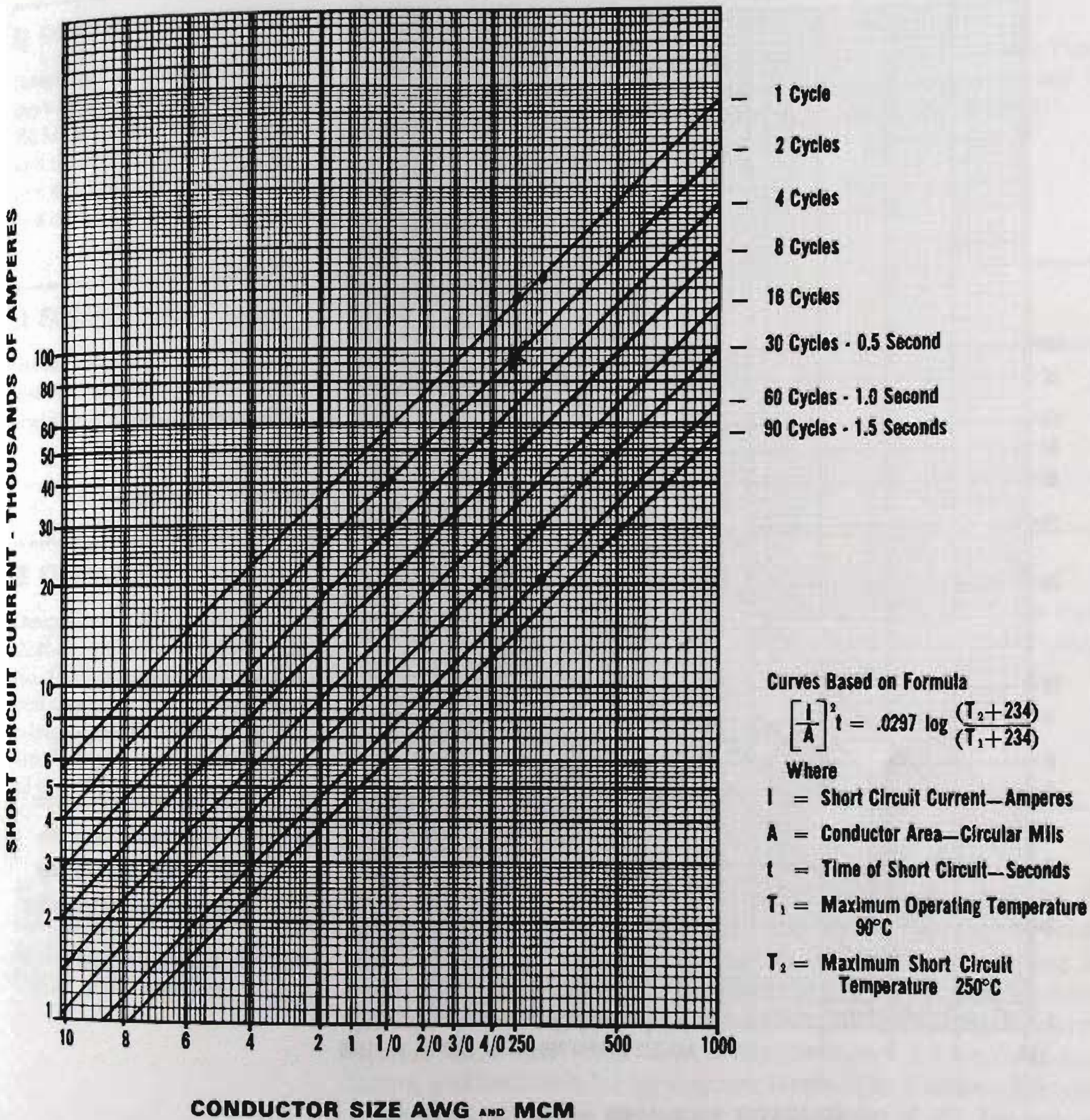


FIGURE 11.6

Allowable short-circuit currents for *copper* conductors with cross-linked synthetic polymer insulation [*NEC* type XHHW, CSA type RW90 (XLPE)]

synthetic polymer insulation, which has a maximum operating temperature of 90°C and a maximum short-circuit temperature of 250°C. Figure 11.7 applies to aluminum conductors with the cross-linked synthetic polymer insulation. Examples 11.5–11.7 will show how to use these graphs.

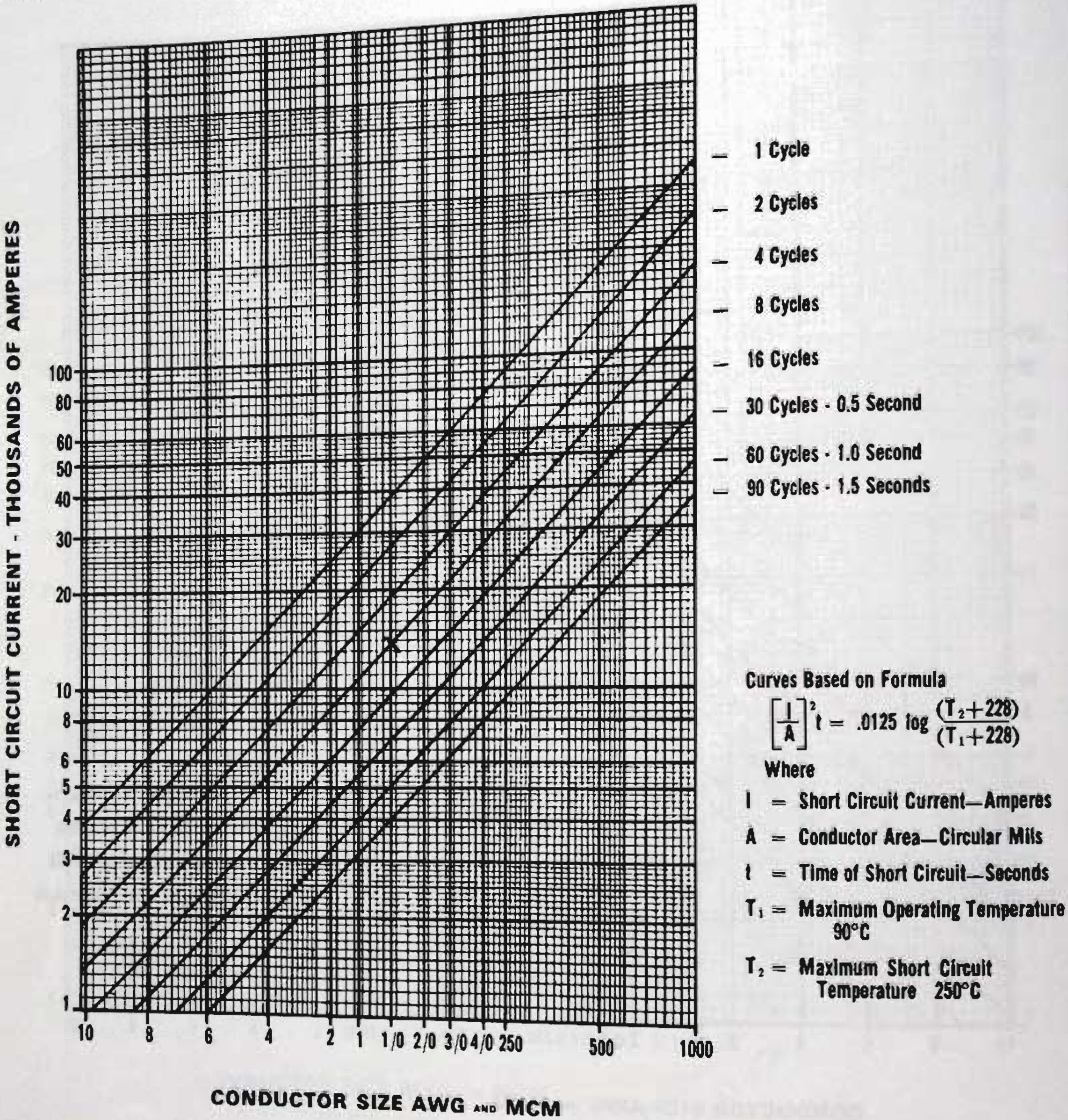


FIGURE 11.7

Allowable short-circuit currents for *aluminum* conductors with cross-linked synthetic polymer insulation [*NEC* type XHHW, CSA type RW90 (XLPE)]

■ EXAMPLE 11.5

Determine the symmetrical short-circuit current rating of a 250 MCM copper conductor with thermoplastic insulation on a 480 V feeder protected by a circuit breaker.

Solution

From Table 11.4, the clearing time is 2 cycles and K_0 is 1.3. From Figure 11.5, the point of intersection of the vertical line for 250 MCM and the diagonal line for 2 cycles is 72 × 1000 A (I_{ASY}). Using Equation 11.1,

$$I_{SYM} = \frac{72{,}000}{1.3} = 55{,}400 \text{ A}$$

■ EXAMPLE 11.6

Repeat Example 11.5 except that the insulation is the cross-linked synthetic polymer type.

Solution

From Figure 11.6, using the same values as in Example 11.5, the intersection of the lines gives 95 × 1000 A. Using Equation 11.1,

$$I_{SYM} = \frac{95{,}000}{1.3} = 73{,}100 \text{ A}$$

■ EXAMPLE 11.7

Determine the symmetrical short-circuit current rating of a No. 1/0 aluminum conductor with cross-linked synthetic polymer insulation on a 4160 V feeder protected by an oil circuit breaker.

Solution

From Table 11.4, the clearing time is 8 cycles and K_0 is 1.1. From Figure 11.7, the point of intersection of the vertical line for No. 1/0 and the diagonal line for 8 cycles is 13.6 × 1000 A (I_{ASY}). Using Equation 11.1,

$$I_{SYM} = \frac{13{,}600}{1.1} = 12{,}400 \text{ A}$$

11.3 MAXIMUM ALLOWABLE VOLTAGE DROP

It is very important to have the correct voltage at the outlet that serves a piece of utilization equipment. Most equipment is voltage sensitive, and an excessive voltage drop impairs the starting and operation of the equipment. See Section 2.9 with regard to motors and their rated voltages. See Chapter 4 with regard to light sources: Section 4.1.4 for incandescent lamps, Section 4.3.8 for fluorescent lamps, and Section 4.5.1 for mercury lamps. The *National Electrical Code* recommends a maximum voltage drop of 3% for any one branch circuit or feeder with a maximum voltage drop from the service entrance to the utilization outlet of 5% [*NEC* Sections 210-19(a) and 215-2(b)].

The voltage drop of a feeder or branch circuit when carrying current (under load conditions) is caused by the resistance and inductive reactance associated with the conductors. Refer to Figure 11.8(a), which shows the equivalent single-phase circuit diagram of a three-phase feeder under balanced load conditions. The resistance *R*

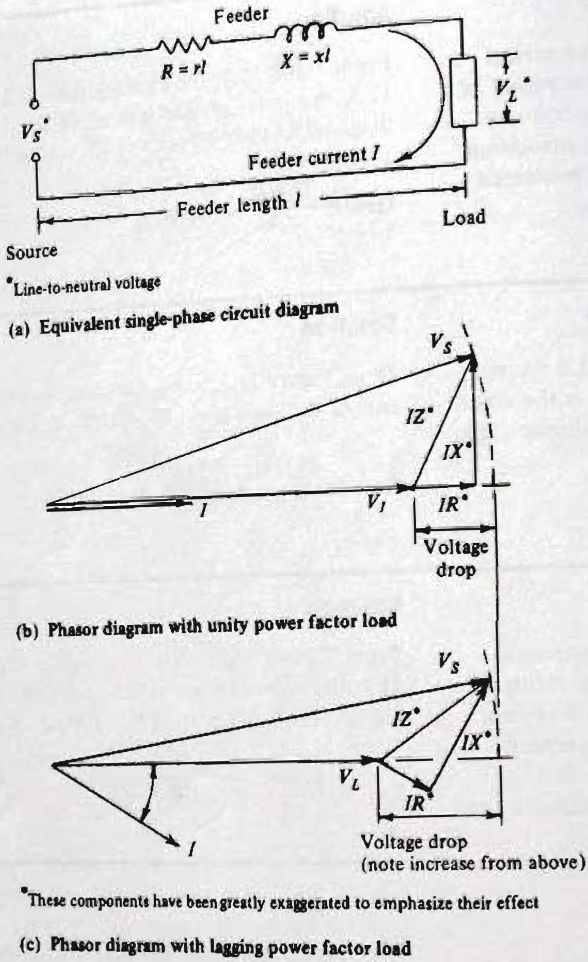


FIGURE 11.8

Voltage drop on a feeder

and the inductive reactance X are shown as lumped values that represent the total resistance and inductive reactance actually distributed over the entire circuit. Figure 11.8(b) shows the voltage and current relationships of the circuit when operating with a unity (100%) power factor load (see Section 1.4.4). The voltage drop is the difference between the voltage at the source of the feeder V_S, which is assumed to be constant, and the voltage across the load V_L, which varies with the feeder current I. This voltage drop in volts is then expressed as a percentage of the source voltage. Therefore,

$$\% \text{ voltage drop} = \frac{V_S - V_L}{V_S} \times 100 \tag{11.2}$$

The voltage drop on the feeder depends on

1. Current I flowing in the feeder
2. Length l of the feeder

3. Resistance per unit of length r
4. Inductive reactance per unit of length x
5. Power factor of the load

The fact that the power factor of the load affects the voltage drop is illustrated in Figure 11.8(c). With a lagging power factor load, the load current lags the voltage, which alters the relationships of the voltage drop components IR and IX with respect to the voltage. This change in relationships increases the difference between V_S and V_L, thus increasing the voltage drop even though the magnitudes (scalor values) of the components have not changed.

The resistance per unit of length depends on

1. Conductor material
2. Cross-sectional area of the conductor (size)
3. Conductor operating temperature

The inductive reactance per unit of length depends on

1. Diameter of the conductor (self-inductance)
2. Spacing between conductors (mutual inductance)
3. Material surrounding the conductors (whether magnetic or nonmagnetic)
4. Frequency of the power supply

The precise calculations to determine the voltage drop for a particular feeder are complex. However, once again tables can be used to give fairly accurate values that are satisfactory for most applications. Because of the many factors previously listed, these tables must be prepared for specific conditions. Refer to Table 11.5, which shows voltage drops for 60 hertz systems. Note that this table applies to three single conductors in conduit, which in effect ties down the conductor spacing. Next, note the various columns for either copper or aluminum conductors and for either magnetic (steel) or nonmagnetic (aluminum or plastic) conduit or armor. Finally, values are listed for 80% and 90% lagging and 100% power factor. The values in the table are for conductors operating at temperatures up to 75°C, with the correction factor for 90°C as per footnote 2. For different sets of conditions, such as conductor spacing, other tables or graphs are required.

The two factors previously listed as affecting the voltage drop and that would be hard to accommodate directly into the table are the current flowing in the feeder and the length of the feeder. Therefore, the values listed in the table represent the voltage drops for each 1000 ampere-feet of circuit. The unit ampere-feet is simply the product of the current times the length in feet. The following examples illustrate the use of Table 11.5.

TABLE 11.5 Voltage Drops for 60 Hz Systems*

Size AWG or MCM	COPPER: Magnetic Conduit or Armour 80% P.F.	90% P.F.	100% P.F.	COPPER: Non-Mag. Conduit or Armour 80% P.F.	90% P.F.	100% P.F.	ALUMINUM: Magnetic Conduit or Armour 80% P.F.	90% P.F.	100% P.F.	ALUMINUM: Non-Mag. Conduit or Armour 80% P.F.	90% P.F.	100% P.F.
14	2.540	2.790	3.067	2.535	2.780	3.060						
12	1.570	1.749	1.917	1.565	1.749	1.923	2.460	2.748	3.020	2.448	2.743	3.020
10	.993	1.103	1.200	.987	1.103	1.201	1.553	1.732	1.900	1.547	1.726	1.900
8	.635	.699	.750	.629	.693	.751	.993	1.103	1.195	.981	1.091	1.195
6	.421	.462	.485	.461	.456	.485	.647	.710	.762	.641	.710	.768
4	.277	.300	.306	.271	.294	.306	.421	.456	.491	.410	.450	.479
2	.185	.196	.196	.179	.191	.191	.271	.294	.300	.266	.289	.306
1	.150	.162	.150	.150	.156	.150	.225	.237	.242	.219	.231	.242
1/0	.127	.133	.121	.121	.127	.121	.185	.196	.191	.179	.191	.191
2/0	.109	.110	.098	.098	.104	.092	.150	.156	.150	.144	.150	.150
3/0	.092	.092	.081	.081	.087	.075	.127	.133	.121	.121	.127	.121
4/0	.081	.075	.064	.069	.069	.057	.104	.104	.098	.098	.104	.098
250	.070	.070	.054	.064	.064	.051	.092	.092	.081	.086	.087	.081
300	.064	.064	.045	.056	.055	.042	.081	.081	.069	.075	.075	.069
350	.058	.055	.039	.051	.049	.036	.075	.075	.058	.069	.069	.057
400	.055	.051	.035	.047	.044	.032	.069	.069	.053	.064	.064	.050
500	.049	.045	.029	.042	.039	.026	.058	.057	.043	.053	.051	.040
600	.046	.041	.024	.038	.034	.022	.055	.051	.036	.048	.046	.034
700	.043	.038	.021	.036	.032	.019	.051	.047	.032	.044	.041	.029
750	.042	.037	.020	.034	.031	.017	.049	.046	.030	.042	.039	.028
1000	.038	.032	.016	.029	.025	.013	.044	.040	.024	.039	.036	.024

* Values are per 1000 ampere-feet for three single conductors in conduit.

1. Values are based on three-phase, line-to-neutral voltages. For line-to-line voltage drops, multiply by a factor of 1.73. For single-phase circuits, multiply by a factor of 2.0.

2. Values are for conductor operating temperatures up to 75°C. For conductors operating at 90°C, multiply by a factor of 1.1.

Source: Courtesy of Canada Wire and Cable Limited

■ EXAMPLE 11.8

Calculate the percentage voltage drop on a 60 Hz, 480 V, three-phase feeder, load current 100 A, power factor of load 100%, length 300 ft, consisting of three No. 2 copper conductors rated for 75°C operation installed in steel conduit.

Solution

From Table 11.5, column 4 (copper, magnetic conduit, 100% P.F.), the voltage drop/1000 ampere-feet for No. 2 is 0.196. From note 2, no correction is needed for 75°C.

Ampere-feet = 100 × 300 = 30,000 = 30 × 1000

Voltage drop (line to neutral) = 30 × 0.196 = 5.88 V

Voltage drop (line to line) = 1.73 × 5.88 = 10.2 V (note 1)

The 10.2 V represents the difference between V_S and V_L. Using Equation 11.2,

$$\% \text{ voltage drop} = \frac{10.2}{480} \times 100 = 2.1\%$$

■ EXAMPLE 11.9

Calculate the percentage voltage drop on a 60 Hz, 208 V, three-phase feeder, load current 290 A, power factor 90% lagging, length 150 ft, consisting of three 250 MCM copper conductors rated for 90°C operation installed in aluminum conduit.

Solution

From Table 11.5, column 6 (copper, nonmagnetic conduit, 90% P.F.), the voltage drop/1000 ampere-feet for 250 MCM is 0.064. From note 2, the correction for 90°C is 1.1 × 0.064 = 0.070.

Amperere-feet = 290 × 150 = 43,500 = 43.5 × 1000

Voltage drop (line to neutral) = 43.5 × 0.070 = 3.05 V

Voltage drop (line to line) = 1.73 × 3.05 = 5.3 V

Using Equation 11.2,

$$\% \text{ voltage drop} = \frac{5.3}{208} \times 100 = 2.5\%$$

11.4 LETTER DESIGNATION OF CABLES

Letter designations are used to identify types of cables with regard to the type of insulation and their conditions of use. The following lists include the common types used for fixed building wiring systems operating on low voltage (up to 1000 volts).

The following letters identify the insulation.

1. According to the type of insulation material:
   A, asbestos
   MI, mineral insulation
   R, rubber
   SA, silicone asbestos (rubber)

T, thermoplastic
V, varnished cambric
X, cross-linked synthetic polymer

2. According to conditions of use:
H, heat resistant up to 75°C
HH, heat resistant up to 90°C (Note: no designation indicates 60°C)
UF, suitable for underground, direct burial
W, moisture resistant, suitable for use in wet locations

The *National Electrical Code* defines a wet location as

> Installations underground or in concrete slabs or masonry in direct contact with the earth, and locations subject to saturation with water or other liquids, such as vehicle washing areas, and locations exposed to weather and unprotected.

Refer to Table 11.1 and note the headings of the columns that show the letter designations of insulated conductors. Some examples are

— THW: thermoplastic insulation, rated for maximum operating temperature of 75°C and suitable for use in wet locations (also dry locations).
— XHHW: cross-linked synthetic polymer insulation, rated for maximum operating temperature of 90°C and suitable for use in wet locations. However, see the asterisk (*) beside this type and the footnote in the table to the effect that the 90°C ampacity applies only in dry and damp locations and that the 75°C ampacity must be used in wet locations.

In addition to the insulation around the conductor, some types of cables have an outer jacket or sheath, either enclosing a single conductor or a group of individually insulated conductors, as shown in Figure 11.2. These outer coverings provide mechanical and/or corrosion protection. The following letters identify some of these types of cables:

— AC, armored cable (flexible metallic interlocked armor sheath)
— L, lead sheath
— MC, metal-clad cable (metallic sheath of interlocking tape or a smooth or corrugated tube)
— NM, nonmetallic sheath cable (moisture resistant, flame retardant)
— N, cables with nylon jacket

Care must be taken in identifying some of the letter combinations. For example, with type MI, the M stands for "mineral," whereas with type MC, the M stands for "metal." For a full description of all types of insulated conductors and their uses, refer to the *National Electrical Code*, Article 310 and Table 310-13.

11.5 RACEWAYS

The function of a raceway is to provide space for, and support and mechanical protection to, the insulated conductors of a feeder or branch circuit. An equal function is to protect people against electrical hazards and to minimize the likelihood of fires being caused by faults in the electrical wiring. As already discussed in Section 11.1.5, the ampacities of conductors are reduced by having them installed in a raceway, but in the interest of safety the *National Electrical Code* requires all wiring must be properly protected (Section 300-4). The final function of metallic-type raceways is to provide for continuity of the equipment grounding system throughout the building (see Section 10.3, this text). Raceways, therefore, are an important part of an electrical system in a building.

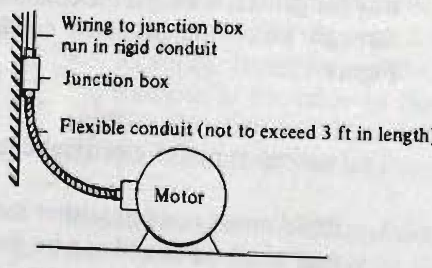
The *NEC* defines a *raceway* as *an enclosed channel designed expressly for holding wires, cables, or busbars*. Raceways may be constructed from metal or insulating material. Raceways may be rigid or flexible conduit, tubing, underfloor raceways, cellular floor raceways, wireways, and busways. The most common type of raceway for general wiring is the conduit, which in effect is a pipe or tube through which the insulated conductors are pulled, as shown in Figure 11.3.

11.5.1 Types of Conduit

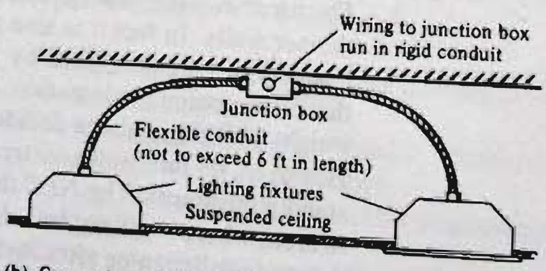
The various types of electrical conduit are as follows:

1. *Rigid metal conduit* (either steel or aluminum) has the thickest wall of all types and can be threaded so that joints can be made very secure and tight.
2. *Intermediate metal conduit* is a thinner-walled rigid metal conduit and may be used the same as rigid metal conduit.
3. *Electrical metallic tubing* (EMT) is a metal conduit with much thinner walls. In fact it is also referred to as thin-wall conduit. Connections are simplified by using threadless components of the compression, indentation, or set-screw type. The lighter weight of EMT is also a decided advantage during installation. However, its thin-wall construction makes it less able to withstand punishment. The *NEC* therefore restricts the use of EMT to areas where it will not be subjected to severe physical damage during installation or after installation.

4. *Rigid nonmetallic conduit* is made of nonmetallic material such as fiber, asbestos cement, and rigid polyvinyl chloride (PVC). Only PVC, however, is permitted to be used both underground and above ground. Rigid nonmetallic conduit cannot be used where subject to physical damage unless approved for such use.
5. *Electrical nonmetallic tubing* is a pliable corrugated raceway of circular cross section that can be bent by hand with a reasonable force. This type can be concealed within walls, ceilings, and floors where the floor, wall, or ceiling provides a thermal barrier of material that has at least a 15-minute fire rating.
6. *Flexible conduit* is constructed so that it can be readily flexed and therefore is not affected by vibration. A common application is for the final connection to a motor, as shown in Figure 11.9(a). The flexible conduit isolates the rigid conduit distribution system from the vibrations and movement of the motor. Another use is for the final connections to recessed lighting fixtures, as shown in Figure 11.9(b). The flexible conduit can be either metallic or nonmetallic. Liquid-tight flexible metal conduit is a special form that allows it to be used where protection from liquids or vapors is required. The *NEC* restricts the use of flexible metal conduit as an equipment grounding conductor, often requiring that an additional grounding jumper be installed (see *NEC* Sections 350-5 and 351-9).



(a) Connection to motor



(b) Connections to lighting fixtures

FIGURE 11.9

Common uses of flexible conduit

All runs of conduit and tubing must be properly protected against corrosion both during installation and after installation. Particular care must be taken where conduit runs are installed in concrete and in wet locations. Metal conduit with galvanized and/or plastic-coated finishes is available. Nonmetallic conduit or tubing cannot be used where its use would substantially increase the possible spread of fire or the products of combustion. For example, *NEC* Section 300-22(b) and (c) prohibits the use of nonmetallic conduit or tubing in ducts, plenums, and other spaces used for environmental air. This includes spaces over hung ceilings that are used for environmental air-handling purposes. Nonmetallic conduit and tubing cannot be used where either the ambient temperature or the insulation temperature limitations of the conductors would exceed those for which the conduit or tubing is approved. Also, the *NEC* carries a warning that *extreme cold may cause some nonmetallic conduit to become brittle and therefore more susceptible to physical damage from physical contact.* With nonmetallic conduit and tubing, a separate ground wire must be installed to maintain the equipment grounding circuit (see Section 10.3 of this text).

Some of the means of running conduit are shown in Figure 11.10. Overhead runs must be properly supported along their entire length. Sufficient access points in the form of junction boxes have to be provided on long runs of conduit to facilitate the installation of the conductors. Otherwise, if a run is too long or has too many bends between access points, the conductors could be damaged as they are pulled through the conduit. The reader is referred to *NEC* Articles 331 and 345 through 351 for the complete set of regulations governing the use and installation of conduit and tubing.

Underfloor raceways are used as a common means of distributing wiring in office areas. This type of system is discussed in Section 12.9 of this text.

11.5.2 Number of Conductors Permitted in Conduit

The number of conductors that can be installed in any one run of conduit must be restricted. The total cross-sectional area of the conductors, including the insulation, must not exceed a specified percentage of the cross-sectional area of the inside of the conduit. This is referred to as the *percentage fill*. If the percentage fill is too high, then the cables can be damaged as they are pulled through the run of conduit. Also the heat buildup within the conduit from the conductor currents could become excessive under operation because of overcrowding.

The *National Electrical Code* restricts the percentage fill to 40% for three or more conductors. Refer to Table 11.6, which shows the maximum number of type THW and XHHW conductors permitted in one run of conduit or tubing. Trade sizes of conduit or tubing are

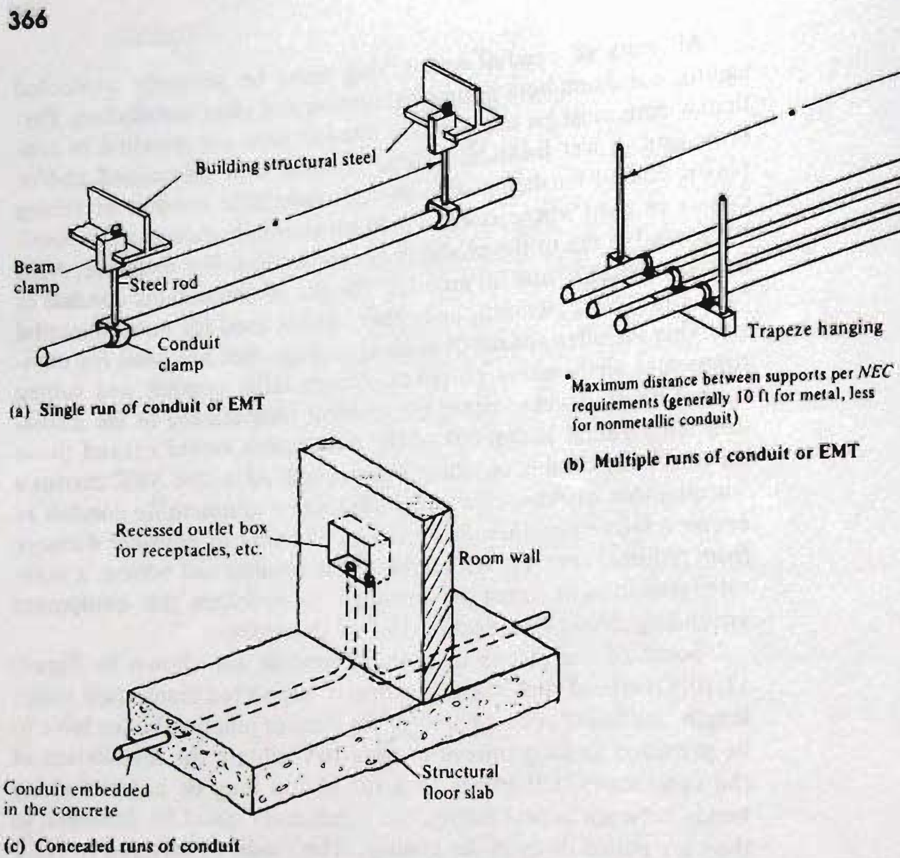


FIGURE 11.10

Common methods of installing rigid conduit

shown from ½ inch to 3 inches and conductor sizes from No. 14 up to 500 MCM. Since each type of insulated conductor has a different insulation thickness, the appropriate type of wire (indicated by letter type) must be selected. This table is based on all conductors in the run of conduit being the same size and type. The trade size of a conduit or tube is actually only its nominal or approximate inside diameter. It is used for the identification of a particular size. For example, the 1 inch trade size conduit has an actual internal diameter of 1.049 inches. The following example illustrates the use of Table 11.6.

■ EXAMPLE 11.10

A three-phase, four-wire feeder requires No. 4/0 type THW conductors. Determine the trade size of conduit required for the feeder.

Solution

Four conductors have to be installed in the conduit (the neutral must be counted). From Table 11.6, for type THW, size 4/0, a 2 in. conduit can only accommodate three conductors; therefore, a 2½ in. conduit (maximum of 5) is required. A common method of indicating the above feeder on a one-line diagram is as follows: 2½" C, 4 -#4/0, THW

TABLE 11.6 Maximum Number of Conductors in Trade Size of Conduit or Tubing (from *NEC* Chapter 9, Tables 3A and 3B)

Conduit Trade Size (inches)		½	¾	1	1¼	1½	2	2½	3
Type Letters	Conductor Size								
THW	14	6	10	16	29	40	65	93	143
	12	4	8	13	24	32	53	76	117
	10	4	6	11	19	26	43	61	95
	8	1	3	5	10	13	22	32	49
	6	1	2	4	7	10	16	23	36
	4	1	1	3	5	7	12	17	27
	3	1	1	2	4	6	10	15	23
	2	1	1	2	4	5	9	13	20
	1		1	1	3	4	6	9	14
	1/0		1	1	2	3	5	8	12
	2/0		1	1	1	3	5	7	10
	3/0		1	1	1	2	4	6	9
	4/0			1	1	1	3	5	7
	250 MCM			1	1	1	2	4	6
	300 MCM			1	1	1	2	3	5
	350 MCM				1	1	1	3	4
	400 MCM				1	1	1	2	4
	500 MCM				1	1	1	1	3
XHHW	14	9	15	25	44	60	99	142	
	12	7	12	19	35	47	78	111	171
	10	5	9	15	26	36	60	85	131
	8	2	4	7	12	17	28	40	62
	6	1	3	5	9	13	21	30	47
	4	1	2	4	7	9	16	22	35
	3	1	1	3	6	8	13	19	29
	2	1	1	3	5	7	11	16	25
	1		1	1	3	5	8	12	18
	1/0		1	1	3	4	7	10	15
	2/0		1	1	2	3	6	8	13
	3/0		1	1	1	3	5	7	11
	4/0		1	1	1	2	4	6	9
	250 MCM			1	1	1	3	4	7
	300 MCM			1	1	1	3	4	6
	350 MCM			1	1	1	2	3	5
	400 MCM				1	1	1	3	5
	500 MCM				1	1	1	2	4

These values apply only when all conductors in the conduit run are the same type and size.

For a complete listing of all types of cables, for conductor sizes above 500 MCM, and for conduit trade sizes above 3 inches, see *NEC* Chapter 9, Tables 1 to 7.

11.6 CONDUCTORS IN PARALLEL

For larger-rated feeders, it may be desirable to parallel two or more conductors per phase, rather than use one large conductor. Paralleling means that the conductors of each phase are electrically joined at both ends to effectively form a single conductor, as shown in Figure 11.11. As previously illustrated in Section 11.1.1, the ampacity of conductors is not a linear function of their size; that is, the doubling of the cross-sectional area of the conductor does not result in the doubling of its ampacity rating. Another reason to avoid using large conductors is the difficulty of pulling them into the raceway. Also, a large-sized conduit is required, which is cumbersome to handle during installation. The general recommendation for conductors installed in conduit is that, if the required conductor size is computed to be larger than 500 MCM, then paralleling should definitely be considered. In fact, the *National Electrical Code* allows conductors size 1/0 and larger to be paralleled (see Section 310-4).

As an example of the desirability of paralleling, consider the following. A three-wire feeder requires an ampacity of 500 amperes. If one THW conductor per phase is used, the size required is 900 MCM (Table 11.1 rated for 520 A). If two conductors in parallel are used, then the size required for each is only 250 MCM (rated 255 A for a total of 510 amperes). The two 250 MCM conductors have a total of only 55% of the cross-sectional area of the 900 MCM conductor and will therefore cost less. The six 250 MCM conductors can be installed in two runs of 2½ inch conduit, whereas the three 900 MCM conductors require a 4 inch conduit.

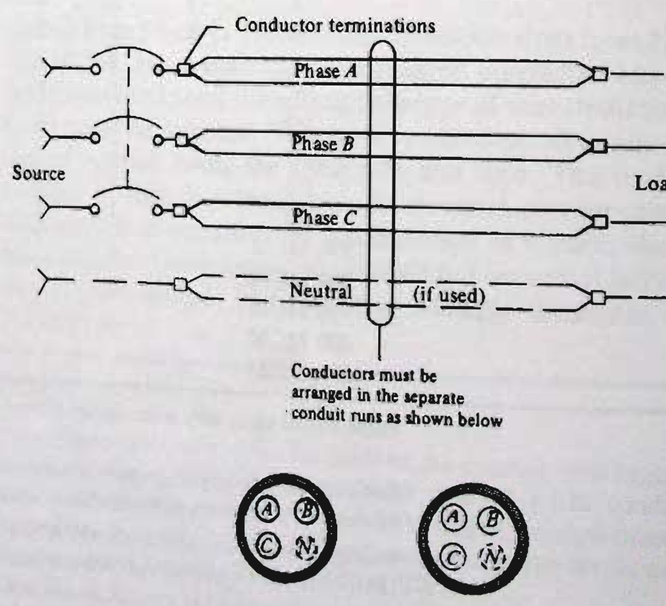


FIGURE 11.11

Conductors run in parallel

In the foregoing example, the six 250 MCM conductors could have been installed in one run of conduit. However, this would mean that the derate factor for more than three conductors in a raceway [Table 11.3(b)] would have to be applied, resulting in larger-sized conductors being required. The recommendation, therefore, is that the parallel conductors be installed in separate runs of conduit. This requires that one of each of the phase conductors and the neutral (if used) must be grouped together in each conduit run, as shown in Figure 11.11. If this is not done, then there is not a complete canceling of the magnetic flux around the conductors, with the result that the parallel conductors do not have the same reactance and therefore do not equally share the total feeder current. In addition, if steel conduits are used, then the residual flux causes severe heating problems in the steel through induced eddy current and hysteresis losses.

The parallel conductors must equally share the total feeder current. Otherwise, one conductor could end up being overloaded, resulting in overheating problems. In addition to the arrangement of the conductors as in Figure 11.11, the parallel conductors in each phase and the neutral must be of the same length, material, and size, have the same insulation, and be terminated in the same manner. The conduits must all be of the same size and type. Refer also to Example 11.14 for the use of parallel conductors where voltage drop is a problem.

11.7 EXAMPLES OF FEEDER DESIGN

In the normal course of the design of a feeder, the unknown factor is the required minimum conductor size that will meet each of the three separate requirements previously outlined: the ampacity rating, the short-circuit current rating, and the maximum allowable voltage drop. However, before proceeding with some design problems, there is one more item to discuss.

Article 220 of the *National Electrical Code* covers Branch-Circuit and Feeder Calculations. Part B of this article is concerned with the ampacity requirements of feeders, and in particular Section 220-10(b) deals with Continuous and Noncontinuous Loads. For a *continuous load,* the maximum current is expected to continue steadily for 3 hours or more. Conversely, a *noncontinuous load* fluctuates and only operates at its maximum current for short periods of time. An example of a continuous load is the general lighting for an office, which usually operates with all the lighting fixtures turned on continuously for 8 hours or more. An example of a noncontinuous load is the lighting in a residential complex, where each lighting fixture is randomly switched on and off, and it is extremely unlikely that all the units would be on at the same time for long periods of time.

Where a feeder supplies any combination of a continuous and/or noncontinuous load, the ampacity of the feeder shall not be less than 125% of the continuous load plus the noncontinuous load. There are two exceptions to this requirement. The first concerns feeders to groups of motors and is covered in Section 13.4 of this text. The second concerns 100% rated overcurrent devices and is covered in Section 11.8. For the method of calculating minimum load requirements for the feeders to panels supplying lighting units and general-purpose receptacles, see Section 12.11.

The following examples show the procedures for the selection of feeder conductors.

EXAMPLE 11.11

Select the size of the conductors and conduit for the feeder required for the following:

- Load is 100 kW at 90% power factor and is noncontinuous.
- Load is less than 50% ballast-type lighting and there are no other loads that cause third harmonics.
- Supply is three-phase, four-wire, 480Y/277 V.
- Length of feeder is 250 ft and it is to be run above grade.
- Available short-circuit current is 17,000 A symmetrical.
- Feeder overcurrent protection is a molded-case breaker.
- Maximum allowable voltage drop is to be 2%.
- Conductors to be copper, type THW in steel conduit.

Solution

Using Equation 1.12,

$$I_L \text{ (of load)} = \frac{100 \times 1000}{(1.73)(480)(0.9)} = 134 \text{ A}$$

(a) Minimum size required for ampacity:

- Minimum ampacity for noncontinuous load is 100%: 134 A.
- Neutral does not count as a fourth current-carrying conductor.
- From Table 11.1, minimum size is No. 1/0 (rated for 150 A).

(b) Minimum size required for short-circuit current:

- From Table 11.4, K_0 factor is 1.3, clearing time is 2 cycles.
- Using Equation 11.1,

$$I_{ASY} = 1.3 \times 17{,}000 = 22{,}100 \text{ A}$$

- From Figure 11.5, minimum size is No. 1 (see Figure 11.12 for method of reading the short-circuit graph).

(c) Minimum size required for voltage drop:

- Maximum allowable = 2% of 277 = 5.54 V (line-to-neutral).
- Ampere-feet = 134 × 250 = 33,500 = 33.5 × 1000.
- Maximum voltage drop/1000 AF = 5.54/33.5 = 0.165.
- From Table 11.5, minimum size is No. 1 with value of 0.162.

(d) Therefore, the ampacity requires the largest size: No. 1/0.

(e) From Table 11.6, the size of conduit is 2 in. for four conductors.

Feeder designation: 2″ C, 4 -#1/0, THW (Cu)

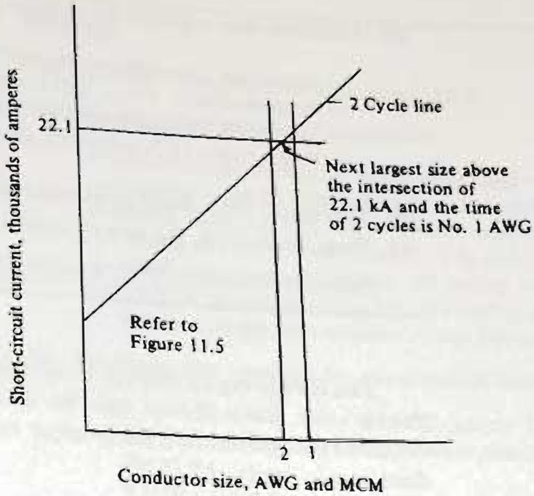


FIGURE 11.12

Determining the minimum conductor size for the short-circuit current in Example 11.11

EXAMPLE 11.12

Repeat Example 11.11, except the available short-circuit current is 35,000 A symmetrical.

Solution

(a) Minimum size for ampacity same as in Example 11.11: No. 1/0.

(b) Minimum size required for short-circuit current:

— K_0 factor and clearing time same as in Example 11.11.
— Using Equation 11.1,

$$I_{ASY} = 1.3 \times 35{,}000 = 45{,}500 \text{ A}$$

— From Figure 11.5, minimum size is No. 3/0.

(c) Minimum size for voltage drop same as in Example 11.11: No. 1.

(d) Therefore, short-circuit current requires largest size: No. 3/0.

(e) From Table 11.6, the size of conduit is 2 in. for four conductors.

Feeder designation: 2″ C, 4 -#3/0 THW (Cu)

EXAMPLE 11.13

Repeat Example 11.11, except the length of the feeder is 330 ft.

Solution

(a) Minimum size for ampacity same as in Example 11.11: No. 1/0.

(b) Minimum size for short-circuit current same as in Example
No. 1.

(c) Minimum size required for voltage drop:

— Maximum allowable = 2% of 277 = 5.54 V (line-to-neutral).
— Ampere-feet = 134 × 330 = 44,200 = 44.2 × 1000.
— Maximum voltage drop/1000 AF = 5.54/44.2 = 0.125.
— From Table 11.5, minimum size is No. 2/0 with value of 0.110.

(d) Therefore, the voltage drop requires the largest size: No. 2/0.
(e) From Table 11.6, the size of conduit is 2 in. for four conductors.

Feeder designation: 2″ C, 4 -#2/0 THW (Cu)

The foregoing examples show that the final selection of the conductor size for a feeder can be dictated by any one of the three requirements and that each must be checked out before the final decision is made.

■ EXAMPLE 11.14

Repeat Example 11.11, except the supply voltage is 208Y/120V. Determine the size required to meet the 2% voltage drop requirement only for this example.

Solution

$$I_L \text{ (of load)} = \frac{100 \times 1000}{(1.732)(208)(0.9)} = 308 \text{ A}$$

— Maximum voltage drop = 2% of 120 = 2.4 V (line-to-neutral).
— Ampere-feet = 308 × 250 = 77,000 = 77.0 × 1000.
— Maximum voltage drop/1000 AF = 2.4/77.0 = 0.031.
— From Table 11.5, minimum size is in excess of 1000 MCM.
— Since this is a very large size, consider two parallel conductors.
— Each conductor will carry 308/2 = 154 A.
— Ampere-feet = 154 × 250 = 38,500 = 38.5 × 1000.
— Maximum voltage drop/1000 AF = 2.4/38.5 = 0.062 (for each conductor).
— From Table 11.5, minimum size is 350 MCM with a value of 0.055.
— From Table 11.6, the size of conduit is 3 in. for four conductors.

Feeder designation: Two parallel runs, each to be 3″ C, 4-350 MCM, THW (Cu)

Example 11.14 illustrates the problem of feeding large loads from a 208Y/120 volt system, especially if there are long feeder distances to contend with. There is a large increase in the size and cost of the feeders, as compared to loads of the same size that are fed from a 480Y/277 volt system. This emphasizes the importance of selecting the highest possible standard voltage for the electrical distribution system within large buildings (see Section 1.8).

■ **EXAMPLE 11.15**

Repeat Example 11.11, except that the 100 kW load is continuous and consists of more than 50% electric discharge type of lighting. Consider both types THW and XHHW conductors (dry location).

Solution

The load has same full-load current of 134 A.

(a) Minimum size required for ampacity:

- Minimum ampacity for continuous load = 125% of 134 = 167.5 A.
- Neutral must be counted as fourth current-carrying conductor.
- From Table 11.3(b), the ampacity adjustment factor is 80% (0.80).
- Rating to select from Table 11.1 is 167.5/0.80 = 209 A.
- THW minimum size is No. 4/0 (rating in table of 230 A).
- XHHW minimum size is No. 3/0 (rating in table of 225 A) (satisfactory for equipment terminals; see Section 11.1.7).

(b) Minimum size required for short-circuit current:

- I_{ASY} = 22,000 A, same as in Example 11.11.
- THW from Figure 11.5, minimum size is No. 1, same as in Example 11.11.
- XHHW from figure 11.6, minimum size is No. 2.

(c) Minimum size required for voltage drop (still based on actual load current of 134 A):

- Maximum voltage drop/1000 AF = 0.165, same as in Example 11.11.
- THW minimum size is No. 1, same as in Example 11.11.
- XHHW correction factor for 90°C is 1.1 (note 2, Table 11.5). The value for use in Table 11.5 = 0.165/1.1 = 0.150. The minimum size is No. 1/0 with a value of 0.133.

(d) Summary

	THW	XHHW
Ampacity	4/0	3/0
Short circuit	1	2
Voltage drop	1	1/0

Therefore, the preferred selection is No. 3/0 XHHW.

(e) From Table 11.6, the conduit size is 2 in. for four conductors.

Feeder designation: 2" C, 4 -#3/0 XHHW (Cu)

■ **EXAMPLE 11.16**

Repeat Example 11.15, except that the available short-circuit current is 53,000 A.

Solution

(a) Minimum sizes for ampacity and voltage drop same as in Example 11.15.

(b) Minimum size required for short-circuit current:

- Using Equation 11.1,

$$I_{ASY} = 1.3 \times 53{,}000 = 68{,}900 \text{ A}$$

- THW: from Figure 11.5, minimum size is 250 MCM.
- XHHW: from Figure 11.6, minimum size is No. 4/0.

(c) Summary

	THW	XHHW
Ampacity	4/0	3/0
Short circuit	250 MCM	4/0
Voltage drop	1	1/0

Therefore, the preferred selection is No. 4/0 XHHW.

(d) From Table 11.6, the conduit size is 2 in. for four conductors.

Feeder designation: 2″ C, 4 -#4/0 XHHW (Cu)

Examples 11.15 and 11.16 show that the use of 90°C rated conductors (for example, XHHW) often allows a smaller size of conductor and conduit to be used. This more than offsets the slightly higher cost of the 90°C rated conductors (as compared to the same size of 75°C rated conductor).

11.8 OVERCURRENT PROTECTION OF FEEDERS

The *National Electrical Code* defines the term *overcurrent* as *any current in excess of the rated current of equipment or the ampacity of a conductor*. An overcurrent may result from an overload, a short circuit, or a ground fault. The reader should review Section 6.1 with regard to overloads and short circuits and to the reference to *NEC* Sections 240-20(a) and 240-21, which govern the requirements and locations of overcurrent protection (fuses and circuit breakers). In addition, *NEC* Section 240-3 states in part that

> Conductors shall be protected against overcurrent in accordance with their ampacities . . . [except that] where the ampacity of the conductor does not correspond with the standard rating of a fuse or a circuit breaker without overload trip adjustments . . . the next higher standard device rating shall be permitted only if this rating does not exceed 800 amperes . . . .

Underwriters Laboratories, Inc., standards require that a fuse must be able to continuously carry 110% of its rated current at an ambient temperature of 25°C and that a circuit breaker must be able to carry 100% of its rated current at an ambient temperature of 40°C. The acceptance tests for these requirements are carried out with the fuse or circuit breaker mounted in the open. However, in practice, the fuses and circuit breakers are mounted within switch or panel enclosures (see Figures 7.12 and 8.10). Even under normal loading, the heat generated by the fuse or circuit breaker plus that generated by the feeder conductors and terminals may cause the ambient temperature within the enclosure to rise above the ambient temperature values used for the UL tests. Since a fuse or thermally operated circuit breaker responds to heat, no matter how it is generated, the protective device may no longer be able to continuously carry its rated current. Therefore, *NEC* Section 220-10(b) requires that the rating of the overcurrent device for a feeder supplying a continuous load shall not be less than 125% of the continuous load current. Continuous loads are discussed in Section 11.7. This in effect means that the protective device cannot be continuously loaded beyond 80% of its rating. The *NEC* allows an exception to this 80% derating rule:

> That where the assembly, including the overcurrent devices protecting the feeder, are listed [that is, approved] for continuous operation at 100% of their rating, then the feeder can be loaded to 100% of its ampacity rating.

However, to date the only fusible equipment that has UL approval for 100% continuous operation is some large bolted-pressure switches rated above 600 amperes and using class L fuses. Also, only low-voltage power and encased-type circuit breakers (Sections 8.5 and 8.8) have UL approval for 100% continuous operation. This is an area that requires a lot more attention by manufacturers and the standards agencies. The 80% derating causes extra costs for electrical systems in requiring oversized feeders, switches, fuses, circuit breakers, panelboards, and the like, when supplying continuous loads.

The following examples illustrate the method of selecting the overcurrent protection (fuse or circuit breaker) for a feeder or subfeeder (see Figure 11.1). The standard ratings of low-voltage fuses and switches are shown in Tables 7.1 and 7.2, respectively. The standard ratings of low-voltage circuit breakers are shown in Tables 8.1, 8.2, and 8.3. For a complete discussion on fuses and circuit breakers, see Chapters 7 and 8, respectively. For the special requirements of overcurrent protection for motor circuits and feeders, see Sections 13.1.1 and 13.4.

EXAMPLE 11.17

elect the molded-case circuit eaker ratings for overcurrent otection of the feeder in xample 11.15. Note that olded-case breakers are not rmally UL listed for 100% ntinuous operation.

Solution

- The minimum trip rating for the breaker is 125% of 134 = 167.5 A.
- From Table 8.1, the next highest standard trip rating is 175 A (the ampacity of the four #3/0 XHHW in conduit is 0.80 × 225 = 180 A).
- The frame size required for the 175 A trip is 225 A, which has an interrupting rating of 22,000 A symmetrical at 480 V (Table 8.1), which is satisfactory for the available short-circuit current of 17,000 A symmetrical (from Example 11.11).

■ **EXAMPLE 11.18**

Current-limiting fuses (Section 7.3) are to be used for the overcurrent protection of the feeder in Example 11.12 (instead of a circuit breaker).

(a) Select the fuse and switch ratings.

(b) Determine the conductor size for the short-circuit current.

Solution

(a) Load current is 134 A and is noncontinuous (from Example 11.11).

— From Table 7.1, the next highest standard fuse rating is 150 A.
— From Table 7.2, the switch rating is 200 A, 600 V.

(b) Prospective short-circuit current is 35,000 A.

— From Figure 7.5, the effective let-through current for a 150 A, 600 V fuse is estimated to be 10,000 A symmetrical (interpolate between the 100 and 200 A, 600 V fuses).
— From Table 11.4, K_0 factor is 1.4 and clearing time is ½ cycle.
— Using Equation 11.1,

$$I_{ASY} = 1.4 \times 10{,}000 = 14{,}000 \text{ A}$$

— From Figure 11.5, the minimum size is No. 4 (using 1 cycle line).

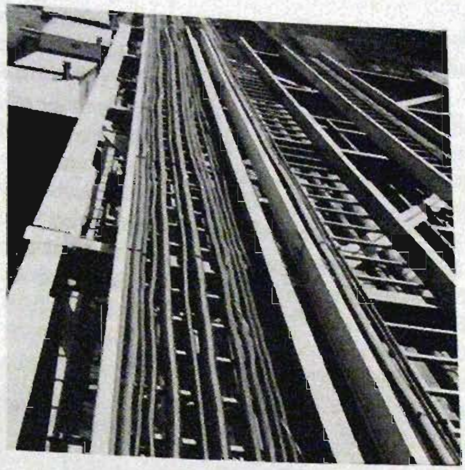
No. 1/0, which is required for ampacity, can now be used for the feeder, rather than No. 3/0 previously required.

Example 11.18 shows the advantage of using current-limiting fuses for the overcurrent protection of feeders in situations where the available fault currents are at a high level. Current-limiting circuit breakers (Section 8.9) also offer the same advantage but at a considerable increase in cost.

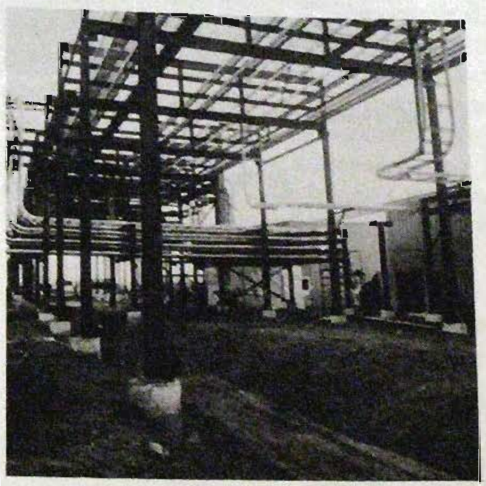
11.9 CABLE TRAYS

A *cable tray* is *an assembly of rigid structural sections that, together with the associated fittings, forms a continuous support system for cables*. Cable tray systems include the ladder type and perforated and solid bottom types. The ladder type, which, as its name implies, resembles a ladder, is generally the type used for feeder runs as it does not impede the dissipation of the heat from the cables. Figure 11.13 shows some typical applications of ladder-type cable trays for spanning open areas. Cable trays are particularly useful where there are a number of cables to be run in the same general direction.

The cables installed in the trays are generally the metal-clad type similar to that shown in Figure 11.2(c). The cable trays must be installed so that they are accessible, except where they pass through a wall or structural floor. There must be sufficient space around the trays to permit access for the installation and maintenance of the cables. Metallic cable trays have to be grounded and can therefore



(a)



(b)

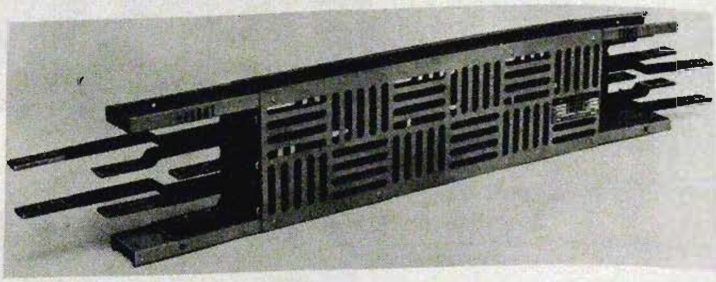
FIGURE 11.13

Typical applications of ladder-type cable trays for the support of electric cables across open spaces

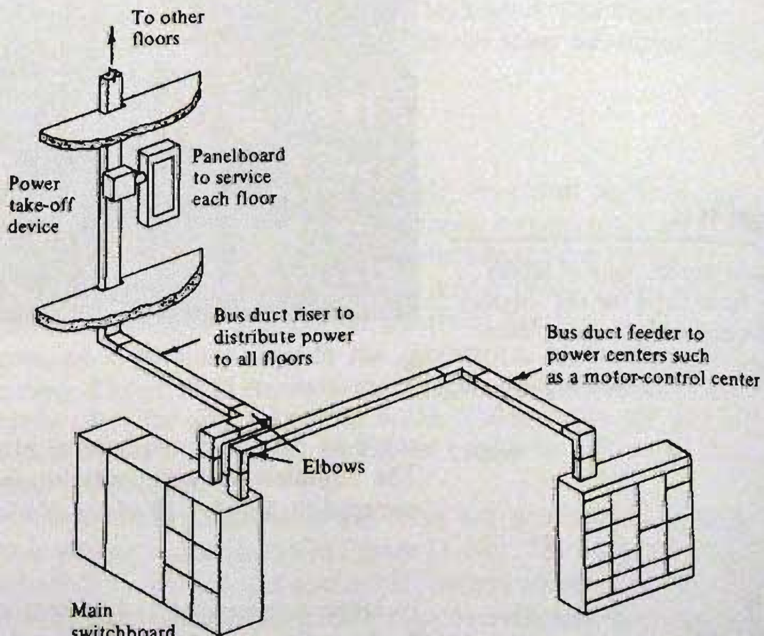
serve as part of the equipment grounding circuit (see Chapter 10). The complete requirements for the installation of cable trays are covered in Article 318 of the *National Electrical Code*.

11.10 BUSWAYS

In large commercial and industrial buildings where high-ampacity feeders are required, the use of insulated conductors in conduit becomes cumbersome and expensive because of the number of parallel runs needed to obtain the desired ampacity. An alternative method is the use of busways for the feeders. A *busway* (also called bus duct) is *a metal enclosure containing factory assembled conductors, which are usually copper or aluminum bars or tubes.* An example of a feeder busway is shown in Figure 11.14(a). This shows one typical section of bus duct, which is usually manufactured in 10 foot lengths. These sections together with available elbows and other manufactured fittings are bolted together on the building site to form complete feeders. Some typical applications for high-rise commercial or institutional buildings are shown in Figure 11.14(b). In large



(a) Typical section of low-impedance bus duct



(b) Applications of feeder bus duct in buildings

FIGURE 11.14

Low-voltage feeder-type busways

industrial plants, feeder bus duct is extensively used in horizontal runs from the main switchboards to the major power centers located throughout the plant.

The type of feeder duct shown in Figure 11.14(a) is known as *low-impedance bus duct*. The low impedance is obtained by the close phase-to-phase spacing of the bus bars, which reduces the inductive reactance of the conductors to a minimum. This type is desirable so that the voltage drop on a feeder is kept as low as possible. Ratings for the feeder busways range from 600 up to 5000 amperes at 600 volts based on a temperature rise of 55°C from an ambient temperature of 40°C. Voltage drops range from approximately 2 to 3.5 volts line-to-line per 100 feet of run, where the load is concentrated at the end of the feeder run. Since the bus bars in the busway can be subjected to severe mechanical stressing during short circuits, they must be adequately braced so that the bars are not permanently bent and their supports broken (see Section 6.2). Short-circuit current ratings vary from 15,000 up to 150,000 amperes symmetrical.

Another common type of busway is the plug-in bus duct shown in Figure 11.15. This type is used in industrial plants as an overhead distribution system to supply readily available power to adjacent machine tools and other utilization equipment. In effect, the plug-in busway is an elongated panelboard with the plug-in openings provided at closely spaced intervals along its entire run from which power can be tapped. The plug-in units are usually switch and fuse combinations or circuit breakers that provide overcurrent protection

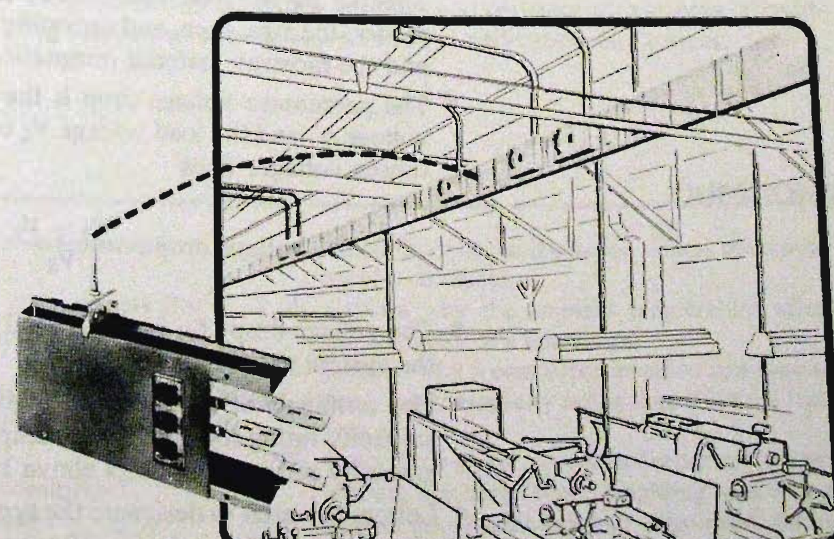


FIGURE 11.15

Typical application of plug-in bus duct in an industrial plant for the branch circuit cable runs to the utilization equipment. Because plug-in busways are used as much for their flexibility as they are to provide feeder capacity, they are available in ratings as low as 100 amperes.

The complete requirements for the installation of busways is covered in Article 364 of the *National Electrical Code*.

SUMMARY

- The connecting wiring within a building is divided into the service entrance, the feeders, and the branch circuits.
- The correct selection of conductors for feeders and circuits must take into account ampacity, short circuit, and voltage drop requirements.
- All conductors installed in a building must be properly protected, usually by installing them in raceways.
- The ampacity rating of conductors in a raceway depends on the conductor material, size, and temperature rating; the number of current-carrying conductors in the raceway; and the ambient temperature.
- The short-circuit current rating of a conductor depends on the conductor material, the temperature limitations of the insulation, and the duration of the short circuit.
- The short-circuit ratings must be based on asymmetrical currents, such that $I_{ASY} = K_0 \times I_{SYM}$, where K_0 depends on the voltage level of the system and the clearing time of the protective device.
- The voltage drop on a 60 hertz feeder installed in a raceway is affected by the load current and power factor; the length of the feeder; the size, type, and operating temperature of the conductors; and the raceway material (magnetic or nonmagnetic).
- The percentage voltage drop is the difference between the source voltage V_S and the load voltage V_L expressed as a percentage of the source voltage. Thus

$$\% \text{ voltage drop} = \frac{V_S - V_L}{V_S} \times 100$$

- The voltage drop of a feeder should not exceed 3%, and the total of the system should not exceed 5%.
- The terminals of UL-approved equipment are limited to the 60°C ampacity rating for circuits 100 amperes and below and to the 75°C ampacity rating for circuits above 100 amperes.
- Letters are used to designate the type of insulation and construction of a cable and its condition of use.

- Raceways provide space, support, and mechanical protection for conductors, and they minimize the hazards from electrical shocks and fires.
- The most common type of raceway used for feeders is conduit, which is available in rigid and flexible, metallic and nonmetallic types.
- Conduit runs must be properly supported and have sufficient access points to facilitate the installation of the conductors.
- Conduits must be large enough to accommodate the number of conductors based generally on a 40% fill ratio.
- Paralleling of conductors should be considered if the use of one conductor per phase requires larger than 500 MCM.
- The load on a feeder must be considered as being continuous if the maximum current is expected to continue steadily for 3 hours or more, in which case the feeder and its overcurrent protection must be rated for a minimum of 125% of the load current, unless the overcurrent protective device is UL approved for continuous operation at 100% of its rating.
- The highest possible standard system voltage should be selected to minimize feeder sizes and costs.
- All feeders must be properly protected against overcurrents.
- Cable trays are used for supporting feeder cables where a number of them are to be run in the same location.
- Low-impedance busways (bus duct) are used in buildings for high-capacity feeders.
- Plug-in busways are used for overhead distribution systems, providing convenient power tap-offs to the utilization equipment.

QUESTIONS

1. State the difference between a feeder and a branch circuit.
2. What are the three separate requirements that can dictate the final selection of the conductor size for a feeder?
3. What is the definition of ampacity?
4. Explain why the conditions of use can affect the ampacity rating of a cable?
5. What does the AWG number designate?
6. What does 500 MCM designate?
7. Explain why the maximum allowable operating temperature of the insulation affects the ampacity of a conductor.
8. Explain why the ambient temperature affects the ampacity of a conductor.
9. Explain why a conductor installed in a raceway has a lower ampacity rating than if it were run in free air.
10. For a three-phase, four-wire feeder supplying an electric discharge type of lighting load (for example, fluorescent lighting), why must the neutral be considered as a fourth current-carrying

conductor in the raceway and how does this affect the ampacity rating of the conductors?

11. What are the ampacity limitations imposed by the termination of conductors at equipment terminals?
12. Explain why it is necessary to check the short-circuit current rating of the conductors in a feeder.
13. Explain why the asymmetrical value of current must be used to determine the short-circuit rating of a conductor.
14. Why is it important to calculate the voltage drop on a feeder or branch circuit?
15. What does the unit of ampere-feet represent and why is it used?
16. Explain the letter designations RHW and THWN.
17. What are the two main functions of raceways?
18. What are the restrictions in the use of nonmetallic (plastic) conduit and tubing?
19. Why must the number of conductors installed in a specific size of conduit be restricted?
20. On large-capacity feeders, why is it advantageous to consider the paralleling of conductors?
21. What is meant by a continuous load and how does a continuous load affect the sizing of a feeder?
22. Explain the significance of an overcurrent.
23. What is a cable tray and why are cable trays used?
24. What is meant by low-impedance bus duct and why is it used?
25. What is meant by plug-in bus duct and why is it used?

PROBLEMS

1. Determine the ampacity of No. 4 XHHW copper conductors, five current-carrying conductors in a raceway in free air, ambient temperature of 40°C.
2. Determine the ampacity of a three-phase, four-wire feeder using No. 1/0 RHW copper conductors installed in a raceway in free air supplying a fluorescent lighting load.
3. Repeat Problem 2, except the feeder is to be installed in a single underground electrical duct with an ambient earth temperature of 20°C.
4. Determine the symmetrical short-circuit current rating of a 300 MCM XHHW copper conductor on a 208 V feeder protected by a circuit breaker.
5. Repeat Problem 4, except the feeder is protected by current-limiting fuses (use 1 cycle line on graph).
6. Calculate the percentage of voltage drop on a 480 V, three-phase feeder supplying a 90 kW, 80% power factor load, length 240 ft, consisting of three No. 1 XHHW copper conductors in an aluminum conduit.
7. Determine the trade size of conduit required for a run of six No. 1/0 XHHW conductors.
8. Select the size of the conductors and conduit for the feeder required for the following:

   —Load is 80 kW at 100% power factor and is noncontinuous.
   —Load is incandescent lighting.
   —Supply is 208Y/120 V, three-phase, four-wire.
   —Length of feeder is 200 ft, to be run above grade.
   —Available short-circuit current is 22,000 A symmetrical.
   —Feeder overcurrent protection is a molded-case breaker.
   —Maximum allowable voltage drop is 3%.
   —Conductors to be type THW, copper in steel conduit.

9. Repeat Problem 8, except the load is fluorescent lighting that will be on continuously for 10 hours.
10. Repeat Problem 8, except the maximum allowable voltage drop is 2%.
11. Repeat Problem 8, except the available fault current is 50,000 A symmetrical.
12. Select the size of conductors and conduit for the feeder required for the following (consider the paralleling of conductors):

   —Load is 268 kW at 90% power factor and is continuous.
   —More than 50% of load has high third-harmonic components.

- Supply is 480Y/277 V, three-phase, four-wire.
- Length of feeder is 235 ft.
- Available fault current is 39,000 A symmetrical.
- Feeder overcurrent protection is a molded-case breaker.
- Maximum allowable voltage drop is 2%.
- Conductors to be type XHHW copper in steel conduit.

13. Select the frame and trip ratings for the circuit breaker protecting the feeder in Problem 8.
14. Select the frame and trip ratings for the circuit breaker protecting the feeder in Problem 9.
15. Select the frame and trip ratings for the circuit breaker protecting the feeder in Problem 11.
16. Select the frame and trip ratings for the circuit breaker protecting the feeder in Problem 12.
17. Repeat Problem 12, except the feeder overcurrent protection will be a power circuit breaker approved for 100% continuous operation.
18. Select the frame and trip ratings for the circuit breaker in Problem 17.

12 Branch Circuits and Computed Loads for Lighting and Receptacles

OBJECTIVES

After studying this chapter, you will be able to:

- Organize the branch circuits for lighting.
- Organize the branch circuits for general-purpose receptacles.
- Lay out the branch circuit wiring on a floor plan.
- Make out a lighting panel schedule.
- Read electrical floor plan drawings.
- Recognize the use of underfloor raceway systems.
- Explain the application of ground-fault circuit-interrupters.
- Compute the loads for the feeders to lighting panels.

INTRODUCTION

A *branch circuit* is *the segment that extends beyond the final automatic overcurrent device in the system to the connection at the utilization equipment*. As discussed in the introduction to Chapter 11, the initial planning of the electrical system involves the preparation of a one-line diagram to establish the general means of distributing the electric power within the building. However, the design of the system cannot be finalized until the requirements of all the branch circuits have been fully determined and their exact loading has been calculated. Thus the final stage in the complete design of an electrical system begins with the preparation of the detailed layouts for all the branch circuits throughout the building.

Refer to Figure 11.1, which shows a typical one-line diagram of an electrical system. Most branch circuits originate at panelboards and/or motor-control centers. There can be branch circuits for lighting and general-use receptacles, for specific-purpose equipment, and for motors. The detailed requirements for specific-purpose equipment, such as electric welders and space-heating equipment, are too broad for the scope of this textbook. The requirements for motors are covered separately in Chapter 13. This chapter then concentrates on the requirements for the branch circuits for lighting and general-use receptacles such as encountered in commercial, institutional, and industrial establishments. The reader is referred to the *National Electrical Code*, Articles 210 and 220, for the general requirements for branch circuits and their computed loads. For reference to the Canadian Electrical Code, see Appendix A.

12.1 BRANCH CIRCUIT CONDUCTORS

The branch circuit conductors must have an ampacity of not less than the maximum load to be served. However, a circuit is not classified by the ampacity rating of the conductors, but rather by the rating of the overcurrent device protecting the circuit. Typical values are 15, 20, 30, 40, and 50 amperes. For example, a circuit may use No. 10 THW copper conductors to compensate for voltage drop. Even though these conductors have an ampacity rating of 35 amperes, if the circuit is protected by a 20 ampere overcurrent device, then the circuit is classified as 20 ampere.

In most areas of large buildings, the branch-circuit wiring is installed in either conduit or electrical metallic tubing (EMT) in order to meet the requirements of the electrical code with regard to the protection of insulated conductors from physical damage. Refer to Sections 11.1 through 11.4 for details of ampacity ratings, temperature ratings, voltage drops, and letter designations of circuit conductors and to Section 11.5 for details of raceways. Refer specifically to Table 11.1 for the ampacities of conductors in raceways and to Table 11.6 for the maximum number of conductors permitted in conduit or EMT.

In Table 11.1, a footnote covering AWG sizes 14, 12, and 10 sets the maximum overcurrent protection for these sizes. For example, the overcurrent protection for No. 12 copper cannot exceed 20 amperes, regardless of the fact that the listed ampacities for this size are higher (for example, THW, 25 A; RHH, 30 A). However, it is advantageous to have these higher ampacity ratings. The ratings as listed in Table 11.1 apply at an ambient temperature of 30°C and with not more than three conductors in a raceway. With higher ambient temperatures and more than three conductors, derating factors must be applied as discussed in Sections 11.1.4 and 11.1.5. A No. 12 AWG conductor may still be satisfactory for a 20 ampere branch circuit, rather than having to go to the next larger size.

■ EXAMPLE 12.1

Six No. 12 RHH copper conductors for a number of 20 A circuits are all to be run in the

Solution

From Table 11.1, the ampacity rating of the conductors is 30 A. The correction factor for 40°C is 0.91. From Table 11.3(b), the adjustment factor for six conductors is 80%.

same conduit. The ambient temperature is 40°C. Determine whether the ampacity rating of the conductors is satisfactory.

$$\text{Ampacity} = 30 \times 0.91 \times 0.80 = 21.8 \text{ A} \quad \text{(satisfactory)}$$

Note that No. 12 THW conductors would not be satisfactory for this application. Their ampacity is listed as 25 amperes and, after the application of the derating factors, they would only be good for 17.6 amperes. Number 10 THW copper conductors would have to be used. However, regardless of ampacity ratings, there are specific *NEC* rules with regard to the minimum temperature rating of conductors used to connect to lighting fixtures (*NEC* Section 410-31). Branch-circuit conductors brought within 3 inches of a ballast in a lighting fixture must have a temperature rating not less than 90°C, such as types RHH, THHN, XHHW, and THW (note that THW has a 90°C rating when used in fluorescent fixtures, *NEC* Table 310-13). Otherwise, the temperature rating of the wiring connected to a lighting fixture shall be suitable for the temperature as listed by the Underwriters Laboratories approval for the fixture.

NEC Section 310-5 states that the minimum size of copper conductors that can be used for branch circuits is No. 14 AWG. However, for commercial and industrial establishments, it is good design practice to specify No. 12 copper as the minimum size even for 15 ampere circuits. The larger size helps to keep the voltage drop within the allowable limits over the longer circuit runs encountered.

12.2 BRANCH CIRCUITS FOR LIGHTING

RULES

Branch circuits for lighting shall have a maximum rating of 20 amperes unless the lighting units have heavy-duty lampholders. Thus, branch circuits for fluorescent lighting and for the smaller-wattage, medium-base incandescent lamps (up to 300 watts) are restricted to 15 or 20 amperes. Fixed lighting units with heavy-duty lampholders [that is, the larger-wattage, mogul-base incandescent and high-intensity discharge (HID) lamps] can be connected to circuits rated up to 50 amperes when installed in other-than-dwelling units. HID lamps are the mercury, metal-halide, and high-pressure sodium lamps. The reader at this time should review Chapter 4 for the details of light sources, in particular, Figure 4.3 on bases for lamps and Tables 4.1 through 4.5 for listings of lamps.

The lighting involved in the general illumination of such areas as offices, schools, and industrial plants is considered to be a continuous load. The *NEC* restricts the maximum loading on a circuit supplying a continuous load to 80% of the rating of the circuit (*NEC* Section 210-22). Thus, on a 20 ampere lighting circuit, the maximum loading is 0.80 times 20, or 16 amperes. The calculated load for circuits supplying electric discharge lamps that have ballasts must be based on the line current to the ballasts (see Figures 4.8 and 4.15) and not just on the wattage of the lamps alone. The total input to the lighting unit must include the ballast losses. See Tables 4.4 and 4.5 for total input watts to ballasts for fluorescent and HID lamps, respectively.

The voltage limitations of branch circuits are governed by *NEC* Section 210-6. All lighting fixtures in dwelling units, guest rooms of hotels, motels, and similar occupancies are restricted to circuits not exceeding 120 volts nominal between conductors (line-to-neutral of 120/240 volt single phase, three-wire and 208Y/120 volt three-phase, four-wire systems). All lighting units using medium-base, screw-shell, incandescent lampholders, regardless of location, are restricted to circuits not exceeding 120 volts nominal. The ballasts for the electric discharge lamps (fluorescent and HID) and lighting fixtures equipped with mogul-base, screw-shell lampholders or with lampholders other than the screw-shell type applied within their voltage rating can be connected to circuits exceeding 120 volts, but not exceeding 277 volts nominal to ground (480Y/277 volt, three-phase, four-wire grounded system). For the illumination of outdoor areas such as roadways, parking lots, and athletic fields, the ballasts for electric discharge lamps can be connected to circuits not exceeding 600 volts nominal between conductors, providing that the lighting units are mounted on poles or similar structures at a minimum height of 22 feet. This permits these outdoor units to be connected to 480 volt ungrounded systems.

The ballasts for fluorescent lamps should be operated from the line-to-neutral voltage of grounded systems as shown in Figure 4.8. This ensures reliable starting, as discussed in Section 4.3.2. Ballasts for HID lamps may be operated either from line-to-neutral or line-to-line voltages. However, if operated from the line-to-line voltage, two-winding ballasts, as shown in Figure 10.20, should be used to permit the grounding of the shell of the lamp socket.

The general illumination of large office and industrial areas is normally provided by fluorescent or HID lamps because of their much higher efficacies (see Introduction to Chapter 4). The fact that these lighting units can be operated from the 480Y/277 volt, three-phase, four-wire system is of considerable advantage. First, the savings in feeder and branch-circuit wiring can be considerable as illustrated in Example 12.2. Second, the voltage drop is far less of a problem. Every 1 volt drop on a 120 volt circuit results in a 0.83% voltage drop, whereas every 1 volt drop on a 277 volt circuit causes only a 0.36% voltage drop. Thus larger areas of the building can be covered from each lighting panel. Finally, both the three-phase motors and the lighting can be supplied from the same system. The relatively small amount of power required for the 120 volt lighting and general-purpose receptacle loads can be supplied from dry-type step-down transformers located throughout the building. It should be noted that the 480Y/277 volt, three-phase, four-wire system must have the neutral solidly grounded. See Section 10.2 for a full description of grounded systems. If the neutral is not grounded, then the voltage to ground is considered to be 480 volts (see *NEC* definition "voltage to ground") and the indoor lighting units cannot be connected to the system.

■ EXAMPLE 12.2

Refer to the lighting layout in Example 5.11 and Figure 5.10. A total of 70 luminaires (lighting units) is required for the area to be lighted. Each luminaire has two 800 mA, 96 in., 113 W fluorescent lamps. The ballast for each lighting unit is rated at 252 W (Table 4.4), with a line current of 2.1 A at 120 V and 0.92 A at 277 V. Determine the minimum number of branch circuits required for the lighting load with a system voltage of (a) 208Y/120 V and (b) 480Y/277 V.

Solution

The maximum allowable rating of each circuit is 20 A. The maximum loading of each circuit is $0.80 \times 20 = 16$ A.

(a) 208Y/120 V system (ballasts connected to 120 V):

— Maximum number of units per circuit is $16/2.1 = 7.6 \approx 7$.
— Minimum number of circuits is $70/7 = 10$.

The logical arrangement is two circuits per row. The circuit loading is $7 \times 2.1 = 14.7$ A.

(b) 480Y/277 V system (ballasts connected to 277 V):

— Maximum number of units per circuit is $16/0.92 = 17.4 \approx 17$.
— Minimum number of circuits is $70/17 = 4.1 \approx 5$.

The logical arrangement is one circuit for each row. The circuit loading is $14 \times 0.92 = 12.9$ A.

17 15.64

Note that it takes only one-half the number of circuits to wire the complete lighting system using 277 V.

12.3 BRANCH CIRCUITS FOR RECEPTACLES

A *receptacle* is defined as *a contact device installed at the outlet for the connection of a single attachment plug*. An *outlet* is further defined as *a point on the wiring system at which current is taken to supply utilization equipment*. A *duplex* receptacle has two devices mounted on a common yoke and is installed in one outlet box, and, similarly, a triplex receptacle has three devices mounted on a common yoke and is installed in one outlet box.

A single receptacle installed on an individual branch circuit must have an ampere rating not less than that of the branch circuit. For example, a single receptacle on a 20 ampere circuit must be rated at 20 amperes. The one exception to this requirement is that two or more 15 ampere receptacles are permitted on a 20 ampere circuit. Figure 12.1(a) shows the configuration of a few of the common ratings of receptacles. The configurations are arranged so that the receptacle will not accept an attachment plug of a different ampere or voltage rating from that of the receptacle. The one exception is the 20 ampere T-slot receptacle, which can also accept a 15 ampere attachment plug of the same voltage rating. Receptacles installed on 15 and 20 ampere branch circuits must be of the grounding type. This means that all 120 volt general-purpose plug outlets must be of the three-pole type. The grounding terminal must be properly bonded to the equipment grounding circuit as shown in Figure 10.11. If the branch-circuit wiring is of the nonmetallic type, then a separate equipment grounding conductor must be run with the circuit conductors for this purpose. The 125 volt, 15 ampere, U-ground duplex receptacle shown in Figure 12.1(b) is a very common type of general-purpose receptacle.

The minimum load for an outlet installed for a specific appliance or load is set by the ampere rating of the appliance or load served. The continuous load supplied by the branch circuit must not exceed 80% of the branch-circuit rating. However, the majority of receptacles are installed for general-purpose use and the exact loads are most likely unknown. In this case, a minimum loading of 180 volt–amperes must be allowed for each general-use receptacle. Figure

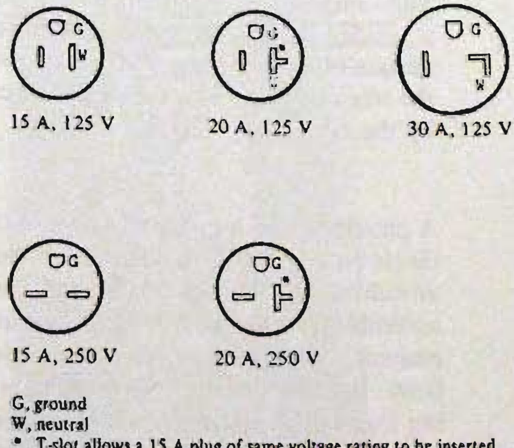


FIGURE 12.1

General-purpose receptacles

(a) Configurations for nonlocking receptacles. (for a complete listing, see ANSI C73 standard and for CSA configurations, see Appendix A)

(b) U-ground duplex receptacle, 125 V, 15 A

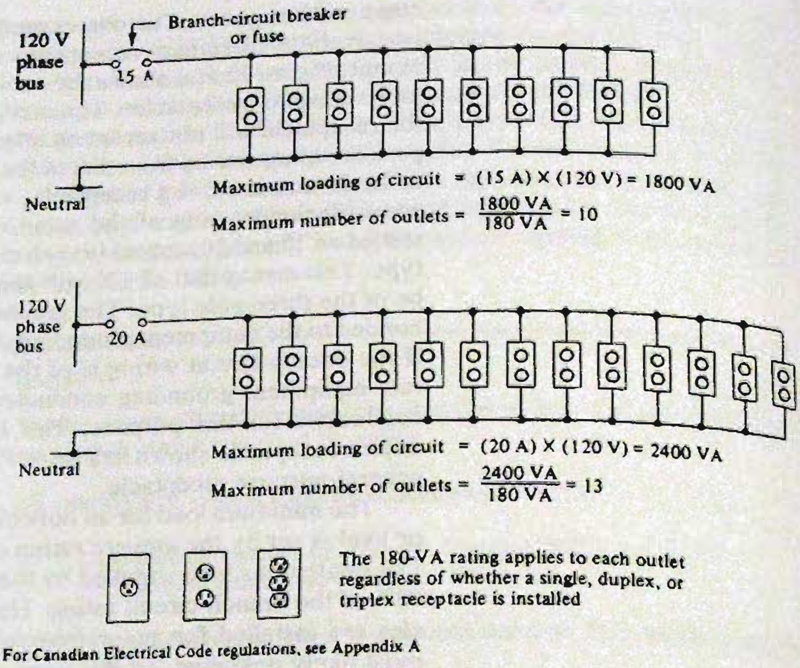


FIGURE 12.2

Maximum number of general-use receptacles permitted on branch circuits

12.2 shows the maximum number of general-use receptacles that are permitted on 15 and 20 ampere branch circuits. Note that the 180 volt–ampere rating is applied per outlet point, regardless of whether a single, duplex, or triplex receptacle is used at that outlet. For certain office and industrial areas, good design practices may dictate the use of fewer receptacles per circuit then the maximum allowed by the code.

12.4 LIGHTING PANELS

A panelboard is a group of panel units designed for assembly into a single panel, including buses, automatic overcurrent devices, and/or switches, for the control of light, heat, and power circuits. This assembly is suitable for mounting in a cabinet, which can then be placed in or against a wall and which is accessible only from the front. In other words, a panelboard is a convenient method of grouping together those overcurrent devices that are fed from a common source and that provide circuit protection to a number of branch circuits. The *NEC* further defines a *lighting and appliance branch-circuit panelboard as one having more than 10% of its overcurrent devices rated 30 amperes or less for which neutral connections are* *provided*. Most panels installed for lighting and receptacle branch circuits (often just referred to as lighting panels) fall within this definition and are therefore subject to the special *NEC* requirements with regard to these types of panels (see *NEC* Sections 384-13 to 384-27 inclusive). Section 384-15 restricts any one lighting panel to a maximum of 42 single-pole overcurrent devices or their equivalent (that is, a two-pole device is considered as two single-pole devices and a three-pole device as three single pole devices in determining this number).

A very common form of lighting panel consists of an assembly of light-duty, molded-case circuit breakers. These types of breakers are discussed in Section 8.4.3. A typical lighting panel using the double-row arrangement of breakers is shown in Figure 12.3(a). In commercial or institutional buildings, these panels can either be flush mounted into a wall in finished areas or they can be surface mounted on a wall in unfinished areas. A growing trend in large office buildings is to provide small electrical closets at the same location on each floor (see Figure 12.8). The panels can then be surface mounted on the walls of the closet, and the feeders supplying the panels can be run vertically up through the closet space. In industrial installations, it is frequently impossible to find a suitable wall in an open manufacturing area on which to mount the panels. Column-width panels specifically designed to fit between the flanges

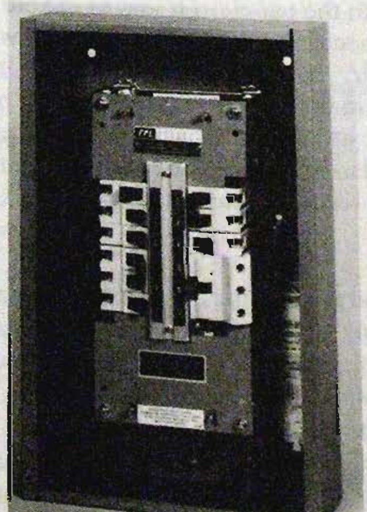
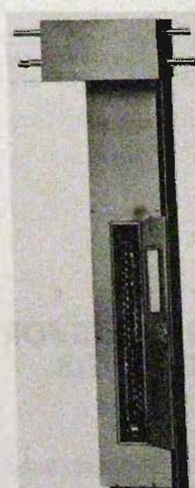


FIGURE 12.3

Lighting and appliance branch-circuit panelboards

(a) Standard panel with double-row arrangement of branch breakers (shown with cover and door removed)



(b) Special column-type panel with single-row arrangement of branch breakers

of the structural steel columns are available for such locations. The circuit breakers are mounted in one vertical row, as shown in Figure 12.3(b). A pull-box containing the neutral connections for all the branch circuits is mounted above the panel, with a continuous wire-way provided to connect the panel with the pull-box.

Standard panels are available for 120/240 volt single-phase, three-wire; 208Y/120 volt, three-phase, four-wire; and 480Y/277 volt, three-phase, four-wire systems. The typical arrangement of circuits for a 120/240 volt, single-phase panel is shown in Figure 1.16. The layout of a three-phase, four-wire panel using the conventional double-row arrangement of branch breakers is shown in Figure 12.5. A panel must have an ampacity rating (capacity of the main bus) not less than that required for the total computed load for the panel. See Section 12.11 for the method of computing this load.

Each lighting panel must be individually protected on its supply side by an overcurrent device having a rating not more than that of the lighting panel. If a panel is supplied through its own individual feeder or subfeeder, as shown in Figure 12.4(a), then a main overcurrent device is not required at the panel if the feeder overcurrent protection is not greater than the rating of the panel. A main overcurrent device (main breaker) is required for a lighting panel that is supplied directly from the secondary of its own step-down transformer, as shown in Figure 12.4(b). If the panel is tapped off a feeder that also supplies other panels, as shown in Figure 12.4(c), then a main breaker is required at each panel to provide individual protection to the panel itself and to enable the panel to be shut off without the necessity of affecting the power to the other panels on the feeder. The feeder arrangement shown in Figure 12.4(c) is often used in multistory buildings where panels are located one above the other on each floor. One vertical feeder is used to feed a number of panels. Note the code requirements for the feeder taps from the main feeder to each panel as detailed on the diagram.

12.5 CIRCUIT ARRANGEMENTS FOR LIGHTING PANELS

For large buildings where three-phase power is normally used, the lighting panels are arranged for three-phase, four-wire operation, as shown in Figure 12.5. The individual circuits for the lighting and receptacle circuits are connected from one phase of the panel to the neutral, as shown. One important advantage of using the three-phase, four-wire configuration is that it permits up to three circuits to be connected to the one common neutral. Note that to make use of this arrangement each circuit selected must be on a different phase. The reader should review the basic voltage and current relationships for three-phase systems given in Section 1.6.

As shown in Figure 12.5, when the loads on each of the three circuits connected to the one common neutral are balanced, the

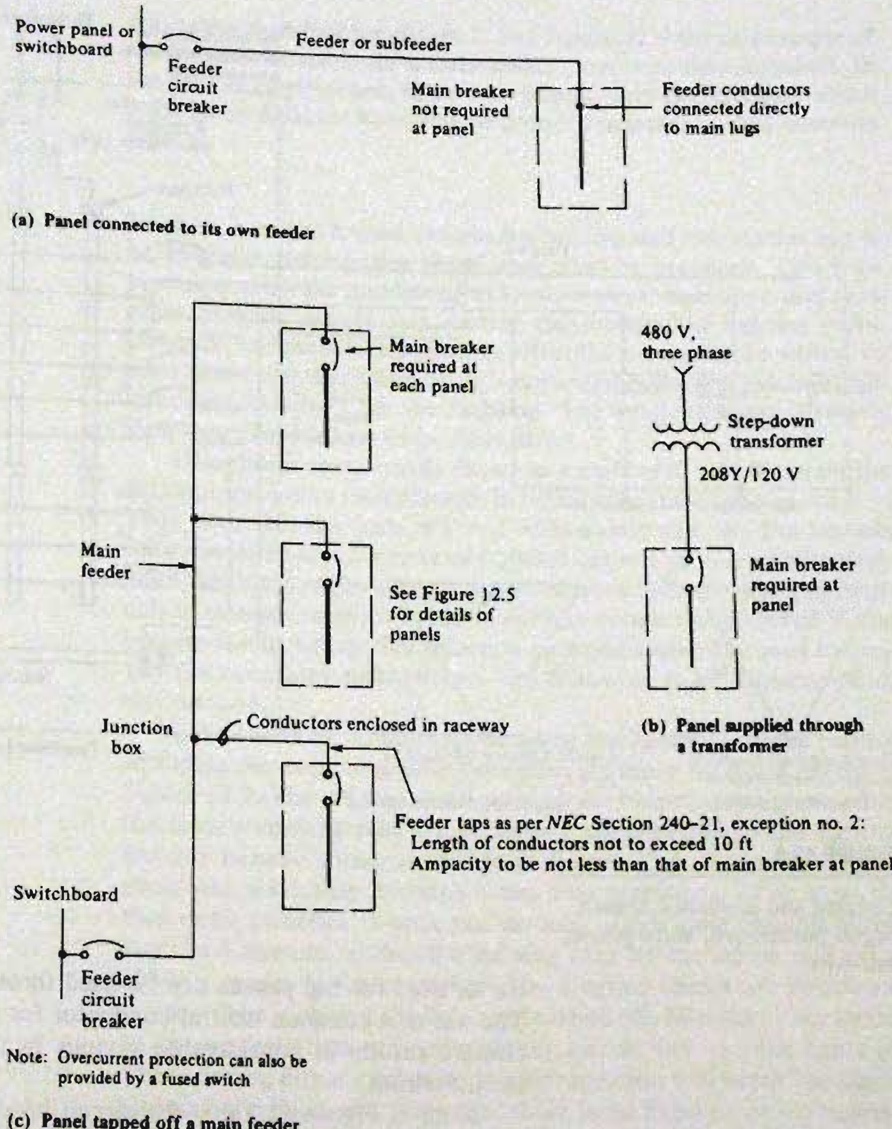


FIGURE 12.4

Requirements for main breakers in lighting and appliance branch-circuit panelboards

neutral current is zero (ignoring any third-harmonic components). Even if the load on one of the circuits is disconnected, the neutral current (the phasor sum of the two remaining circuit currents) still only equals the magnitude of one of the circuit currents. Therefore, the magnitude of the neutral current can never exceed the magnitude allowed for each of the circuit currents and the same size of conduc-

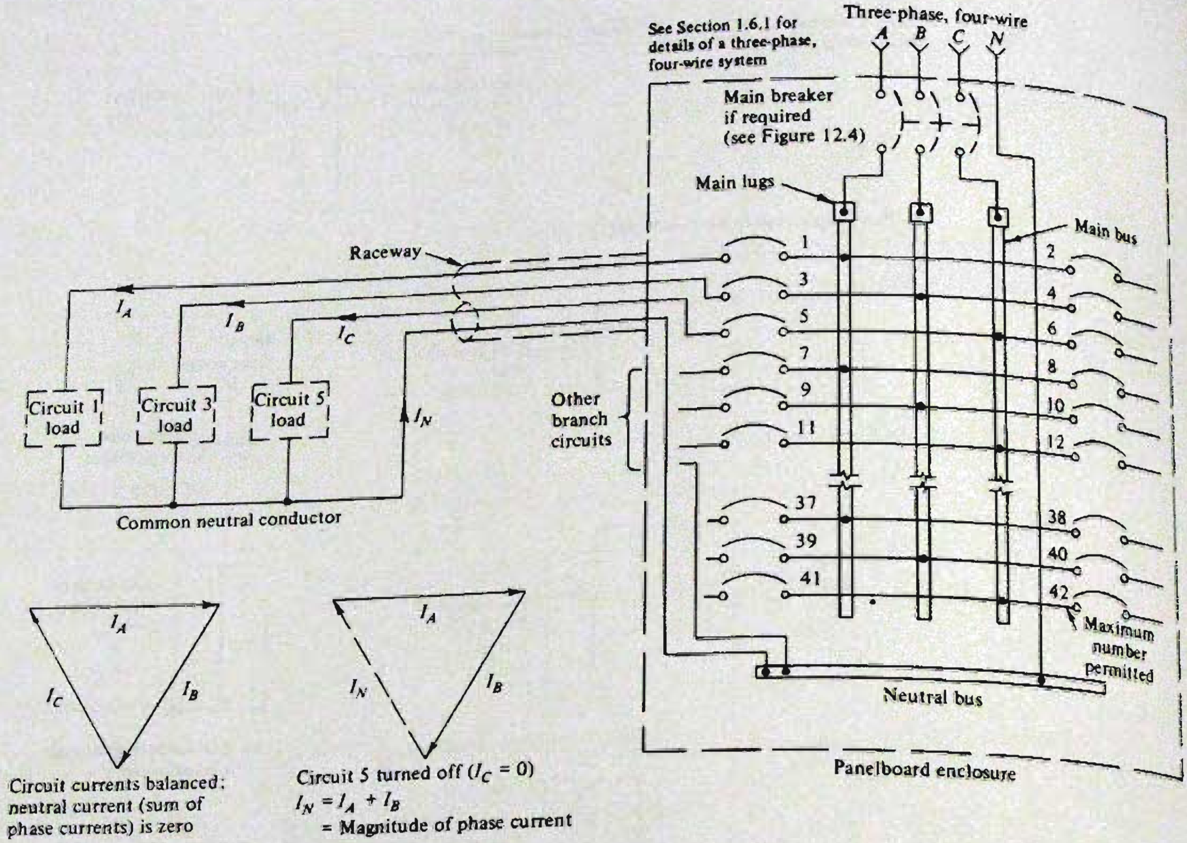


FIGURE 12.5

Lighting and appliance branch-circuit panelboard, three-phase, four-wire.

tor as used for the phases can be used throughout for the neutral. The use of a common neutral conductor for each grouping of three circuits results in considerable savings in the cost of the branch circuit wiring.

Note in Figure 12.5 that the circuit breaker connections to the main bus are arranged so that consecutive breakers on one side are on different phases. For example, circuits 1, 3, and 5 are connected to phases *A*, *B*, and *C*, respectively, and can therefore be grouped together on the one common neutral, as shown. Similarly, circuits 2, 4, and 6 can be grouped together, 7, 9, and 11, and so on. On the other hand, a combination of circuits 1, 2, and 3 would not be acceptable for grouping together as both circuits 1 and 2 are connected to phase *A*. Circuit 2 must be connected to a different neutral circuit conductor than that for circuit 1. See Figure 12.9 for an example of the layout of circuits for a three-phase, four-wire lighting panel. In the case of single-phase, three-wire panels, only two circuits, which must be on different lines, can be grouped together on one common neutral.

12.6 MODIFIED CONNECTION DIAGRAMS FOR FLOOR LAYOUTS

To show how the branch circuits for lighting and receptacles are to be arranged, a floor plan of the area must be prepared. This floor plan must show the location of walls, doorways, stairways, and such other building details that dictate the location of lighting units, switches, and receptacles and that affect the routing of the wiring. In most instances, this information is copied from the architectural and structural drawings for the building. The branch-circuit wiring is then superimposed on these floor plans.

Floor plans are normally drawn to a scale of $\frac{1}{8}$" = 1'-0" unless the layout is unusually complicated, in which case the scale may be $\frac{1}{4}$" = 1'-0". Note that the scale of $\frac{1}{8}$" = 1'-0" is a ratio of 1 : 96. For layouts drawn using SI units, a scale of 1 : 100 (1 cm = 1 m) is normally used. With this scale of drawing, it would be very difficult (and impractical) to attempt to show every individual conductor involved in the branch-circuit wiring. Therefore, a modified method is used to convey the necessary information. The following is an explanation of this method.

Let us start by completely detailing the lighting in three rooms, including the switching. The floor plan for these rooms is shown in Figure 12.7. The schematic diagram of the branch circuit, including the local switching and the necessary connections to the lighting fixtures in each room, is shown in Figure 12.6. Room 3 requires three-way switching because it has two entrances. Note how the three-way switches (which are actually single-pole, double-throw switches) operate so that the lighting may be turned on and off at either entrance in any sequence. The diagram shows the position of the switches such that the lights are turned off. Moving either switch to its other position will complete the circuit and turn the lights on. Then moving either switch to its other location will break the circuit and turn the lights off. Note that there is no fixed on or off position for either switch.

Figure 12.7(a) indicates on the floor plan the complete connection diagram, showing all the runs of individual conductors and their connections that are necessary to complete the system. As can be appreciated, to draw all the branch-circuit wiring throughout the building in this degree of detail would be very time consuming and indeed next to impossible to show clearly on a layout scaled at $\frac{1}{8}$" = 1'-0". Therefore, the modified connection diagram as shown in Fig-

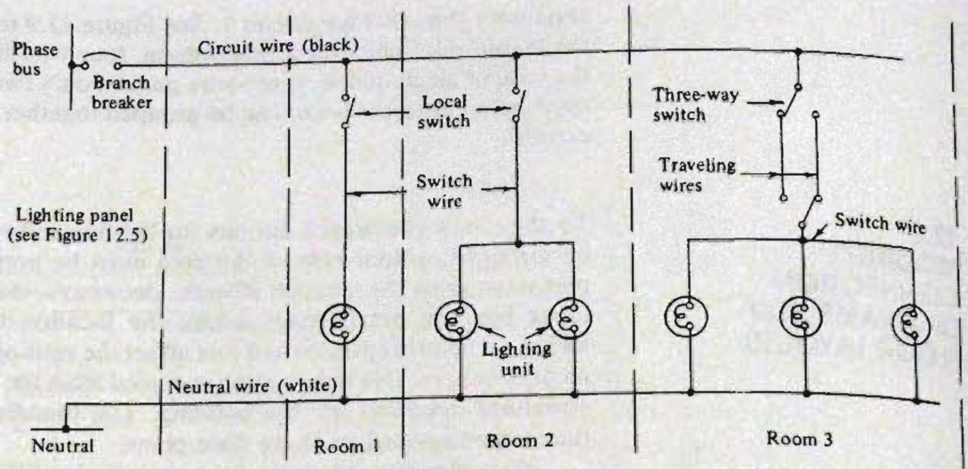


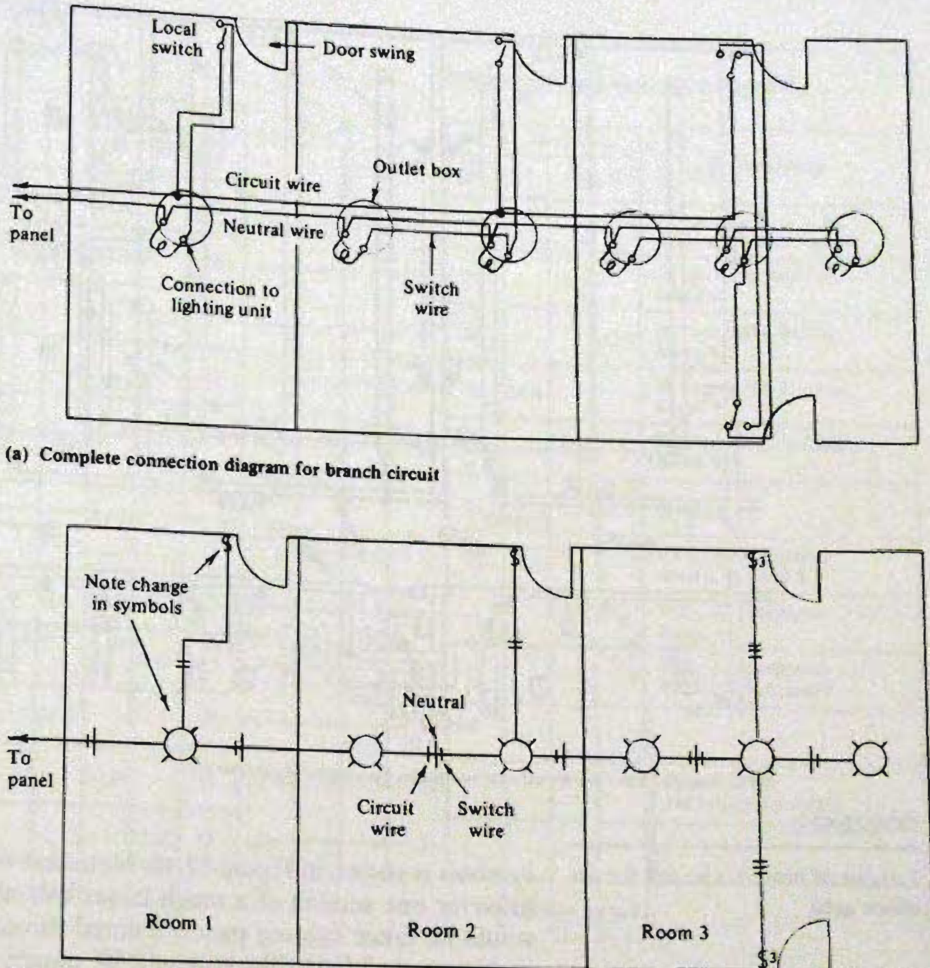
FIGURE 12.6

Schematic diagram for lighting layout as shown in Figure 12.7

ure 12.7(b) is the method adopted to actually show the branch-circuit wiring. In this method, the solid line becomes the routing of the wiring, and the actual number of wires in any one section is indicated by the number of marks. As discussed in Section 12.1, the wiring in large buildings is installed in conduit or EMT. The solid line then indicates the run of conduit or EMT into which the individual insulated conductors are pulled. See Section 11.5 for details of raceways. Note the change of symbols for the modified connection diagram. The symbol is chosen to reflect the function of the device, as there is no need to show the detailed connections to it.

If we refer again to Figure 12.6, there are three classifications of conductors in the complete circuit: the circuit wire (which is at the circuit potential of 120 volts), the neutral wire (which is at ground potential) and the switch wire (which is energized only when the local switch is closed). To differentiate these wires in each run of conduit, the method shown in Figure 12.7(b) has been adopted for the sample layout as shown in Section 12.7. More is stated in this section about the identification of the wires.

The layout shown in Figure 12.7(b) is for the lighting only. Most areas also require branch-circuit wiring for receptacles. In commercial, institutional, and industrial types of buildings, it is normal practice to have circuits dedicated solely to lighting and other circuits dedicated solely to receptacles. Also, for practical reasons, the runs of wiring are usually kept separate, since the wiring for the lighting is run at the ceiling level and the wiring for the receptacles is run at the floor level. To differentiate between these runs on the floor plans, a solid line indicates a run of conduit at ceiling level and a dashed line



(a) Complete connection diagram for branch circuit

See Figure 12.10 for a complete description of symbols

(b) Modified connection diagram for branch circuit

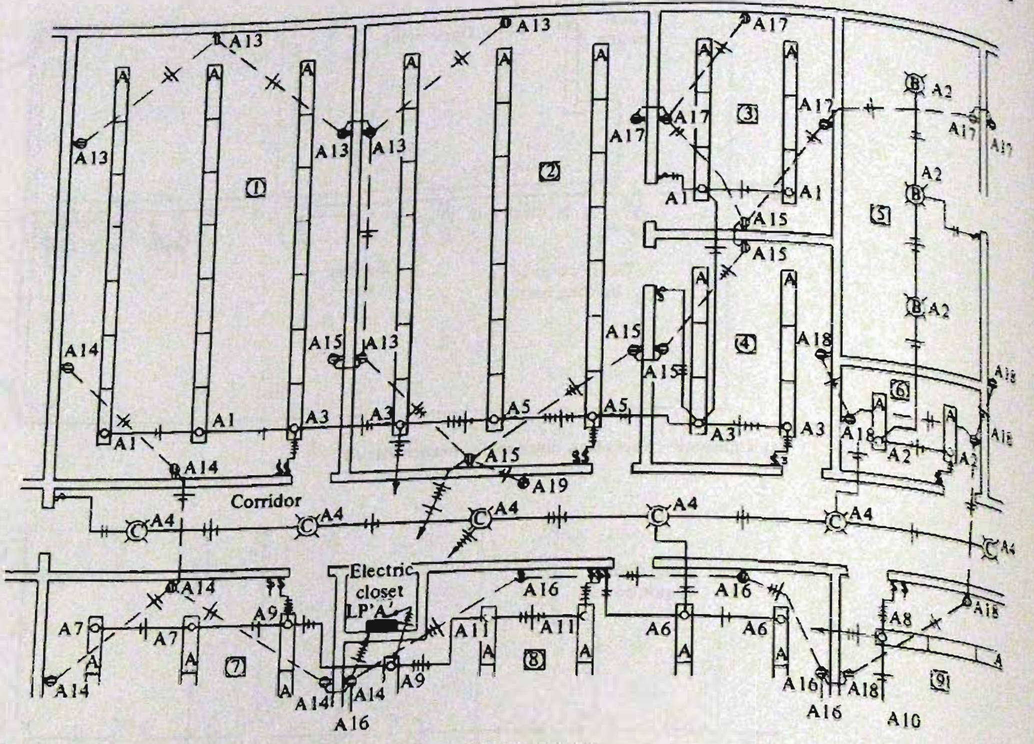
FIGURE 12.7

Method of showing branch-circuit wiring on floor plan

indicates a run of conduit at floor level (usually concealed in the structural floor member). See the legend of symbols in Figure 12.10 for more details on the method of indicating branch-circuit wiring.

12.7 EXAMPLE FLOOR LAYOUT OF LIGHTING AND RECEPTACLES

Figure 12.8 shows the layout of an area that is part of an office building. The branch circuits for the lighting and for the receptacles are indicated using the modified method just discussed in Section 12.6. The panel schedule is shown in Figure 12.9 and the legend of



Note: Details such as windows and door swings have been omitted from floor plan

FIGURE 12.8

Layout of branch circuits for an office area

symbols is shown in Figure 12.10. Note that the layout is only meant to cover one section of a much larger overall area. As such, there would be other lighting panels located throughout the area, and in multistory buildings, there would be panels on each floor. Therefore, a means of identifying each panel must be adopted. One method is simply to assign a letter designation to each panel. The letter A has been selected for the panel shown on the layout, and thus the circuits from this panel are identified as A1, A3, A5, and so on (note the A identification has nothing to do with phase A). There is local switching of the lights in each room. See Section 12.8 for further discussion on the switching of lighting systems. The power supply to the lighting panel is 208Y/120 volts, three-phase, four-wire.

As noted in the legend, the fluorescent lighting units (designated type A) draw a line current of 0.80 ampere at 120 volts. Following the code rules discussed in Section 12.2 for the branch circuits for lighting, 20 ampere circuits are used, which permits a maximum loading of 16 amperes. This then allows a maximum of 16/0.80 = 20

Lighting panel A

System: 208Y/120 volts, 3-PHASE, 4-WIRE

Description	Load (A) A	Load (A) B	Load (A) C	Bkr. Trip (A)	Ckt.	Ckt.	Bkr. Trip (A)	Load (A) A	Load (A) B	Load (A) C	Description
20 Type A ltg. fixtures Rooms 1 and 3	16.0			20	1	2	20	6.6			3 Type B, 2 Type A ltg. fixtures, Rooms 5 and 6
20 Type A ltg. fixtures Rooms 1, 2, and 4		16.0		20	3	4	20		15.0		6 Type C ltg. fixtures, Corridor
14 Type A ltg. fixtures Room 2			11.2	20	5	6	20			12.8	16 Type A ltg. fixtures Room 8
16 Type A ltg. fixtures Room 7	12.8			20	7	8	20	14.4			18 Type A ltg. fixtures Room 9
15 Type A ltg. fixtures Rooms 7 and 8		12.0		20	9	10	20		9.6		12 Type A ltg. fixtures Room 9
16 Type A ltg. fixtures Room 8			12.8	20	11	12	20			16.0[a]	Spare
6 Duplex receptacles Rooms 1 and 2	12.0[b]			15	13	14	15	12.0			6 Duplex receptacles Rooms 1, 7, and 8
6 Duplex receptacles Rooms 1, 2, 3, and 4		12.0		15	15	16	15		10.0		5 Duplex receptacles Room 8
6 Duplex receptacles Rooms 2, 3, and 5			12.0	15	17	18	15			12.0	6 Duplex receptacles Rooms 4, 5, 6, and 9
1 20 amp. receptacle Corridor	16.0			20	19	20					Spaces only No breakers installed
Spare		12.0[a]		15	21	22					
Spare			12.0[a]	15	23	24					
	56.8	52.0	48.0					33.0	34.6	40.8	

Total load phase A: 89.8 A

Total load phase B: 86.6 A

Total load phase C: 88.8 A

Total load on panel: 31.8 kVA

[a]Allowance for future loads

[b]Allowance for each duplex receptacle, 240 VA

Note: Figure 12.8 does not show the complete layout for all the above circuits
See Appendix A for modifications to meet Canadian Electrical Code regulations

FIGURE 12.9

Lighting panel schedule for layout of Figure 12.8

of the type A fixtures to be connected to one circuit. However, the arrangement of the fixtures must also be taken into account so that the wiring and switching are kept as simple as possible. Two basic rules to follow are that (1) the minimum number of circuits should be used for each room, and (2) where possible each continuous row of fixtures should be on the same circuit. Considering room 1, there are 3 rows of 7 for a total of 21 type A fixtures in this room, just one

Legend of Symbols for Layout Shown on Figure 12.8

A	Fluorescent fixture, 2 F40CW lamps, 120 V, 0.80 A input to ballast
B	Incandescent fixture; 120 V, 200 watt
C	Incandescent fixture, 120 V, 300 watt, medium base
O A1	Ceiling mounted outlet box (circuit 1, panel A)
A14	Duplex receptacle, 125 V, 15 A (circuit 14, panel A)
	Single receptacle, 125 V, 20 A
$	AC general-use snap switch, 120 V, 20 A, single pole
$_3$	AC general-use snap switch, 120 V, 20 A, three-way
LP'A'	Surface-mounted panelboard (lighting panel A)
1	Room number
	Wiring concealed in wall or ceiling
	Wiring concealed in floor
	Branch circuit homerun to panelboards } (three circuit wires on common neutral)
Neutral; * Circuit wires; Switch wires	Run of wiring indicating number and type of wires (i.e., two circuit wires, one neutral, and two switch wires) *On side toward direction back to panelboard

Method of Showing Wiring as per ANSI Standards

	Indicates three wires, four marks = four wires, etc.
1 2	Branch circuit homeruns to panelboard, number of arrows = number of circuits, numerals indicate circuit numbers

Refer to American National Standards Institute publication Y32.9 for a complete list of recommended symbols.

FIGURE 12.10

Graphic symbols for electric wiring and layout diagrams

more than can be accommodated on one circuit. It would create an illogical switching and circuiting pattern to put two complete rows plus six units of the third row on one circuit, leaving just one unit for a second circuit. Note that the same problem applies to room 2. Therefore, as shown on the plan, three circuits (A1, A3, and A5) are used for these two rooms, with two complete rows (total of 14 units) put on each of these circuits. This leaves spare capacity on these circuits, so the six type A units in room 3 are also put on circuit A1 and the six type A fixtures in room 4 are also put on circuit A3, which then brings these circuits up to their maximum loading.

The possible extra loading for circuit A5 is not so straightforward. The next adjacent areas are rooms 5 and 6. The loading in room 5 consists of three type B, 200 watt incandescent units with a demand of $(3 \times 200)/120 = 5.0$ amperes. This is too much to add to circuit A5. The two type A units in room 6 could easily be added to circuit A5, but a new circuit must be brought to room 5; so it is decided to put both rooms 5 and 6 on this new circuit (A2). The loading on circuit A5 is left at only 14 type A units or 11.2 amperes. Because of this lighter loading on circuit A5, which is connected to phase *C*, the loadings on subsequent groups of circuits are arranged to offset this unbalance as shown in the panel schedule. The total load on the panel should be balanced between the three phases as closely as possible (within ±10%), as per the total loads indicated at the bottom of the panel schedule.

Circuits A1, A3, and A5 were chosen for the first grouping of circuits so that the one common neutral can be used for wiring these circuits and for the homerun (see Figure 12.5). The term *homerun* applies to *that portion of the branch circuit wiring running from the closest outlet point back to the panel*. There are no further connections to the circuits. The homerun is indicated on the floor plan by a line with an arrow pointing in the direction of the panel. Note that, with regard to the local switching in rooms 1 and 2, a minimum of one switch is required for each circuit in the room. If separate switching of each row of fixtures had been desired, then three switches per room would be required and an extra switch wire run to the third row.

It is the usual practice to locate the lighting branch circuits at the top of the panel, with the branch circuits for the receptacles coming next. Therefore, circuits A2, A4, and A6 are chosen for the next grouping of circuits, followed by A7, A9, and A11. The final two lighting circuits required are assigned to A8 and A10, with circuit A12 left as a spare for possible future lighting.

The circuiting for the receptacles in the example layout is done on the basis that 15 ampere branch circuits are used, with a maximum of six duplex receptacles connected to each circuit. This is less than the maximum permitted by the code (see Section 12.3), but it reduces the possibility of overloading the circuit by having too many pieces of office equipment plugged in at the same time on the same circuit. In calculating the load on the lighting panel, a rating of 240 volt–amperes is assumed for each 15 ampere duplex receptacle. Note that the receptacle circuits are also grouped together so that the one common neutral can be used (for example, A13, A15, and

A17). Figure 11.10(c) shows the typical method of running conduit to the outlet boxes for receptacles.

It is a good idea to locate a few 20 ampere receptacles at regular intervals around an office area. These receptacles, each on their own dedicated 20 ampere circuit, are required for cleaning equipment such as floor polishers. If such equipment is plugged into the general 15 ampere circuit, it usually trips the circuit breaker on starting. The example layout includes one 20 ampere receptacle located in the hallway.

The complete circuiting of the area covered by lighting panel A is shown on the lighting panel schedule. Note that the panel layout includes some spare breakers for future use and some spaces. The spaces permit the installation of additional breakers if and as required. As well as serving as a record of the circuits being used during the design and construction of the electrical system, the panel schedule should be posted on the door of the lighting panel as a reference for maintenance purposes.

The method used to identify circuit wires, neutral wires, and, in the case of lighting circuits, switch wires on the sample layout (Figure 12.8) is detailed in the legend of symbols (Figure 12.10). Also shown is the American National Standards Institute (ANSI) recommended method of showing branch circuit wiring and homeruns. The more detailed method used in this textbook has been adopted to help the reader follow the wiring and to better understand the number of wires required for the circuiting and switching. In practice, a complete legend of symbols should be presented with every set of electrical floor plans so that there is no misunderstanding as to the precise intent of each symbol. Refer to ANSI publication Y32.9 for a complete listing of the recommended graphic symbols for electrical wiring and layout diagrams used in architecture and building construction.

The reader is referred to Chapter 3 of the *National Electrical Code* with regard to wiring methods and materials. In particular Article 300 covers wiring methods, Article 310 covers conductors for general wiring, and Article 370 covers outlet, device, pull and junction boxes, and conduit bodies and fittings. The following are a few of the requirements that affect the layout of the branch circuit wiring. A box or fitting must be installed at each conductor splice connection point, outlet, switch point, junction point, or pull point for the connection of conduit, electrical metallic tubing, surface raceway, or other raceways. Junction, pull, and outlet boxes must be so installed that the wiring contained in them can be rendered accessible without removing any part of the building. Boxes must be of sufficient size to provide free space for all conductors plus any device (switch, receptacle) or fitting (fixture stud, cable clamp) that is enclosed in the box. To ensure that standard boxes can be used, the number of wires routed through any one box should be limited to conform with the requirements of *NEC* Section 370-6.

NEC Article 410 covers the installation of lighting fixtures and receptacles. In particular, note that lighting fixtures cannot be used as raceways for circuit conductors unless specifically approved for such. One exception to this requirement is that fixtures designed for end-to-end assembly to form a continuous row are permitted to carry through conductors of a two-wire or multiwire branch circuit supplying the fixtures. Another exception allows one additional two-wire branch circuit to be carried through the fixtures to supply switched night-lighting units.

The partial layout shown in Figure 12.8 is meant only to introduce the method of organizing branch circuits for a typical office area. No attempt is made to show such items as separate night lighting, exit lights, and emergency lighting systems. The requirements for emergency systems and exit lights are covered by municipal, state, federal, and other codes or governmental agencies having jurisdiction. Where emergency systems are required, their installation is covered by *NEC* Article 700.

12.8 SWITCHING OF LIGHTING SYSTEMS

The example layout shown in Figure 12.8 includes local switching of the lighting at the entrance to each room using direct-acting, ac, general-use snap switches of the type shown in Figure 12.11. These switches are available with 15, 20 and 30 ampere ratings and are designed for installation in flush-mounted device boxes. As previously mentioned in Section 12.2, in large buildings it is advantageous to supply fluorescent and HID-type lighting from the 480Y/277 volt systems. If local switching is desired, ac general-use snap switches rated for 277 volts are available. See also *NEC* Article 380.

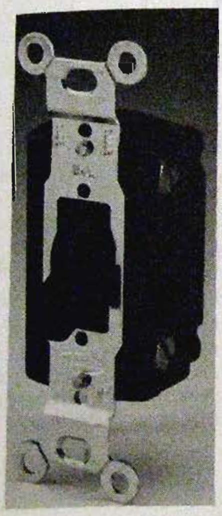


FIGURE 12.11

AC general-use snap switch

In many commercial establishments with wide-open areas, local switching of lights is often not practical. The lighting is instead switched directly from the lighting panel using the branch circuit breakers. The area lighting of large, open industrial areas is also normally switched using the branch circuit breakers at the lighting panel. Where circuit breakers are used to frequently switch the lighting circuits, they should be the type marked SWD. These breakers have been tested and found suitable for the greater frequency of on–off operations required for switching duty, as compared to the infrequent use normally encountered with breakers used only for overcurrent protection and maintenance. A further step in the control of large-area lighting is to have a separate lighting panel feeding only the lighting branch circuits. The panel is then energized through a magnetic contactor, which can either be controlled manually through a remote on–off push button or automatically by a time switch or photoelectric device.

Finally, a more sophisticated and flexible means of switching individual and/or blocks of lighting units involves the use of low-voltage, remote-control switching relays. The basic operation of these relays is shown in Figure 12.12. The relays are operated from a low-voltage source (usually 24 volts) through a step-down control transformer. The contacts of the relays can switch circuits up to 277 volts. The relays can be installed in the outlet boxes for the lighting units if desired so that the branch-circuit wiring goes directly to the lighting unit. The cost of then installing the low-voltage control wiring to the switching points is much less than that for power circuit wiring. The system is flexible in that each relay can be controlled from more than one point, or, conversely, a number of relays can be controlled simultaneously from one point. Programmable lighting controllers specifically designed for use with the low-voltage switching relays are available. These controllers can automatically

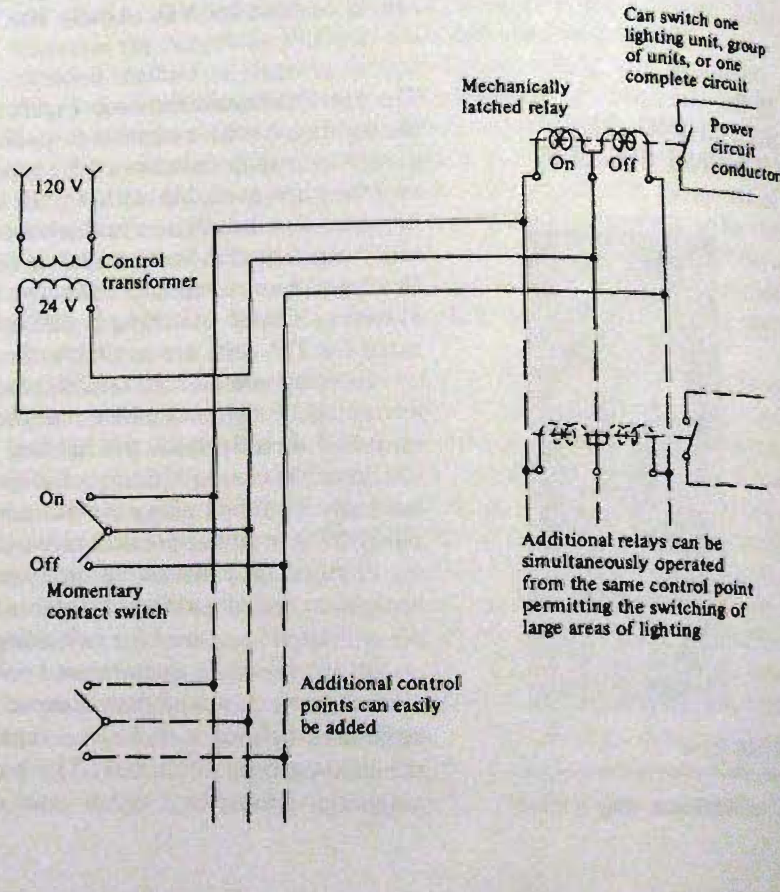


FIGURE 12.12

Low-voltage, remote-control switching for lighting switch lighting units to control lighting levels as activities in the area change throughout the day (for example, after hours for cleaning purposes). Passive infrared control devices are now available that sense when a person enters or leaves an area and automatically turns the lights on or off. The off function has a 12 minute delay feature to allow the occupant to leave the room momentarily without any unnecessary switching of the lights.

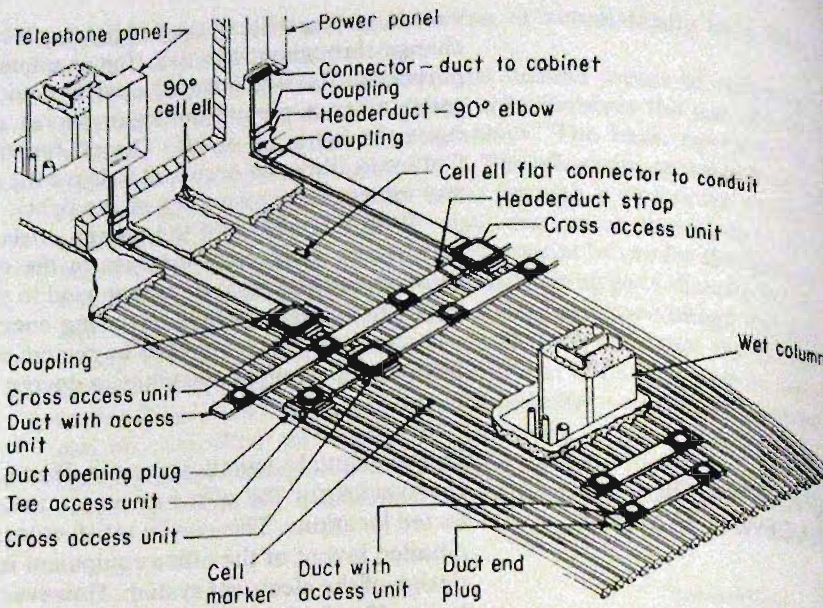
With the advent of the energy crisis in the 1970s and with the subsequent substantial increase in the cost of electrical energy, a great deal more attention is now paid to the switching of the lighting in a building as a means of saving energy. The added cost of the switching controls can often be recovered within a reasonable time from the accumulated savings in energy consumption.

12.9 UNDERFLOOR RACEWAY SYSTEMS

In the example layout shown in Figure 12.8, the general-purpose receptacles for the office areas are installed in the walls at preselected locations. This can be satisfactory if the rooms are small and a detailed layout of the office equipment is available at the time of the design of the electrical system. However, this is often not the case in large office buildings, especially those built for the purposes of renting space to various tenants. At the time of the design of the building, little if anything is known of the detailed layout of the rentable space. Therefore, a flexible system is required that will allow power wiring to be taken at a later time to any area of the floor for connection to receptacles. Such a system is an *underfloor raceway system*.

There are two basic types of such systems: *underfloor duct* and *cellular floor systems*. Underfloor duct is a system of parallel ducts spaced not more than 6 feet apart running just beneath the finished floor level. Normally, the ducts for the power wiring are combined with side-by-side runs of ducts for the telephone system wiring and in some cases for separate in-house communication or signaling system wiring. Junction boxes are located at a maximum spacing of 40 feet along the runs, with cross runs to connect the junction boxes.

Cellular floor systems make use of the cellular floor decks that are installed as part of the structure of the building. Cellular metal floor raceways are the hollow spaces provided by the forming of sheet metal sections that are used as the structural floor members. Cellular concrete floor raceways are the hollow spaces left in the precast concrete floor slabs that are used as the structural floor members. The cells are normally divided into groups of two (power and telephone) or groups of three (power, telephone, and communications), depending on the requirements of the area. Header ducts are installed at right angles to the cells, which provide access to predetermined cells.



HEADER DUCTS may be installed on top of cellular flooring parallel with or at right angles to structural cell members, with access boxes of various sizes to coincide with local wiring requirements. Diagram shows how power and telephone circuits can be routed longitudinally through floor cells, then shifted laterally via header ducts to bypass such obstructions as structural columns or riser shafts.

FIGURE 12.13

Cellular metal floor raceway system

The complete matrix of ducts or cells in any one area is then connected by header ducts to separate power, telephone, and communication panels. Figure 12.13 shows a typical cellular metal floor system complete with header ducts and connections to a power panel and a telephone panel. The view shows the system just prior to the finished concrete fill being poured over the entire floor.

At the time of the design and layout of the electrical system, an estimated number of branch circuit breakers is specified to be included in the power (that is, lighting) panel for the eventual use for the receptacle circuits. As soon as the layout details of any particular area are known, floor receptacle assemblies can be easily installed at any location on the floor (for example, within the area covered by a desk). Markers are installed in the floor during construction so that the exact location of the nearest power duct or cell can be determined. Access to the floor duct or cell is then obtained by cutting through the concrete floor finish using a properly sized concrete-boring drill. The necessary branch-circuit wiring is pulled through the header duct and cell system from the lighting panel. After the electrical connections are made to the receptacle, the receptacle assembly is firmly attached to the floor.

Metal underfloor duct and cellular metal floor raceway systems must be so constructed that adequate electrical and mechanical continuity of the complete system is maintained to provide proper grounding of the system and of the power receptacles. In the case of the cellular concrete floor raceway systems, separate grounding conductors must be installed in the cells as necessary to maintain the grounding system to the receptacles. *NEC* Articles 354, 356, and 358 cover the requirements with regard to the installation of underfloor duct, cellular metal floor, and cellular concrete floor raceway systems, respectively.

12.10 GROUND-FAULT CIRCUIT-INTERRUPTERS

In Section 10.5, the protection of systems and equipment against ground faults is thoroughly discussed. However, equally important is the protection of personnel from the shock hazards of ground faults, which requires a level of response as low as 5.0 milliamperes. Refer to Figure 10.12(a) which shows the possible shock-voltage exposure with respect to a piece of equipment that has a ground fault. If the equipment grounding circuit to the equipment is not installed properly or, worse still, if it is accidentally broken, anyone touching the faulted equipment is subject to the shock voltage and can then become part of the return path of the ground-fault current. In situations where the person could be grounded, such as working outdoors on wet ground or in areas with grounded water pipes such as bathrooms, the shock could easily be fatal. The protection of a circuit to such an area then requires a ground-fault circuit-interrupter (GFCI), which can automatically disconnect the circuit when the flow of current to ground exceeds 5.0 milliamperes. Protection may be provided either by a GFCI circuit breaker mounted in a panelboard, which protects the entire branch circuit, or by a GFCI-type receptacle that protects anything plugged into the receptacle. Figure 12.14 shows the connection and method of operation of a GFCI circuit breaker.

The *National Electrical Code* requires that all 125 volt, single-phase, 15 and 20 ampere receptacles in the following areas shall have ground-fault protection for personnel: receptacles in the bathrooms of dwelling units and of guest rooms in hotels and motels; receptacles installed in the garages of dwelling units and outdoors where there is direct grade-level access; receptacles in dwelling units within 6 feet of the kitchen sink and located above the counter top; receptacles in wet areas of health-care facilities; receptacles within 20 feet of swimming pools; and receptacles in commercial garages. In addition, all underwater lights in swimming pools operating at more than 15 volts shall have GFCI protection. This list is not meant to cover all the areas requiring GFCI protection, but rather to indicate the type of areas involved. Certainly, GFCI protection

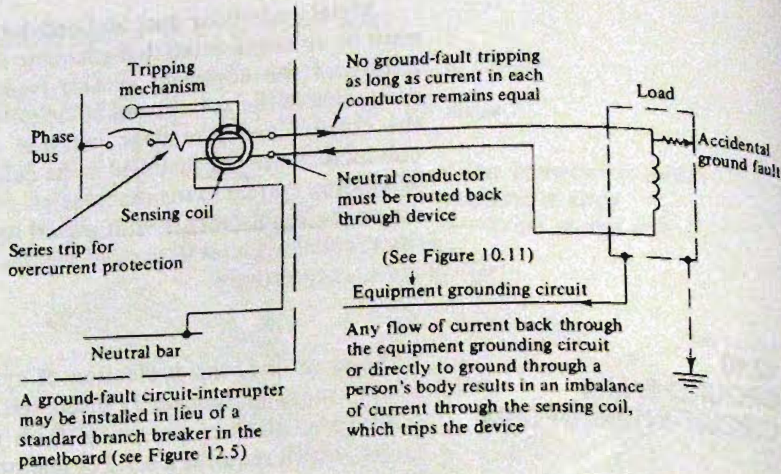


FIGURE 12.14

Connection and method of operation of a ground-fault circuit-interrupter (GFCI)

should be provided for any type of circuit where there is any danger to personnel from ground faults. The *NEC* permits the feeders to panels supplying 15 and 20 ampere receptacle branch circuits to be protected by a GFCI in lieu of providing GFCIs for the individual branch circuits. It may be more economical or convenient to install GFCIs for feeders, but there is the disadvantage that a ground fault on any one circuit will de-energize all the circuits.

12.11 COMPUTED LOADS FOR LIGHTING AND RECEPTACLES

After determining the branch circuit requirements for a lighting and appliance branch-circuit panelboard (lighting panel), the total load has to be calculated for the purpose of selecting the feeder to the panel. Notwithstanding the determination of this load from the actual loads connected to each circuit, the *NEC* regulations require that a unit load, based on volt–amperes per square foot, be used to compute the minimum loading. Refer to Table 12.1 [*NEC* Table 220-3(b)], which shows the type of occupancies for which this requirement applies and the unit loads per square foot associated with each type of occupancy. Note that, for buildings laid out using the SI units, the conversion factor is listed at the foot of the table.

For office buildings, the unit loading for the general lighting is listed as 3½ volt–amperes per square foot. Refer to Example 5.15, which shows the calculations for the lighting of a commercial area to a level 1000 lux (100 footcandles). The unit load for the layout (item 14) is calculated to be 3.33 watts per square foot. Since two lamp high power factor ballasts are normally used for good quality fluorescent lighting fixtures, the loading in volt–amperes would be virtually the same. Refer next to the layout shown in Figure 12.8. Using room 1 as being typical of the lighting load, the total area of the room

TABLE 12.1 Unit Loads for General Lighting (from *NEC* Table 220-3(b))

Type of Occupancy	Unit Load per Square Foot (volt–amperes)
Armories and auditoriums	1
Banks	3½[b]
Barber shops and beauty parlors	3
Churches	1
Clubs	2
Court rooms	2
Dwelling units[a]	3
Garages: Commercial (storage)	½
Hospitals	2
Hotels and motels, including apartment houses without provisions for cooking by tenants[a]	2
Industrial commercial (loft) buildings	2
Lodge rooms	1½
Office buildings	3½[b]
Restaurants	2
Schools	3
Stores	3
Warehouses (storage)	¼
In any of the above occupancies except one-family dwellings and individual dwelling units of two-family and multifamily dwellings:	
Assembly halls and auditoriums	1
Halls, corridors, closets, stairways	½
Storage spaces	¼

For SI units, 1 square foot = 0.093 square meter.

[a] All general-use receptacle outlets of 20-ampere or less rating in one-family, two-family, and multifamily dwellings and in guest rooms of hotels and motels [except those connected to the receptacle circuits specified in Section 220-4(b) and (c)] shall be considered as outlets for general illumination, and no additional load calculations shall be required for such outlets.

[b] In addition, a unit load of 1 volt–ampere per square foot shall be included for general-purpose receptacle outlets when the actual number of general-purpose receptacle outlets is unknown.

is 20 by 30 feet, or 600 square feet. There are 21 fixtures in the room with an input of 96 volt–amperes (120 volts time 0.8 ampere), for a total of 21 times 96 = 2016 volt–amperes. The unit loading is 2016 divided by 600 = 3.36 volt–amperes per square foot. These examples indicate that the minimum value of 3½ volt–amperes per square foot required by the code is very adequate for most office areas, especially with the advent of the more efficient fluorescent and HID lamps and energy-saving ballasts. However, should the actual connected load for the general lighting exceed the load computed using the values in Table 12.1, the actual load must be used for the feeder calculations. The general lighting load for such areas as offices, banks, stores, and schools is considered to be a continuous load, and therefore the computed load for the feeder must be based on 125% of the continuous load (see Section 11.7).

As explained in Section 12.9, the detailed loads for the general-purpose receptacles in office areas are usually not known at the time of designing the electrical system. For this situation, refer to the footnote to Table 12.1, which states that an additional unit load of 1 volt–ampere per square foot be added for the general-purpose receptacle outlets.

The demand factor for a load is the measure of the part of the load that will actually be called for at any given time (averaged over a short period of time). It is therefore the ratio of the maximum demand to be expected as compared to the total connected load for

TABLE 12.2 Lighting Load Feeder Demand Factors (from *NEC* Table 220-11)

Type of Occupancy	Portion of Lighting Load to Which Demand Factor Applies (volt–amperes)	Demand Factor (%)
Dwelling Units	First 3000 or less at	100
	From 3001 to 120,000 at	35
	Remainder over 120,000 at	25
Hospitals[a]	First 50,000 or less at	40
	Remainder over 50,000 at	20
Hotels and motels, including apartment houses without provision for cooking by tenants[a]	First 20,000 or less at	50
	From 20,000 to 100,000 at	40
	Remainder over 100,000 at	30
Warehouses (storage)	First 12,500 or less at	100
	Remainder over 12,500 at	50
All others	Total volt–amperes	100

[a] The demand factors of this table shall not apply to the computed load of feeders to areas in hospitals, hotels, and motels where the entire lighting is likely to be used at one time, as in operating rooms, ballrooms, or dining rooms.

TABLE 12.3 Demand Factors for Nondwelling Receptacle Loads (from *NEC* Table 220-13)

Portion of Receptacle Load to Which Demand Factor Applies (volt–amperes)	Demand Factor (%)
First 10 kVA or less	100
Remainder over 10 kVA at	50

Applies to receptacle loads computed at not more than 180 volt–amperes per outlet.

that part of the system under consideration. Table 12.2 (*NEC* Table 220-11) shows the demand factors that are allowed for general lighting loads according to types of occupancy. These demand factors can only be used in computing the load for the feeders. They cannot be used for determining the number or size of the branch circuits for the general illumination. For receptacle loads in other-than-dwelling units, either the demand factors listed in Table 12.2 or those listed in Table 12.3 (*NEC* Table 220-13) may be used. The receptacle loads for Table 12.3 are based on the minimum of 180 volt–amperes per outlet, as discussed in Section 12.3. For the purposes of computing the minimum ampacity rating of a feeder, the nominal system voltage can be used in the calculations.

■ EXAMPLE 12.3

A lighting panel supplies the lighting and receptacle load for an office area of 10,000 sq. ft. There are a total of 100 general-use duplex receptacles. The service is 208Y/120 V, three phase, four wire. Calculate the minimum ampacity rating for the feeder conductors to the panel. For these calculations, assume that the entire lighting load is continuous, and the actual lighting load is less than the computed lighting load.

Solution

— General lighting load, from Table 12.1:

(10,000 ft² at 3.5 VA/ft²) × 1.25 = 43,750 VA

— Receptacle load: 100 × 180 VA = 18,000 VA:

From Table 12.3: first 10,000 VA at 100%	= 10,000 VA
Remaining (18,000 − 10,000) VA at 50%	= 4,000 VA
Total computed load	= 57,750 VA

— Minimum ampacity $= \dfrac{57{,}750}{1.732 \times 208} = 160.4 \approx 160$ A

■ **EXAMPLE 12.4**

Refer to Figure 12.4(c). Assume that the feeder shown supplies three lighting panels in a hospital. Each panel supplies the lighting and receptacle load for an area of 12,000 sq. ft., 2000 sq. ft. of which is corridor, closet, and stairway areas. Each panel supplies 120 general-use duplex receptacles. The areas fed by the panels do not include any operating rooms, general office areas, or dining rooms. Assume the actual connected lighting loads are less than the computed lighting loads. The service is 208Y/120 V, three phase, four wire. Determine the minimum ampacity for (a) the taps to each panel and (b) the main feeder supplying the three panels.

Solution

(a) For the feeder taps to each panel:

— General lighting load, from Table 12.1:

2000 ft^2 at 0.5 VA/ft^2	= 1,000 VA
(12,000 − 2000) ft^2 at 2.0 VA/ft^2	= 20,000 VA
— Receptacle load: 120 × 180 VA	= 21,600 VA
Total computed load	= 42,600 VA

— Net computed load using demand factors from Table 12.2:
42,600 VA at 40% (50,000 VA or less) = 17,040 VA

— Minimum ampacity $= \dfrac{17{,}040}{1.732 \times 208} = 47$ A

(b) For the main feeder:

— Total computed load for 3 panels = 3 × 42,600 = 127,800 VA
— Using demand factors from Table 12.2:

First 50,000 VA at 40%	= 20,000 VA
Remainder (127,800 − 50,000) at 20%	= 15,560 VA
Net computed load	= 35,560 VA

— Minimum ampacity $= \dfrac{35{,}560}{1.732 \times 208} = 98.8 \approx 99$ A

Note that, in both Examples 12.3 and 12.4, had the actual lighting loads exceeded the computed lighting loads using Table 12.1, then the actual lighting loads would be used in the calculations. In the case of Example 12.3, the actual lighting load would again be multiplied by the 1.25 factor as required for a continuous load.

Refer to Section 11.7 for complete examples showing the selection of the actual wire sizes and types for feeders, taking into account derating factors, available short-circuit current, and voltage drop. Refer to *NEC* Article 220 for the complete requirements of feeder calculations, and to NEC Chapter 9 for examples of calculations.

SUMMARY

- A branch circuit is that segment of the electrical system between the final overcurrent device and the outlet for the utilization equipment.
- A branch circuit is classified by the rating of the overcurrent device protecting the circuit.
- Branch circuits for lighting are restricted to a maximum of 20 amperes unless supplying heavy-duty lampholders.

- The continuous load on a branch circuit is restricted to a maximum of 80% of the rating of the circuit.
- Branch circuits for the lighting in dwellings and guest rooms are restricted to a maximum of 120 volts.
- Branch circuits for medium-base, screw-shell incandescent lampholders are restricted to a maximum of 120 volts.
- Branch circuits for electric discharge lamp type of lighting fixtures may be 277 volts nominal.
- The minimum load for general-use receptacles is 180 volt–amperes per outlet.
- The maximum number of general-use receptacles allowed on a 15 ampere circuit is 10 and on a 20 ampere circuit is 13.
- A lighting and appliance branch-circuit panelboard (often referred to as simply a lighting panel) is one that has more than 10% of its overcurrent devices rated at 30 amperes or less for which neutral connections are provided.
- A lighting panel is restricted to a maximum of 42 single-pole overcurrent devices.
- A lighting panel must be individually protected on its supply side by its own overcurrent device.
- Branch circuits that are connected to a common neutral must each be on separate lines (120/240 volt, single-phase, three-wire systems) or separate phases (three-phase, four-wire systems).
- The modified connection diagram is used to show the layout of the branch circuits on building floor plans.
- Single-phase loads must be arranged so that the total loading on a panel is reasonably balanced between the phases.
- A junction box or fitting must be installed at each conductor splice connection point, outlet, switch point, junction point, or pull point.
- All boxes and fittings must be accessible.
- A lighting fixture cannot be used as a raceway for circuit conductors unless specifically approved for such.
- Attention should be paid to the switching of the lighting units providing general illumination as a means of reducing the energy consumption of a building.
- Underfloor raceway systems provide a flexible means of distributing power to floor outlets in office and store areas.
- Ground-fault circuit-interrupters provide protection to personnel in areas where they could accidently be exposed to the hazards of ground faults.

- The minimum ampacity for the feeder to a panelboard must be based on the computed loads as per the *National Electrical Code* requirements.

QUESTIONS

1. Define a branch circuit.
2. How is a branch circuit classified?
3. What is the maximum rating permitted for the overcurrent protection of a general-purpose circuit consisting of (a) three No. 14 RHH copper and (b) three No. 10 THW copper.
4. What type of conductors must be used for connecting to a ballast inside a lighting fixture?
5. What is the maximum current rating permitted for a circuit that supplies lighting fixtures with medium-base lampholders?
6. What is the maximum current rating permitted for a circuit that supplies lighting fixtures with mogul-base lampholders?
7. What is the maximum continuous load permitted on a circuit?
8. What is the maximum circuit voltage permitted for medium-base, screw-shell lampholders?
9. What is the maximum circuit voltage permitted for indoor fluorescent lighting fixtures (other than in dwelling units)?
10. What are the advantages of supplying the lighting for large areas from 480Y/277 volt systems?
11. What is the minimum rating permitted for a single receptacle on a 30 ampere circuit?
12. What is the maximum number of general-use 15 ampere duplex receptacles permitted on a 15 ampere circuit? Explain how this is determined.
13. What is the definition of a lighting and appliance branch-circuit panelboard?
14. What is the maximum number of single-pole overcurrent devices permitted in one panelboard?
15. A lighting panel rated for 200 amperes is fed by a feeder that has 200 ampere overcurrent protection. Is a main breaker required at the panel? Explain.
16. A lighting panel is connected to the secondary of a 480-208Y/120 volt, three-phase transformer. Is a main breaker required at the panel?
17. Explain how and why three circuits can be connected to one common neutral on a three-phase, four-wire system.
18. In the layout in Figure 12.8, explain why a maximum of 20 type A fluorescent lighting units can be connected to one 20 ampere circuit.
19. What is a homerun and how is it designated on a layout drawing?
20. What is the significance of the SWD marking on a branch-circuit breaker used in a lighting panel?
21. What is a low-voltage, remote-control switching relay?
22. Why are underfloor raceway systems used?
23. Explain the GFCI circuit breaker.
24. List at least four types of circuits (by location) that require GFCI protection.
25. What is the unit loading for the general lighting and general-use receptacles (number unknown) for office areas?
26. What is a demand factor?

PROBLEMS

1. Nine No. 14 THW copper conductors for a number of 15 A circuits are all run in the same conduit. The ambient temperature is 35°C. Determine whether the ampacity rating of the conductors is satisfactory.
2. Six No. 10 RHH copper conductors for a number of 30 A circuits are all run in the same conduit. The ambient temperature is 35°C. Determine whether the ampacity rating of the conductors is satisfactory.
3. Refer to the lighting layout in Example 5.13 and Figure 5.11(b). A total of 35 lighting fixtures is required. The ballast for each fixture is rated at 450 W (Table 4.4), with a line current of 1.62 A at 277 V. The system is 480Y/277 V, three phase four wire. Determine (a) the minimum number of

branch circuits required for the lighting and (b) the practical number to use, taking into account the arrangement of the fixtures.

4. Refer to the lighting layout in Example 5.14 and Figure 5.12. A total of 28 lighting fixtures is required. The ballast for each fixture is rated at 295 W (Table 4.5), with a line current of 1.1 A at 277 V. The system is 480Y/277 V, three-phase, four-wire. Determine the minimum number of 30 A branch circuits required for the lighting.

5. It is estimated that an office area requires a total of 115 general-use, 120 V duplex receptacles. Calculate the minimum number of 20 A circuits required.

6. A lighting panel supplies the lighting and receptacle load for an office area of 12,000 sq. ft, of which 1000 sq. ft are corridors and stairwells. There are a total of 150 general-use receptacles. The service is 208Y/120 volt, three-phase, four-wire. Calculate the minimum ampacity rating for the feeder conductors to the panel. Assume that the entire lighting load is continuous and that the actual lighting load is less than the calculated load.

7. Repeat Problem 6, except that the number of general-use receptacles is unknown.

8. Refer to Figure 12.4(c). Assume that the feeder shown supplies three lighting panels in a motel. Each panel supplies the lighting and receptacle load for an area of 14,000 sq. ft, 1500 sq. ft of which is corridor, closet, and stairway areas. Each panel supplies 50 general-use duplex receptacles. The areas fed by the panels do not include any dining rooms or kitchens or any appliances. Assume the actual lighting loads are less than the computed loads. The service is 208Y/120 V, three-phase, four-wire. Determine the minimum ampacity for (a) the taps to each panel and (b) the main feeder supplying the three panels.

13 Branch Circuits and Feeders for Motors

OBJECTIVES

After studying this chapter, you will be able to:

- Define the special problems of motor branch circuits.
- Identify the essential components of a motor branch circuit.
- Select the protective device for a motor branch circuit.
- Select the overload protection for a motor.
- Size the motor branch circuit conductors.
- Select the disconnecting means.
- Select the conductors and size the protective device for a feeder to a group of motors.
- Apply the special rules for a single motor tap.

INTRODUCTION

The design of the branch circuits and feeders for motors requires special considerations. Electric motors have unique starting and running characteristics, as discussed in Chapter 2. Also of great importance is the protection of personnel from the electrical and mechanical hazards of motors and the safeguarding of the equipment from damage.

Motors typically have starting currents that are many times (for example, six times) their full-load running currents. Unless this large transient starting current, which can last for upward of 15 seconds, is allowed for in the design of the circuit feeding the motor, the motor will be unnecessarily shut down. Once the motor is properly started and running, it must then be protected from overheating due to mechanical overloading of the motor. The protective devices must be able to bypass the transient starting currents, yet still be able to react very accurately to any overloads and protect the motor from being damaged. The circuit conductors, switches, and controllers must all be rated to carry the maximum load current that the motor is permitted to carry on a continuous basis. The branch circuit and motor must be protected from damage due to possible short circuits. In addition to these electrical requirements, it is mandatory that the motor and its controller be provided with a safe disconnecting means so that they can be isolated from the electrical supply in order that maintenance of the equipment can be done with no hazard to personnel.

The material presented in this chapter concentrates only on the requirements for alternating current, squirrel-cage induction motors, which are by far the most common motors used in buildings (Section 2.5). There are induction motors used for continuous duty (that is, loaded on a continuous basis), and there are motors used for short-time, intermittent, periodic, or varying duty, such as motors used for positioning and for elevators. Unless otherwise noted, all discussions are with regard to continuous-duty motors that are stationary and permanently connected to the power system.

The reader is referred to the *National Electrical Code* (*NEC*), Article 430, Motors, Motor Circuits, and Controllers, for the complete requirements for all types of motors. The reader should also refer to the Occupational Safety and Health Administration (OSHA) regulations 1910.305(j)4. There are many exceptions to the general code requirements permitted for small fractional horsepower motors that plug into outlets. Again the reader is referred to *NEC* Article 430 for these exceptions. For the Canadian Electrical Code requirements, see Appendix A.

13.1 BRANCH CIRCUIT FOR A SINGLE MOTOR

The branch circuit for a single motor consists of all conductors and electrical equipment between the point of connection of the final overcurrent device protecting the motor and the motor. Figure 13.1 illustrates the essential components of a motor branch circuit, which are:

1. Branch-circuit, short-circuit, and ground-fault protection
2. Branch-circuit conductors
3. Motor controller with overload protection
4. Disconnecting means

The motor controller can be any switch or device used to start and stop the motor by making and breaking the motor current. One of the most common forms of controller for three-phase motors of 1 horsepower and greater is the magnetic type of starter, which is discussed in Chapter 14.

The *National Electrical Code* requires that, where the current rating of a motor is used to determine the ampacity of conductors,

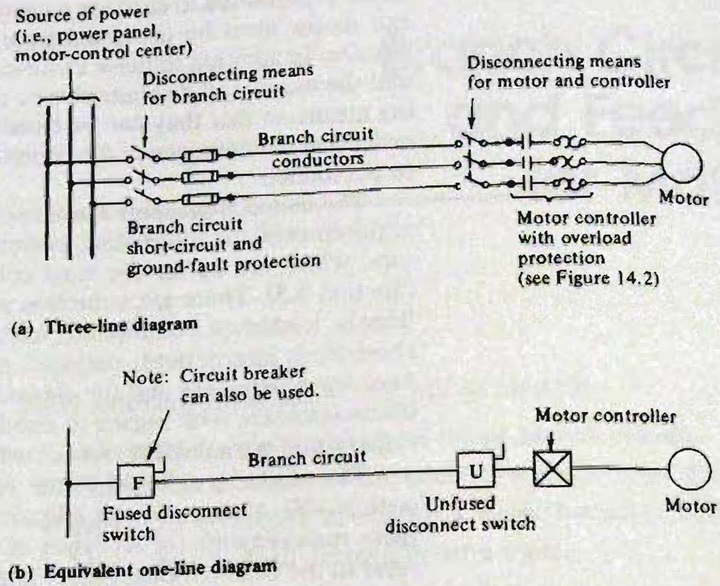


FIGURE 13.1

Typical branch circuit for squirrel-cage induction motor

the ampere rating of switches, branch-circuit protective devices, and so on, the values listed in *NEC* Tables 430-147 to 430-150 including notes be used, instead of the actual current rating marked on the motor nameplate. Tables 13.1 and 13.2 show the *NEC* values for single- and three-phase alternating current motors, respectively.

The rated full-load currents of motors for a given voltage and horsepower rating may vary slightly depending on their rated speed (number of poles) and application. Therefore, the final selection of the motor overload protection, which is very critical, shall be based on the actual motor nameplate current rating. This latter requirement makes certain that the overload protection is then matched to the actual motor being protected.

The requirements for motor branch circuits, which are 600 volts and less, are as outlined in the following articles.

13.1.1 Short-Circuit and Ground-Fault Protection

As required for any feeder, the motor branch circuit must have a protective device located at the point where the circuit conductors receive their supply of current (see Section 6.1). However, the protective device cannot be rated to match the ampacity of the motor branch-circuit conductors because of the high starting current of the motor. Figure 13.2(a) shows the plot of the typical motor current as a function of time from the instant of starting up to the full-load running of the motor. The diagram also shows the typical response

TABLE 13.1 Full-Load Currents for Single-Phase Alternating Current Motors (from *NEC* 430-148)

HP	115 V	230 V
$\frac{1}{6}$	4.4	2.2
$\frac{1}{4}$	5.8	2.9
$\frac{1}{3}$	7.2	3.6
$\frac{1}{2}$	9.8	4.9
$\frac{3}{4}$	13.8	6.9
1	16	8
$1\frac{1}{2}$	20	10
2	24	12
3	34	17
5	56	28
$7\frac{1}{2}$	80	40
10	100	50

The values of full-load currents given are for motors running at usual speeds and motors with normal torque characteristics. Motors built for especially low speeds or high torques may have higher full-load currents, and multispeed motors will have full-load current varying with speed, in which case the nameplate current ratings shall be used.

To obtain full-load currents of 208- and 200-volt motors, increase corresponding 230-volt motor full-load currents by 10% and 15%, respectively.

The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120 and 220 to 240.

curve for a nontime-delay fuse, indicating its relationship to the motor current. If the rating of the fuse is too low, then the large starting current of the motor will blow the fuse before the motor can accelerate to its rated speed. Figure 13.2(b) similarly shows the relationship with a time-delay fuse, indicating why it can have a lower rating yet still not blow during starting. Figure 13.3 shows the relationship between a typical circuit breaker with inverse time-delay elements and the motor starting and running currents.

Another approach to motor circuit protection is to use a circuit breaker with adjustable magnetic trip action [see Figure 8.5(b)], thus providing instantaneous tripping only. The trip unit is set to exceed the locked-rotor (that is, starting) current of the motor. Therefore, the breaker will only be tripped if there is a short circuit on the motor branch circuit or within the motor. As such, this device is

TABLE 13.2 Full-Load Currents[a] for Three-Phase Alternating Current Motors (from *NEC* 430-150)

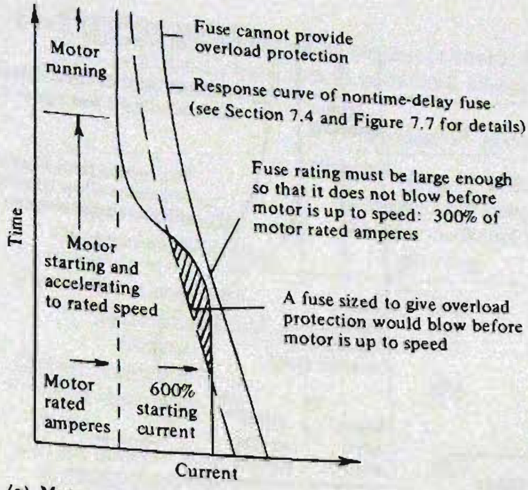
	Induction Type, Squirrel-Cage and Wound-Rotor (A)					Synchronous Type Unity Power Factor[b] (A)			
HP	**115 V**	**230 V**	**460 V**	**575 V**	**2300 V**	**230 V**	**460 V**	**575 V**	**2300 V**
½	4	2	1	.8					
¾	5.6	2.8	1.4	1.1					
1	7.2	3.6	1.8	1.4					
1½	10.4	5.2	2.6	2.1					
2	13.6	6.8	3.4	2.7					
3		9.6	4.8	3.9					
5		15.2	7.6	6.1					
7½		22	11	9					
10		28	14	11					
15		42	21	17					
20		54	27	22					
25		68	34	27		53	26	21	
30		80	40	32		63	32	26	
40		104	52	41		83	41	33	
50		130	65	52		104	52	42	
60		154	77	62	16	123	61	49	12
75		192	96	77	20	155	78	62	15
100		248	124	99	26	202	101	81	20
125		312	156	125	31	253	126	101	25
150		360	180	144	37	302	151	121	30
200		480	240	192	49	400	201	161	40

For full-load currents of 208- and 200-volt motors, increase the corresponding 230-volt motor full-load current by 10% and 15%, respectively.

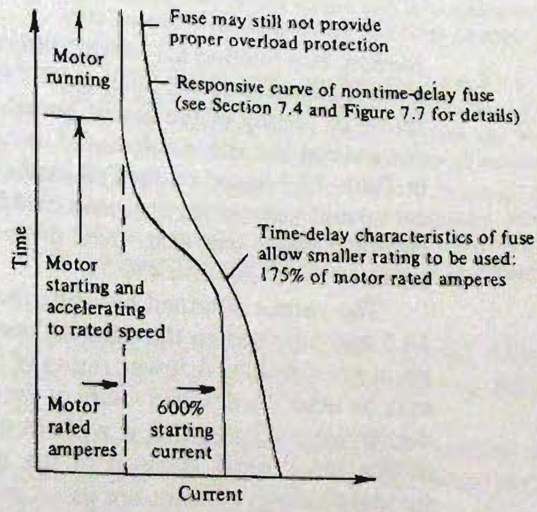
[a] These values of full-load current are for motors running at speeds usual for belted motors and motors with normal torque characteristics. Motors built for especially low speeds or high torques may require more running current, and multispeed motors will have full-load current varying with speed, in which case the nameplate current rating shall be used.

[b] For 90% and 80% percent power factor, the figures given shall be multiplied by 1.1 and 1.25, respectively.

The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120, 220 to 240, 440 to 480, and 550 to 600 volts.



(a) Motor starting using nontime-delay fuses



(b) Motor starting using time-delay fuses

FIGURE 13.2

Relationship of fuse rating to motor starting current

referred to as a motor short-circuit protector (MSCP). An MSCP can only be used as part of a complete combination starter unit that provides coordinated motor branch-circuit overload and short-circuit and ground-fault protection and that has been approved for such purpose.

From the foregoing, it is evident that the protective device for a motor branch circuit cannot adequately protect the circuit against overloads, but can only provide short-circuit and ground-fault pro-

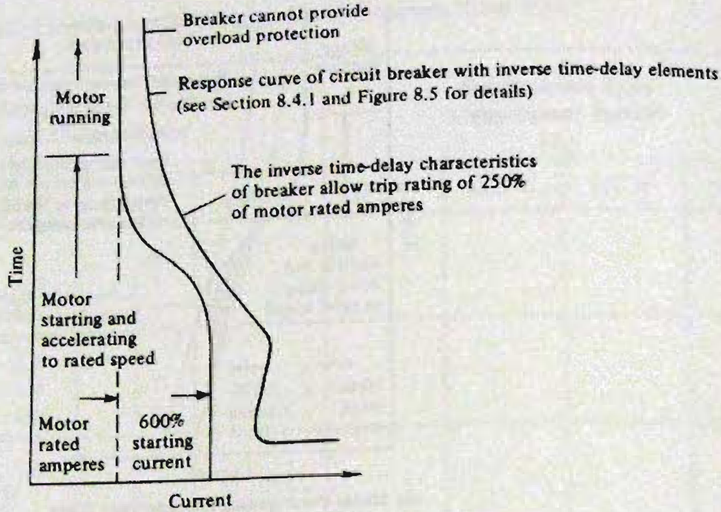


FIGURE 13.3

Relationship of circuit breaker rating to motor starting current

tection. See Section 6.1 for the differences between an overload and a short circuit, and see Section 10.5 for ground-fault protection. The rating or setting of the motor branch-circuit protective device shall not exceed the value calculated using the percentage values shown in Table 13.3 based on the full-load current of the motor. Where the calculated value does not correspond to a standard rating of fuse or circuit breaker trip unit, then the next higher rating is permitted. Refer to *NEC* Section 430-52.

The values obtained by using the percentages as listed in Table 13.3 and adjusted to the next highest standard rating are the maximum permissible. A lower rating of fuse or circuit breaker trip unit may be used if a detailed study of the time–current characteristics of the device indicates that it will not operate to shut down the motor during the normal start-up of the motor (see Section 16.4). The standard ratings of fuses are listed in Table 7.1, and those for circuit breakers are listed in Tables 8.1, 8.2, and 8.3.

13.1.2 Overload Protection

Each motor must be protected against harmful heating due to failure to start or from mechanical overloading of the motor. Since the branch-circuit protective device cannot properly provide this protection, the motor must be separately protected against overloads. Refer to *NEC* Section 430-32. The most common method is to have overload relays mounted integral with a magnetic contactor. These overload relays are responsive to the motor current and operate automatically to open the contactor if a harmful overload occurs.

TABLE 13.3 Maximum Rating or Setting of Motor Branch-Circuit, Short-Circuit, and Ground-fault Protective Devices

Type of Branch Overcurrent Device	Percent of Motor Full-Load Current: Full-Voltage Starting or Reduced Voltage Resistor or Reactor Starting	Percent of Motor Full-Load Current: Reduced Voltage Autotransformer or Wye–Delta Starting
Fuse: Nontime-delay	300	250
Time-delay (dual element)	175	175
Circuit breaker with inverse time-delay element	250	200
Circuit breaker with only instantaneous trip unit	700	700

1. The values given are for single- and three-phase ac squirrel-cage and synchronous motors with locked-rotor (starting) currents of 600% of motor full-load current.
2. For description of fuses, see Sections 7.4 and 7.5.
3. For description of circuit breakers, see Sections 8.4 and 8.5.
4. For description of reduced-voltage starters, see Section 14.4.
5. For a complete set of values for all types of motors, see *NEC* Table 430-152.

The contactor, complete with overload relays, is known as a magnetic motor starter. These starters are fully discussed in Section 14.2.

The overload devices shall be rated or set at a maximum value determined by applying the following percentages to the motor nameplate full-load current:

—Motors with a marked service factor of 1.15: 125%
—Motors with a marked service factor of 1.0: 115%

See Section 2.8 for the explanation of the service factors of motors. The overload device must still be able to pass the normal 600% starting currents of the motor for the time taken for the motor to accelerate up to its rated speed. However, since they do not also have to respond to large short-circuit currents, they can be designed to meet this requirement, as shown in Figure 13.4.

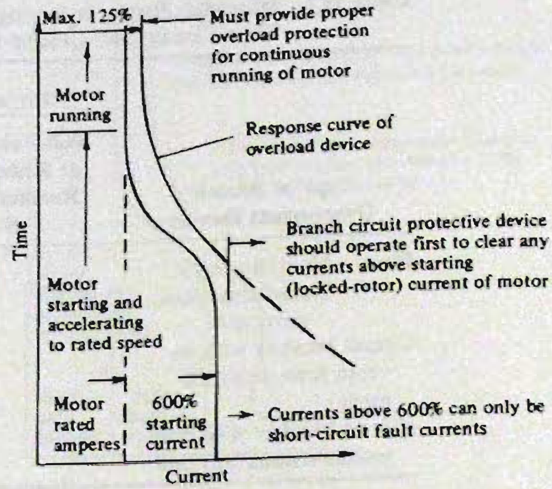


FIGURE 13.4

Relationship of overload device to motor current

13.1.3 Branch-Circuit Conductors

The ampacity of the branch-circuit conductors to the motor must not be less than 125% of the full-load current of the motor (see *NEC* Section 430-22). This, in effect, means that the conductors are loaded to only 80% of their rating under full-load conditions, which is standard for circuits with continuous loads. Note that it is not necessary to size the conductors to match the rating permitted for the branch-circuit protective device, which can be as high as 700% of the motor full-load current. The conductors are adequately protected by the motor overload protection. Any excess load currents can only be the result of motor operation and therefore must pass through the overload devices. Even though these devices are often located at the motor end of the branch circuit, when they operate they will interrupt the flow of current in the complete circuit. Any short circuit on the circuit conductors or within the motor will be cleared by the branch-circuit protective device located at the source end of the circuit, as shown in Figure 13.1.

The selection of conductor sizes to meet the ampacity requirements is detailed in Section 11.1. Where motors are connected to large-capacity systems, the short-circuit current ratings should be investigated as in Section 11.2. On long circuit runs, the conductor sizes must be investigated for excessive voltage drop, as in Section 11.3.

13.2 DISCONNECTING MEANS

Motors and controllers must be provided with a means of safely disconnecting them from their source of supply so that maintenance of the controller, motor, and its driven equipment can be done with no hazard to personnel. Disconnecting means must be provided for each motor, each controller, and each branch circuit. Refer to *NEC* Article 430, part H.

13.2.1 Location

Each disconnecting means shall be located so as to be readily accessible. The *National Electrical Code* defines *readily accessible* as

> Admitting close approach: not guarded by locked doors, elevation, or other effective means and capable of being reached quickly for operation without the necessity of removing obstacles or resorting to portable ladders or chairs.

The disconnecting means for the branch circuit, as for any circuit, shall be located at the source of supply for the circuit. The disconnecting means for the motor shall be located within sight from the motor and its driven equipment. Similarly, the disconnecting means for the controller shall be located within sight from the controller. The *NEC* defines *within sight from* as *the disconnecting means being visible and not more than 50 feet from the equipment being controlled.*

When the source for the motor branch circuit is within sight from the motor, then the same disconnecting means can be used to satisfy all the code requirements, as shown in Figure 13.5(a). Where the source for the motor branch circuit is not within sight from the motor, an additional disconnecting means is required, as shown in Figure 13.5(b). If the source, controller, and motor are all not within sight from each other, three separate disconnecting means are required, as shown in Figure 13.5(c).

Where several motors are controlled from one location, such as a motor-control center, it may not be possible to locate the control center within sight from all the motors. Where any motor and its driven equipment is not within sight from its controller location, it is permissible to delete the disconnecting means at the motor, providing that *the controller disconnecting means is capable of being locked into the open (off) position.* The controller must also be clearly marked as to the equipment being controlled. Motor-control centers are discussed in Section 14.5.

13.2.2 Ratings and Types

The disconnecting means shall have an ampacity rating of at least 115% of the full-load current rating of the motor. The disconnecting means shall open all the ungrounded supply conductors and shall be gang operated so that the one operating mechanism opens all poles simultaneously. There shall be a clear indication as to whether the disconnect is in the open (off) or closed (on) position. The disconnecting means shall be horsepower rated, which means that it is

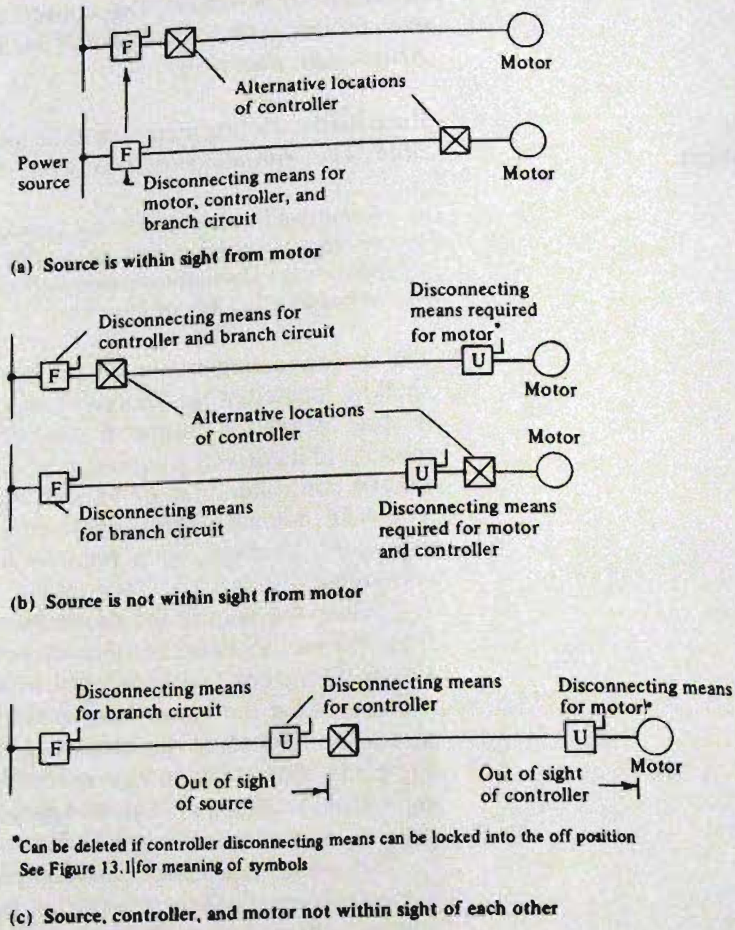


FIGURE 13.5

Disconnecting means required for motor branch circuits

capable of safely interrupting the locked-rotor current of a motor of the same horsepower rating. The horsepower rating is required in the event that a motor stalls and the motor controller fails to properly open the circuit. When the disconnect switch is operated, it then has to interrupt the locked-rotor current of the motor, which is typically 600% of the motor full-load current. Table 13.4 lists the standard sizes and ratings of three-pole motor circuit switches up to 600 amperes. Note that the switches are horsepower rated only up to 100 horsepower. For motors larger than 100 horsepower, a general-use or isolating switch may have to be used, in which case it must be clearly marked "Do not operate under load." Another exemption from the horsepower rating requirement is for stationary motors

TABLE 13.4 Standard Ratings of Three-Pole Motor Circuit Switches (rated 250 and 600 V)

	Maximum Horsepower Rating								
	Fused						Unfused		
	240 VAC[a]		480 VAC[a]		600 VAC[a]				
Ampere Rating	Nontime-Delay Fuses	Time-Delay Fuses	Nontime Delay Fuses	Time-Delay Fuses	Nontime-Delay Fuses	Time-Delay Fuses	240 VAC[a]	480 VAC[a]	600 VAC[a]
30	3	7½	7½	15	10	20	7½	15	20
60	7½	15	15	30	20	50	15	30	50
100	15	30	25	60	30	75	30	60	75
200	25	60	50	100	60	100	60	100	100
400	50	100	—	100	—	100	100	—	—
600	—	—	—	—	—	—	—	—	—

[a] System voltage. See Table 7.2 for dimensions of switches.

rated at 2 horsepower or less and 300 volts or less. The disconnecting means can then be a general-use switch having an ampere rating not less than 200% of the full-load current rating of the motor.

When fuses are used for the protection of the motor circuit, the fuses and the disconnecting means can be mounted in the same enclosure. Figure 7.12 shows a typical fusible switch. The motor circuit switch must be sized to accommodate the size of fuse as required by Table 13.3. When nontime-delay fuses are used, the switch ampere rating may be more than three times the full-load current of the motor because of the size of fuse required. When time-delay (dual-element) fuses are used, a smaller-sized switch is possible because these fuses are required to be rated at only 175% of the motor full-load current. This can result in considerable savings in the cost and space requirements of the switch. The ratings of switches using each type of fuse are shown in Table 13.4. Example 13.2 illustrates a specific motor branch circuit where the size of the motor circuit switch, when using time-delay fuses, can be reduced.

Circuit breakers can be used as the disconnecting means because they are tested to interrupt a minimum of 600% of their current rating. Automatic circuit breakers (with integral trip units) are used for both the motor branch-circuit overcurrent protection and the disconnecting means. Where only disconnecting means are required, then nonautomatic breakers (with no trip units) are used.

The motor controller and its disconnecting means may also be mounted in the same enclosure. However, the disconnecting means cannot be part of the actual controller itself because it must be possible to isolate the entire controller mechanism from its supply to allow for maintenance. Figure 14.3 shows examples of motor starters together with the branch-circuit overcurrent protection and disconnecting means all mounted in one enclosure. These are referred to as combination starters and are the common arrangement used in motor-control centers (Section 14.5).

13.3 EXAMPLES OF MOTOR BRANCH CIRCUITS

The following examples illustrate the application of the electrical code rules to the design of motor branch circuits.

■ EXAMPLE 13.1

Design the branch circuit for a 40 hp, 460 V, three-phase squirrel-cage induction motor, service factor 1.15, with nameplate full-load current of 50 A. The motor will be started full voltage. There will be non-time-delay fuses for the circuit protection, motor circuit switches for disconnecting means, and type THW copper conductors. Ambient temperature will be 30°C. The motor controller will be adjacent to the motor, but both will be out of sight from the branch circuit source of supply.

Solution

1. From Table 13.2, the rated current of a 40 hp motor is 52 A (this value must be used except for overload protection).
2. Branch-circuit protective device and disconnecting means:
   From Table 13.3, maximum fuse = 300% of 52 = 156 A
   From Table 7.1, the next largest standard size is 175 A
   From Table 13.4, switch size is 200 A (hp rating of 50)
3. Overload protection:
   From Section 13.1.2, maximum allowed = 125% of 50 = 62.5 A
   (note use of the actual nameplate full-load current)
   See Section 16.5 for selection of actual heater element.
4. Branch-circuit conductors:
   From Section 13.1.3, minimum ampacity = 125% of 52 = 65.0 A
   From Table 11.1, conductor size is No. 6 THW (rated at 65 A)
   From Table 11.6, conduit size is 1 in. (three conductors)
5. Unfused disconnect switch for controller and motor:
   From Table 13.4, switch size is 100 A (hp rating of 60); also exceeds 115% of motor full-load amperes

Figure 13.6(a) shows the one-line diagram for this circuit. Note that the nominal voltage for the power source is 480 V (see Section 1.8).

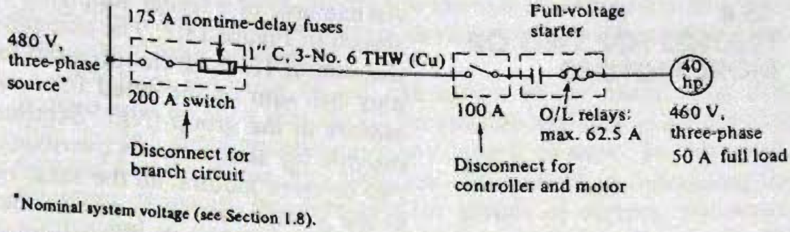
■ EXAMPLE 13.2

Repeat Example 13.1, except that time-delay fuses will be used for the circuit protection.

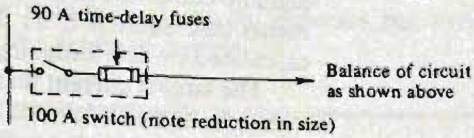
Solution

— From Table 13.3, maximum fuse = 175% of 52 = 91 A
— From Table 7.1, the nearest standard size is 90 A (note that size could be increased to 100 A)
— From Table 13.4, switch size is 100 A (hp rating of 60)

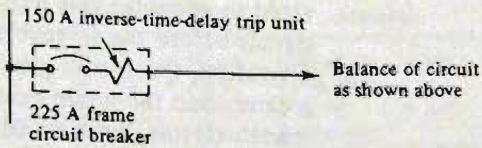
All other aspects of the circuit remain the same [see Figure 13.6(b)]. This example shows the advantages in using time-delay (dual-element) fuses in reducing the size and cost of the fused switch.



(a) Branch circuit for Example 13.1



(b) Changes for Example 13.2



(c) Changes for Example 13.3

FIGURE 13.6

One-line diagrams for Examples 13.1, 13.2, and 13.3

EXAMPLE 13.3

Repeat Example 13.1, except that a molded-case circuit breaker with time-delay element will be used for the circuit protection.

Solution

— From Table 13.3, maximum breaker = 250% of 52 = 130 A
— From Table 8.1, the next highest standard trip rating is 150 A
— Frame size of breaker is 225 A

All other aspects of the circuit remain the same [see Figure 13.6(c)].

In the foregoing examples, only the ampacity requirement for the branch-circuit conductors is considered. On large-capacity systems, the conductors should also be sized for the available short-circuit current as in Section 11.2. On long branch-circuit runs, the conductors should also be sized to meet the voltage drop requirements as in Section 11.3. The interrupting capacity of the branch-circuit overcurrent device must be suitable for the available short-circuit current.

13.4 FEEDERS FOR TWO OR MORE MOTORS

An example of a feeder supplying a group of two or more motors is shown in Figure 13.7. The ampacity of the feeder shall be equal to the sum of 125% of the rated full-load current of the largest motor, plus the sum of the rated full-load currents of all the remaining motors in the group (*NEC* Section 430-24). It is not necessary to provide for simultaneous overloads on all motors. Where there are two or more motors, all the same rating, that are the largest motors in the group, then only one of the motors need be treated as the largest. If there are other types of loads, such as lighting, being supplied by the feeder in addition to the motors, then these loads shall be computed in accordance with the appropriate *NEC* requirements (see Section 12.11 this text) and added to the motor load as calculated by the foregoing.

The largest current that the feeder to a group of motors will have to handle occurs when the largest motor is started at a time when all the other motors in the group are running and drawing their full-load currents. This is based on the assumption that only one motor will be starting at any one instant. The feeder protective device must be sized to allow for this transient condition and not react to open the circuit before the largest motor has accelerated to its rated speed. Therefore, the feeder protective device shall be rated or set at not greater than the value calculated by taking the largest rating of the branch-circuit short-circuit and ground-fault protective device allowed for any motor of the group, and adding to this value the rated full-load currents of all the remaining motors (*NEC* Section 430-62). If other types of loads are being supplied by the feeder in addition to the motors, then these loads will be added to the calculated value. Note that the code does not allow the next largest standard size of fuse or circuit breaker to be selected, as is permitted for individual motor circuit protection.

Since the rating or setting of the feeder protective device may be higher than the ampacity of the feeder conductors, precise overload protection is not provided to the feeder. However, overloads on the feeder can only occur if too many of the motors are being overloaded at the same time, which is not likely. Also, any excessive

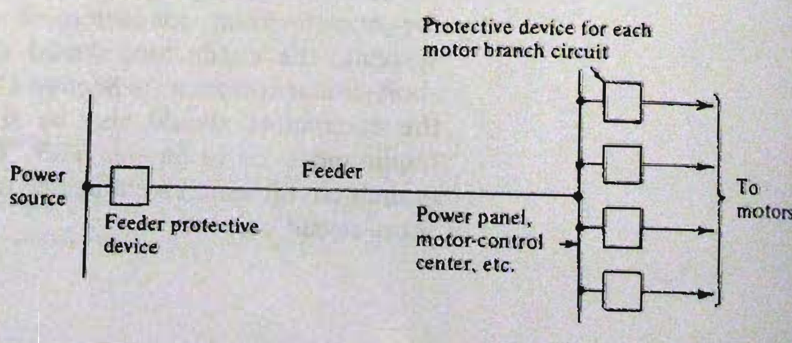


FIGURE 13.7

Feeder for a group of motors

overloads on individual motors are cleared by their own overload protection. The feeder protective device does provide short-circuit and ground-fault protection.

For large industrial plants, the nature of the work being performed may be such that all the motors are unlikely to be running fully loaded simultaneously for any length of time. In this case, demand factors of less than 100% may be used when calculating the minimum ampacity requirements for groups of motors. However, permission to use lower demand factors must be granted by the authority having jurisdiction for the installation (*NEC* Section 430-26).

The following examples illustrate the method of designing a feeder to a group of motors.

■ EXAMPLE 13.4

Design the feeder for the following group of 200 V, three-phase squirrel-cage induction motors: 1-10 hp, 1-15 hp, 1-20 hp, and 1-40 hp. The individual motors will be protected by dual-element (time-delay) fuses, and they will be started full voltage. The feeder will also be protected using dual-element fuses mounted in a motor circuit switch. Feeder conductors will be type THW copper.

Solution

Motor Horsepower	Motor Full-Load Amperes	Feeder Calculations: Ampacity		Feeder Calculations: Protection	
40	104 × 1.15[a] = 120 A	125% of 120	= 150	175%[b] of 120	= 210
20	54 × 1.15 = 62 A	Plus 100% of remaining	= 142		= 142
15	42 × 1.15 = 48 A				
10	28 × 1.15 = 32 A				
		Min. ampacity	= 292 A	Max. rating	= 352 A

[a] Values from Table 13.2 for 230 V are increased by 15% for 200 V motors from the footnote to the table. *Note:* The 1.15 factor used here is not related to the service factor.

[b] As in Table 13.3, using time-delay fuses.

1. Feeder conductors and conduit:
   From Table 11.1, conductor size = 350 MCM THW (rated 310 A)
   From Table 11.6, conduit size = 2½ in. (three conductors)
2. Feeder protective device:
   From Table 7.1, the nearest standard fuse size is 350 A (<352 A)
   From Table 13.4, the switch size is 400 A

Figure 13.8 shows the one-line diagram of the feeder.

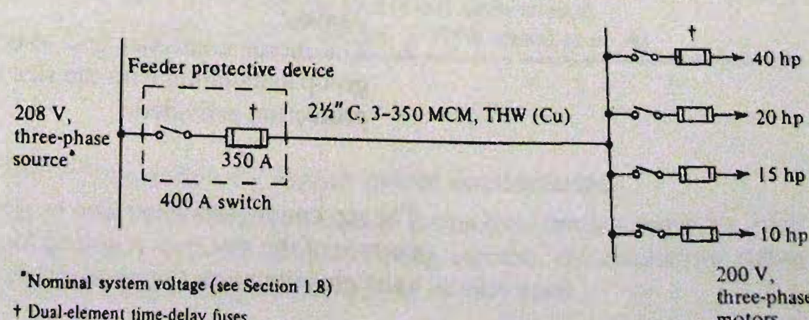


FIGURE 13.8

One-line diagram for Example 13.4

■ EXAMPLE 13.5

Repeat Example 13.4, except that the feeder protective device will be a circuit breaker.

Solution

Maximum trip rating of breaker = (250%[a] of 120) + 142
= 300 + 142 = 442 A

From Table 8.1, the nearest standard trip rating that does not exceed 442 A is 400 A. In Figure 13.8, the 400 A fused switch would be replaced with a 400 A frame breaker with 400 A trip unit.

[a] From Table 13.3.

Once again, the foregoing examples considered only the ampacity requirements for the feeder conductors. Short-circuit and voltage drop requirements should also be investigated.

13.5 SINGLE MOTOR TAPS

In an industrial plant, it is often convenient to run a main branch circuit overhead through the building from which motors at different locations are fed. It is then necessary to tap off the main branch circuit conductors with a run down to the motor and its controller at floor level. Rather than require that the tap conductors be the same size as the main conductors, the following is permitted [*NEC* section 430-53(d)]. Refer to Figure 13.9. The size of the tap conductors down to the motor controller may be reduced without requiring additional overcurrent protection at the point of the tap (which would be hard to reach) providing that:

1. The ampacity of the tap conductors to the motor is a minimum of one-third the ampacity of the main branch-circuit conductors.
2. The distance from the tap to the motor controller with overload devices is a maximum of 25 ft.
3. The tap conductors are adequately protected from physical damage.
4. The motor controller and overload devices are each listed for group installation with the size of the branch-circuit overcurrent protection provided.

The tap conductors must also be a minimum of 125% of the full-load current of the motor as required for any motor circuit. The following examples illustrate the application of the foregoing requirements.

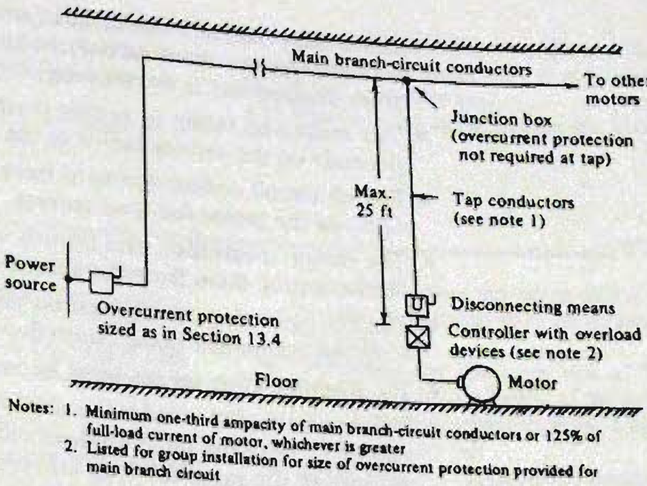


FIGURE 13.9

Tap for single motor from main branch circuit

EXAMPLE 13.6

The overhead main branch-circuit conductors are No. 1/0 THW copper. Determine the minimum size of THW conductors permitted for the tap down to the motor controller (maximum distance of 25 ft) for a 10 hp, 460 V, three-phase motor.

Solution

— From Table 11.1, the ampacity of 1/0 THW is 150 A
— Minimum ampacity for tap conductors is one-third of 150 = 50 A
— From Table 11.1, select No. 8 THW (rated at 50 A)
— From Table 13.2, the motor full-load current is 14 A (ampacity rating of No. 8 THW exceeds 125% of 14 A)

EXAMPLE 13.7

Repeat Example 13.6, except the motor is 40 hp.

Solution

— From Table 13.2, the motor full-load current is 52 A
— Minimum ampacity of tap conductors is 125% of 52 = 65 A
— No. 8 THW as in Example 13.6 is not large enough
— Tap conductors required are No. 6 THW (rated at 65 A)

SUMMARY

- Motor branch circuits require special consideration.
- The rating of the branch-circuit protective device must be high enough to bypass the motor starting current, the maximum rating permitted depending on the type of device used.

- Since the protective device does not provide proper overload protection, separate overload devices must be used to protect the motor from damage due to overheating.
- The maximum rating or setting permitted for the overload devices depends on the service factor of the motor.
- Branch circuit conductors must have a minimum ampacity rating of 125% of the motor full-load current.
- The motor, controller, and branch circuit must all have means of disconnecting them from the source of supply.
- The disconnecting means must be visible and not more than 50 feet from the equipment being controlled.
- The disconnecting means must be horsepower rated.
- The ampacity of the feeder to a group of motors must be equal to the sum of 125% of the rated full-load current of the largest motor, plus the sum of the rated full-load currents of all the remaining motors.
- The protective device for the feeder to a group of motors shall be rated or set at not greater than the value calculated by taking the largest rating of the branch-circuit short-circuit and ground-fault protective device allowed for any motor of the group and adding to this value the rated full-load currents of all the remaining motors.
- Conductor sizes may be reduced for a tap to a single motor, providing that the tap conductors are not less than one-third the ampacity of the main conductors and do not extend more than 25 feet to the motor overload devices.

QUESTIONS

1. Outline the essential components of a motor branch circuit.
2. What are the special problems with regard to motor branch circuits?
3. Why must the overload protection for a motor be based on the actual motor nameplate current rating, rather than on the values listed by the *NEC* (Tables 13.1 and 13.2)?
4. Explain why the motor branch-circuit protective device (the fused switch or circuit breaker) can provide only short-circuit and ground-fault protection.
5. What is the function of the motor overload protection?
6. Why does the maximum rating or setting permitted for the overload protection depend on the service factor of the motor?
7. Explain why it is not necessary to size the motor branch-circuit conductors to match the rating permitted for the branch-circuit protective device.
8. What is the purpose of the disconnecting means for the motor and its controller?
9. What is meant by readily accessible?
10. What is meant by within sight from?
11. When can the same disconnecting means be used for the motor, its controller, and the motor branch circuit?
12. A motor is controlled from but is out of sight from a motor-control center. What are the requirements for deleting the disconnecting means at the motor?
13. Explain why the motor disconnecting means must be horsepower rated.

14. Explain why the use of time-delay fuses can often result in a smaller rating of disconnect switch being required as compared to using nontime-delay fuses.
15. Does the protective device for a feeder to a group of motors necessarily provide overload protection to the feeder? If not, why not?
16. What is a motor tap?
17. What are the requirements for a single motor tap?

PROBLEMS

Note: The following problems are based on the motors being the squirrel-cage induction type, continuous duty.

1. Determine the minimum size of type THW copper conductors required for the branch circuit to a 10 hp, 200 V, three-phase motor.
2. Determine the maximum standard fuse rating permitted for the short-circuit and ground-fault protection for the branch circuit to a 50 hp, 460 V, three-phase motor that has reduced-voltage autotransformer starting. Fuses are the nontime-delay type.
3. Determine the maximum standard trip rating permitted for the short-circuit and ground-fault protection for the branch circuit to a 30 hp, 200 V, three-phase motor that has reduced-voltage autotransformer starting. The circuit breaker has inverse time-delay elements.
4. Determine the maximum overload setting permitted for a 100 hp, 460 V, three-phase motor, service factor 1.15, whose nameplate current rating is 120 A.
5. Select the rating of the fused disconnect switch required for the branch circuit to a 25 hp, 575 V, three-phase motor. The motor is started full voltage, and the fuses are the nontime-delay type.
6. Repeat Problem 5, except the fuses are time-delay.
7. The motor in Problem 5 is out of sight from its controller. Select the rating of the unfused disconnect switch that must be located adjacent to the motor.
8. Determine the minimum size of THW copper conductors for the feeder to the following group of 200 V, three-phase motors: 1-25 hp, 1-10 hp, 1-5 hp and 1-3 hp.
9. Determine the maximum standard fuse rating permitted for the short-circuit and ground-fault protection of the feeder in Problem 8. The fuses are the nontime-delay type and the motors are to be started full voltage. Also select the rating of the fused disconnect switch.
10. Repeat Problem 9, except fuses are time-delay.
11. Repeat Problem 8, except motors are 460 V, three-phase.
12. Determine the maximum standard fuse rating permitted for the short-circuit and ground-fault protection of the feeder in Problem 11. The fuses are the nontime-delay type, and the motors are started full voltage. Also select the rating of the fused disconnect switch.
13. Repeat Problem 12, except fuses are time-delay.
14. Refer to Figure 13.9. The overhead main branch-circuit conductors are No. 2 THW copper. Determine the minimum size of THW conductors permitted for the tap down to the motor controller (maximum distance of 25 feet) for a 15 hp, 200 V, three-phase motor.

14 Motor Starters and Motor-Control Centers

OBJECTIVES

After studying this chapter, you will be able to:

- Recognize manual and magnetic starters.
- Describe the operation of magnetic starters.
- Identify the NEMA sizes for starters.
- Describe the operation of overload relays.
- Recognize combination starters.
- Read basic schematic motor-control diagrams.
- Explain the characteristics of two- and three-wire control.
- Determine the need for separate control circuit protection.
- Describe the operation of full-voltage reversing starters.
- Recognize the problems of reduced-voltage starting.
- Explain the characteristics of autotransformer and wye–delta starting.
- List the advantages of motor-control centers.
- Recognize the classifications of motor-control centers.
- Lay out a motor-control center.
- Describe the operation of medium-voltage starters.

INTRODUCTION

Motors constitute by far the largest load on the electrical system of typical industrial plant. Even in a commercial type of building, mo tors still account for a significant part of the total load. The prope control of these motors is very important. A motor controller is device or group of devices that serves to govern, in a predetermine manner, the electric power delivered to the motor. The motor co troller can incorporate features to start and stop the motor, to r verse the direction of rotation of the motor, to protect the mot against overloads, undervoltage, and single phasing, and to contr the operating characteristics of the motor, such as acceleration, speed, torque, and braking. Article 430, Parts F and G of the *National Electrical Code (NEC)*, cover the requirements for motor controllers and their associated control circuits. For the Canadian Electrical Code requirements, see Appendix A.

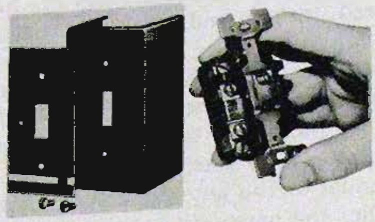
A motor starter is a basic type of controller whose primary function is to start and stop the motor. Starters can be either the manual or the automatic type. The automatic type can in turn be either the magnetic or the solid-state type. Magnetic starters have been the standard for many years and are still in wide use because of their proven reliability. The solid-state starters have only recently come on the market and have had only limited acceptance to date. The discussions in this text are therefore confined to the magnetic type of automatic starter.

This chapter covers the standard motor starters used with ac squirrel-cage induction motors, along with standard features such as overload, undervoltage, and single-phase protection, reversal of direction of rotation, and reduced voltage starting, which are or can be easily incorporated into a starter. Squirrel-cage induction motors account for the large majority of all drives used today. These motors are self-starting, requiring only that power be connected to the stator terminals to start and run. The reader should refer to Sections 2.5 and 2.6 of this textbook for a review of three-phase, squirrel-cage induction motors and single-phase ac motors, respectively. Also included in this chapter are a few basic control circuits for the magnetic starter. The reader is referred to the books listed in the bibliography for a more comprehensive coverage of motor control circuits and their associated control devices.

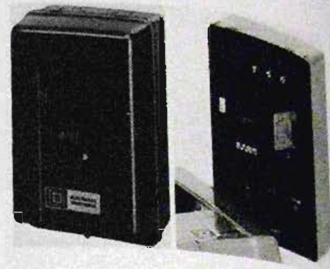
Where it is convenient to mount a number of starters at one location, the use of motor-control centers is recommended. The general arrangements for the layout of these centers are discussed and a sample layout is presented. The majority of the discussions in this chapter are with regard to low-voltage starters. Starters rated for voltages above 600 volts are discussed briefly at the end of the chapter.

14.1 MANUAL MOTOR STARTERS

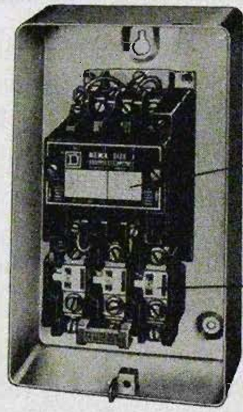
Manual motor starters are used where only on–off operation is required for small, single- or three-phase motors and where full-voltage starting is satisfactory. Typical applications include the control of small machine tools, pumps, and fans. A manual starter consists of a hand-operated snap switch combined with an overload mechanism that will automatically release the closed switch in the event of an overload on the motor. Low-voltage protection is not obtainable with a manual starter. This means that in the event of a power



(a) Single-phase manual starter



(b) Three-phase manual starter



(c) Three-phase magnetic starter (cover removed)

FIGURE 14.1

Full-voltage nonreversing (FVNR) motor starters

interruption all motors controlled by manual starters will instantly restart upon return of the power, a situation that is not always desirable. Remote operation of a manual starter is not possible.

Figure 14.1(a) shows a typical single-phase manual starter. These starters have a maximum rating of 1 horsepower up to 230 volts ac and are available in either single- or two-pole versions. Figure 14.1(b) shows a typical three-phase manual starter. These starters have a maximum rating of 7½ horsepower up to 230 volts and 10 horsepower at 460 and 575 volts ac. The starters are very compact and can either be surface mounted in their own enclosures, as shown, or mounted in a recessed box with a flush face plate.

14.2 FULL-VOLTAGE NONREVERSING MAGNETIC STARTERS

A magnetic starter is required where a three-phase motor is to be remotely controlled by means of a push-button station or an automatic sensing device (for example, a thermostat). A magnetic starter must also be used to control any motor with a horsepower rating beyond that of manual starters (above 7½ horsepower at 200 volts and 10 horsepower at 460 and 575 volts). A major advantage of magnetic starters is that they are very versatile and can accommodate a great many variations in the method of control.

The full-voltage nonreversing (FVNR) starter is used where full-voltage starting is acceptable and where the motor is to start up and run in one direction only. As discussed in Section 2.5.2 and as indicated in Table 2.2, the starting current of a general-purpose squirrel-cage induction motor is 600% of its full-load running current when full voltage is applied at the instant of starting. The motor itself is designed to withstand this inrush current during a normal start-up cycle. The problem then is whether the system supplying the motor can accept this sudden surge of current without encountering unacceptable voltage dips. With most systems of modern design, unless the motor is large enough to be a significant part of the total system load, full-voltage starting is satisfactory.

A starter must be able to continuously carry the full-load current and safely interrupt the locked-rotor current of the motor it is controlling. If the motor stalls, or if it does not start properly (it is jammed and cannot begin to turn), then the current drawn by the motor is referred to as the locked-rotor current. This current is typically 600% of the full-load current of the motor (the same as the starting current), and the starter must be able to safely open the circuit under this condition. Since both the full-load and locked-rotor currents are a function of the horsepower rating of the motor at a specified voltage, starters are rated for the maximum horsepower that they can safely handle at these voltages. The starters are classified by a size number. Table 14.1 shows the maximum horsepower ratings of starters ranging from NEMA (National Electrical Manufacturers Association) size 00 to size 9. Figure 14.1(c) shows a typical size 1, three-phase FVNR magnetic starter mounted in its own enclosure. As the NEMA size classification increases, so does the physical size of the starter, as larger contacts are needed to carry and break the higher motor currents and heavier mechanisms are required to open and close the contacts. Low-voltage magnetic starters are suitable for operation on systems up to a maximum of 600 volts nominal.

The magnetic starter is basically an on–off device operated by electromagnetic means. When the starter coil is energized through a separate control circuit, the resulting magnetic field mechanically forces the main contacts of the starter to close, thus starting the motor. The coil must then be continuously energized to hold the contacts closed and keep the motor running. When the coil is de-energized, the main starter contacts are forced open by either spring pressure or gravity, thus stopping the motor. The coil and contact assembly is called a *magnetic contactor*. With the addition of over-

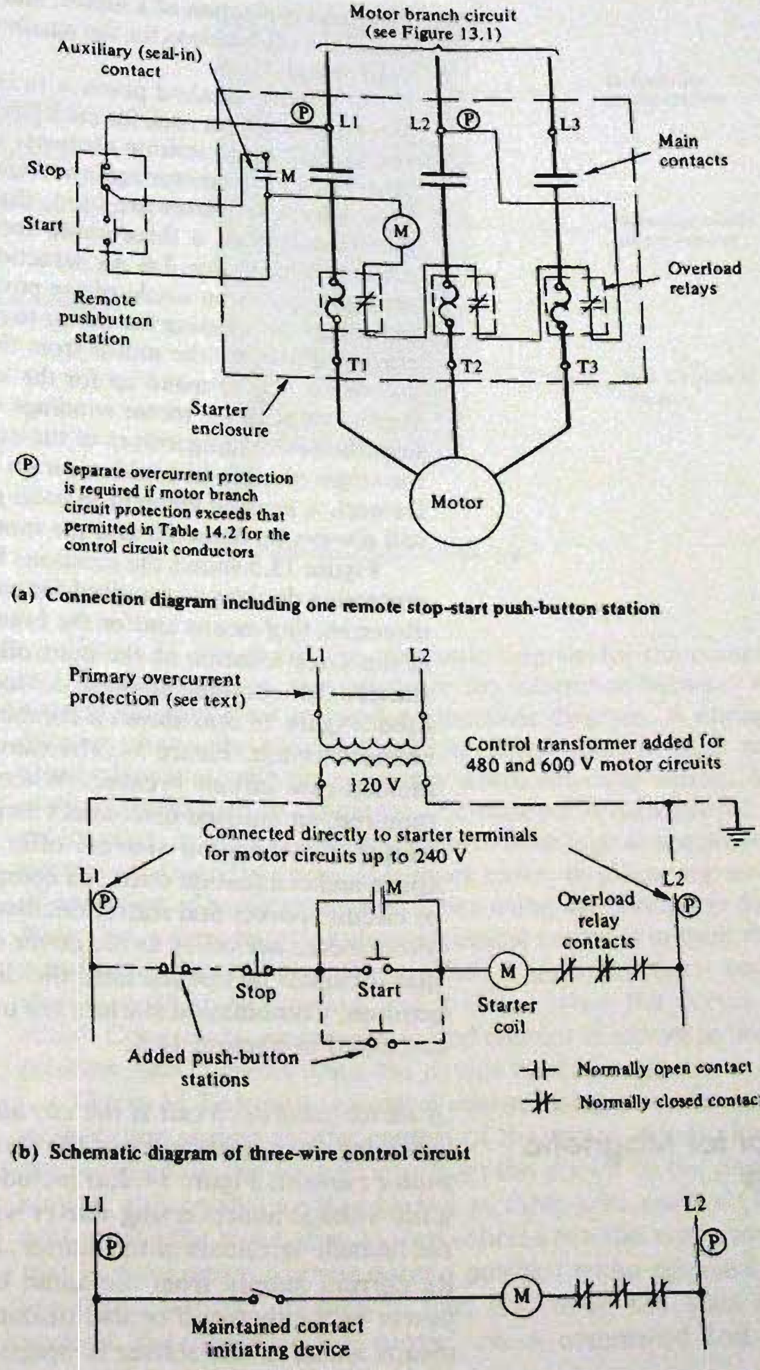
TABLE 14.1 Horsepower Ratings of Low-Voltage Starters

NEMA Size	Maximum Horsepower			
	Single-Phase (V)		Three-Phase (V)	
	115 V	230 V	200 V	460 and 575 V
00	$\frac{1}{3}$	1	$1\frac{1}{2}$	2
0	1	2	3	5
1	2	3	$7\frac{1}{2}$	10
2	3	$7\frac{1}{2}$	10	25
3	$7\frac{1}{2}$	15	25	50
4	—	—	40	100
5	—	—	75	200
6	—	—	150	400
7	—	—	—	600
8	—	—	—	900
9	—	—	—	1600

load relays, the assembly then constitutes the basic magnetic starter, as shown in Figure 14.1(c).

Figure 14.2(a) shows a representative connection diagram of the standard full-voltage nonreversing magnetic starter, indicating the starter coil, the three main (or power) contacts, one auxiliary contact, which is connected in the control circuit, and the overload relays. Additional auxiliary contacts, either normally open or closed, can be added for use in more advanced control schemes (for example, to operate indicating lights or to provide interlocking with other motors).

The overload relays are connected on the loadside of the magnetic contactor as shown on the connection diagram. Each relay has two major parts. There is the thermal sensing element, often referred to as the heater, which is directly acted on by the line current drawn by the motor. If the motor load current exceeds the rated value of the thermal element for a specified length of time, the relay reacts to open the overload contacts, which in turn breaks the control circuit to the starter coil, thus shutting down the motor. The time–current response characteristics of the overload relay must ensure that the motor is automatically shut down before an overload can persist to the point where the motor becomes overheated and damaged. Section 16.4 describes the common types of thermal-responsive relays, and Figure 16.5 shows typical time–current characteristic curves. Example 16.8 shows the method of selecting the actual overload relay heater elements for a motor starter. Section 13.1.2 of this textbook outlines the *NEC* code requirements for the



(a) Connection diagram including one remote stop-start push-button station

(b) Schematic diagram of three-wire control circuit

(c) Schematic diagram of two-wire control circuit

FIGURE 14.2

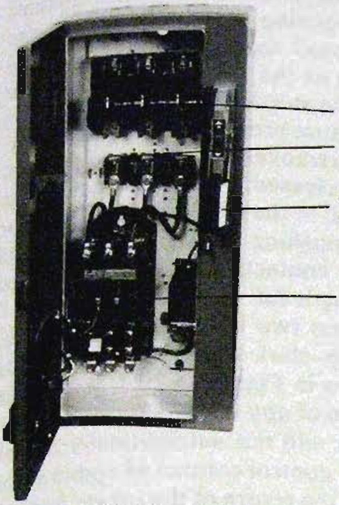
Full-voltage, nonreversing, three-phase magnetic starter overload protection of a motor, and Section 13.3 includes an example of the calculations for the maximum allowable rating of the overload relays.

It is now standard practice to install three overload relays in a three-phase starter, one for each phase connection to the motor. The reason that three sensing elements are used is to provide complete protection to the motor against single phasing. It is always possible, especially when fuses are used, that one phase of the system will fail, thus leaving a three-phase motor running on one phase. As discussed in Section 2.6, an induction motor, once it is turning, can continue to run on single-phase power even though the torque is a pulsating one, causing the motor to run much noisier. However, the current drawn by the motor from the remaining two lines must increase by 73% to make up for the loss of the third line. This extra current through the motor windings still connected can rapidly overheat the motor. Regardless of the combination of events that cause the single phasing (it could occur on the primary of the supply transformer), a sensing element in each phase ensures that the problem will always be detected and the motor shut down.

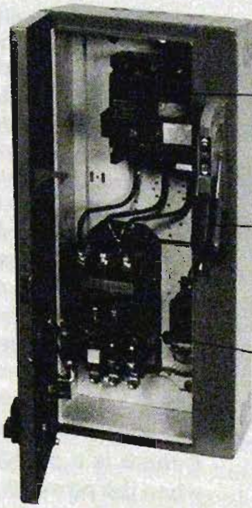
Figure 13.5 shows the locations for the disconnecting means and protective devices as required for motor branch circuits. Where the disconnecting means and/or the branch-circuit protective device are at the same location as the controller (motor starter), combination starters that combine all these devices into the one enclosure can be used. Figure 14.3(a) shows a combination starter with a fusible disconnect switch. Figure 14.3(b) shows a combination starter with a molded-case circuit breaker. Where only disconnecting means is required, an unfused disconnect switch is used for the combination starter. Combination starters offer a compact unit that can save space and installation costs, as compared to using a separate switch or circuit breaker and starter enclosures. A combination starter also offers increased safety as the cover of the unit can be interlocked so that it cannot be opened until the disconnecting means is in the off position. Combination starters are used in motor-control centers, as discussed in Section 14.5.

14.2.1 Control for Magnetic Starters

A *motor control circuit* is the *circuit that carries the electric signal directing the performance of the starter but does not carry the main motor current*. Figure 14.2(a) includes the typical control wiring for a full-voltage nonreversing starter with the control circuit tapped off the lineside terminals of the starter. Since the control circuit derives its current supply from the same branch circuit that supplies the power to the motor, it is also disconnected when the disconnecting means ahead of the starter is opened (see Figure 13.1).



(a) Combination fusible switch type



(b) Combination circuit breaker type

FIGURE 14.3

Combination full-voltage, nonreversing magnetic starters

Figure 14.2(b) shows the schematic diagram for the control circuit for the starter in part (a). Note the difference between a connection diagram [part (a)] and a schematic diagram. A connection diagram shows the various electrical components in their relative physical location with the necessary interconnecting wiring. A schematic diagram does not show the components in their proper physical location, but rather arranges them in their logical sequence in the control scheme. Therefore, it is much easier to follow the sequence of operation of a control scheme when using the schematic diagram. Note that wiring diagrams show electrical contacts in their de-energized or nonoperative position. Thus a normally open contact is shown in the open position, and it closes when the device is activated. Conversely, a normally closed contact is shown in the closed position, and it opens when the device is activated.

Figure 14.2(a) shows a control scheme using a remote stop–start push-button station for the control of the motor. Since three wires are required for the connections from the starter to the push-button station, this arrangement is known as *three-wire control.* The push buttons for the three-wire control scheme are the momentary type; that is, they return to their normal position when released. Following the schematic diagram in part (b), when the start button is pushed, the circuit to the starter coil is completed and the main contacts of the starter close to start the motor. At the same instant, the auxiliary contact M closes, completing the circuit around the start button so that when it is released the circuit to the coil is maintained. Contact M is referred to as the *seal-in contact*, as the control circuit is now sealed in until the stop button is operated. The momentary depression of the stop button breaks the control circuit, releasing the starter contacts, which removes the power to the motor. By the time the stop button is released, the M contact of the starter has opened, blocking the circuit to the starter coil. The motor can only be restarted by once again pushing the start button. Note that the closing of the main starter contacts connects the motor directly across the line, hence starting it full voltage.

The three-wire control scheme has two important advantages. First, any number of additional stop–start stations can be easily added to the control circuit, as shown in Figure 14.2(b), without in any way interfering with the operation of any other station. Second, if there is a power failure, the motor will not automatically restart when the power is restored. Since the control contact M opens when the loss of power releases the starter, the return of the power in itself cannot re-energize the starter coil. Once again the start button must be operated before the motor restarts. This is very important when there are many motors on a system. If all the motors were to automatically restart the instant that the power returned, their combined starting currents could easily trip out the main protective device of the system, resulting in the shut down of the system once again. Using the three-wire control scheme for each motor allows for the orderly restarting of the motors by operating personnel.

The system voltage does not have to totally collapse for the motor starter to drop out and stop the motor. The starter coil generally is unable to hold the starter contacts closed if the voltage falls below 50% to 60% of normal. Thus even a prolonged (more than a few cycles) drop of the voltage at the starter terminals will stop the motor. This feature is referred to as undervoltage protection and is desirable to prevent the motor from laboring under prolonged low voltage (see Section 2.9).

A *two-wire control circuit*, as shown in Figure 14.2(c), cannot offer the same advantages as the three-wire control scheme. First, the initiating device must have maintained contacts. Therefore, other on–off devices cannot be added to the control circuit. Second, after a power failure, the motor will automatically restart upon the return of the power, as the maintained initiating contact device remains closed. However, in spite of these disadvantages, the two-wire control scheme has to be used where the motor is controlled by a remote device, such as a thermostat, pressure switch, float switch, or limit switch.

In either the two- or three-wire control schemes, the opening of any one of the overload relay contacts breaks the control circuit to the starter coil, removing the power from the motor. The overload contact normally remains open and requires manual resetting. This allows the motor and its driven equipment to be inspected before any attempt is made to restart the motor.

The arrangement shown in Figure 14.2 uses the motor circuit voltage for the control circuit. This is generally satisfactory up to 240 volts. For motor circuit voltages of 480 and 600 volts, a small step-down control transformer can be used to provide 120 volts for the control circuit for greater operator safety. This transformer is mounted in the starter enclosure, and its primary is tapped from the lineside terminals of the starter, as shown with dashed lines in Figure 14.2(b).

Note that Figure 14.2 shows no separate overcurrent protection for the control circuit. Table 14.2 shows the maximum rating of the overcurrent protective device in amperes allowed for copper conductors when used for control circuit wiring. Note that the rating depends on whether or not the control conductors extend beyond

TABLE 14.2 Overcurrent Protection of Conductors Used for Control Circuit Wiring

Size of Copper Conductor	Maximum Rating of Overcurrent Protective Device (A)	
	Wiring Does Not Extend beyond Starter Enclosure	Wiring Extends beyond Starter Enclosure
14	100	45
12	120	60
10	160	90
Larger than No. 10	Note 1	Note 2

Notes: 1. 400% of value specified in *NEC* Table 310-17 for 60°C rated conductors.

2. 300% percent of value specified in *NEC* Table 310-16 (Table 11.1 this text) for 60°C rated conductors.

The above applies to control circuit conductors tapped from the line side of the motor starter as shown in Figure 14.2 and protected by the motor branch circuit short-circuit and ground-fault protection as shown in Figure 13.1.

For the complete requirements for the protection of motor-control circuits, see *NEC* Article 430, Part F and Table 430-72(b).

the starter enclosure. For example, for the control circuit shown in Figure 14.2, which has control wiring extending beyond the starter enclosure, if No. 14 copper conductors are used, no additional overcurrent protection is required for the control circuit, providing that the rating of the overcurrent protective device for the motor branch circuit (Figure 13.1) does not exceed 45 amperes. If the rating does exceed 45 amperes, either larger control circuit conductors must be used or a separate overcurrent protective device (fuses) rated at 45 amperes or less must be installed at the points marked Ⓟ on the diagram. If a step-down control transformer is used and is mounted within the starter enclosure as previously discussed, then the primary overcurrent protection of the transformer cannot exceed 500% of its rated primary current. This applies if the rated primary current does not exceed 2 amperes, which is the case for all but the largest starters. If separate primary overcurrent protection is required for the control transformer, then fuses are normally used.

14.3 FULL-VOLTAGE REVERSING MAGNETIC STARTERS

The full-voltage reversing (FVR) starter is used where it is necessary to be able to start and run a motor in either direction. The direction of rotation of three-phase induction motors can be easily reversed by simply interchanging any two of the three line connections to the motor (see Section 2.3.1). The reversing starter consists of two magnetic contactors mounted in one enclosure. One contactor is connected to apply the three phases to the motor so that the motor starts up and runs in the forward direction. The other contactor is connected so that when it closes two of the lines to the motor are interchanged, thus reversing the direction of rotation of the motor. The power connections and the control circuit for the reversing starter are shown in Figure 14.4. The two contactors must be interlocked so that it is impossible to close the second contactor if the other contactor is already closed. Otherwise, if both contactors were to be closed at the same time, there would be a dead short-circuit across two of the phases. The standard overload relays are incorporated into the starter as shown. Combination reversing starters similar to those described for nonreversing starters are also available.

The control circuit shown in Figure 14.4(b) is the most basic scheme. With the motor running in the forward direction, the stop button must first be pressed to open the forward contactor before the reverse button can be used to reverse the direction of the motor, and vice versa, when going from reverse to forward. If desired, with the use of double-contact forward and reverse pushbuttons, the scheme can easily be modified so that it is possible to go directly from forward to reverse, and vice versa, without having to first push the stop button.

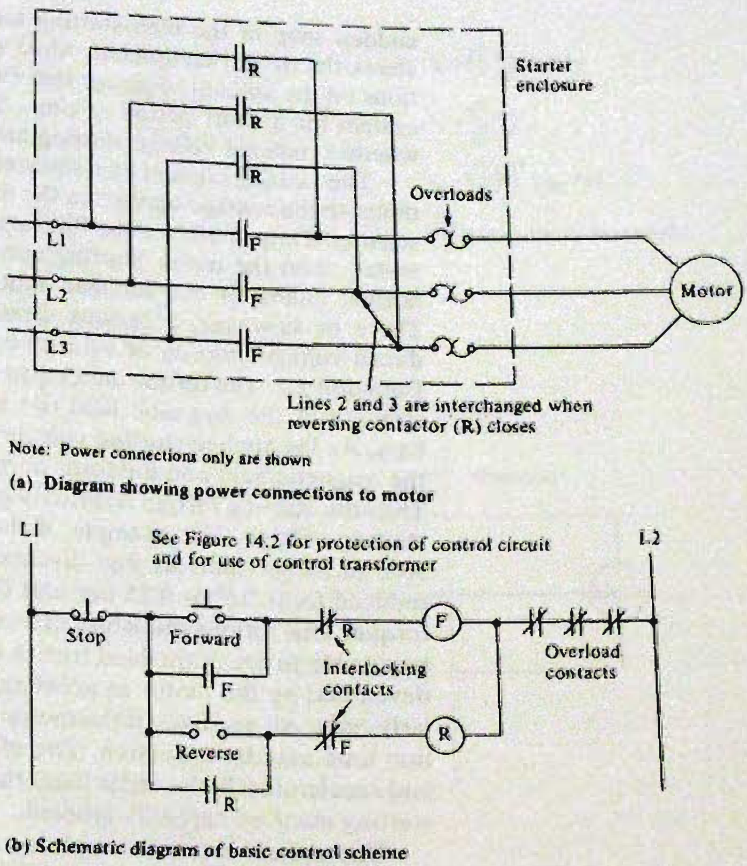


FIGURE 14.4

Full-voltage reversing magnetic starter

Reversing starters can also be applied for motor plugging, which is an operation where the reversal of torque is used to rapidly bring a motor and its driven equipment to a full stop. With this scheme, there is only a start and a stop button. The start button closes the forward contactor the same as for a standard starter. However, when the stop button is pushed, the forward contactor drops out, and the reversing contactor is automatically closed to plug the motor to a stop. A zero speed switch mounted on the motor shaft is used to then open the reversing contactor and finally remove all power before the motor can start up in the reverse direction.

14.4 REDUCED-VOLTAGE NONREVERSING MAGNETIC STARTERS

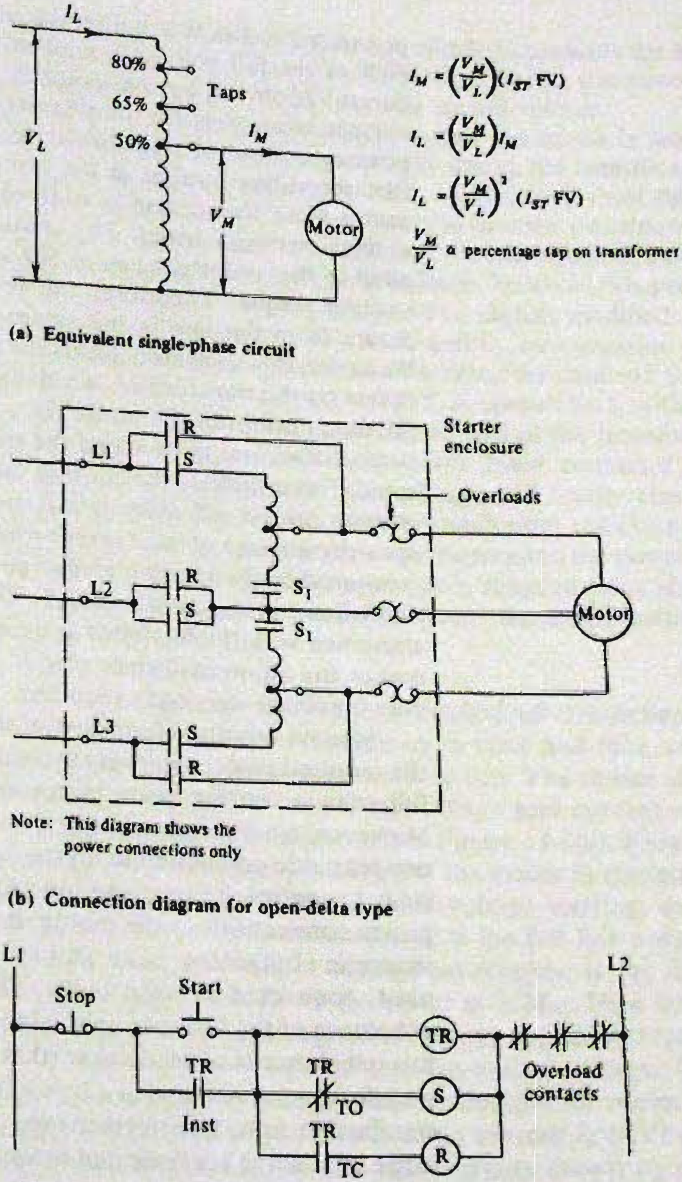
The reduced-voltage nonreversing (RVNR) starter is used where ful voltage starting would cause serious problems. If full-voltage start ing were to be used, the 600% starting current could cause unaccept able voltage disturbances on the balance of the system, or th sudden snap of the high starting torque could mechanically overstress the driven equipment. Most power companies have restrictions on the amount of power that can suddenly be taken from their system for a short period of time. These restrictions often dictate whether reduced voltage starting has to be used.

The starting current of a squirrel-cage motor is directly proportional to the voltage applied to the motor terminals at the instant of starting. Thus, if 50% of the full rated voltage is applied to start the motor, then the motor starting current will be reduced to 50% of normal (300% of the full-load motor current rather than 600%). There is, however, a serious disadvantage inherent with the reduced-voltage starting of squirrel-cage induction motors. Refer to Equation 2.2. The torque developed by a motor depends on both the strength of the magnetic field (ϕ) and the current (I) in the rotor bars. As the applied starting voltage is reduced, both the strength of the magnetic field and the rotor current are proportionally reduced. Thus the starting torque is directly proportional to the square of the starting voltage. For example, if the starting voltage is reduced to 50% (0.50 per unit) as just discussed, then the starting torque is reduced to $(0.50)^2$ or 0.25 per unit (25%) of the full-voltage starting torque. This serious reduction in torque could result in the motor not being able to break the load free to start it turning. Also, the torque developed by the motor to accelerate the load up to speed is similarly reduced, and even if the motor does start turning, the acceleration time may be excessive. Therefore, where a motor has to start and accelerate a high-inertia load, the application of reduced voltage starting must be carefully studied.

The easiest means of applying a reduced voltage to the motor terminals at the instant of starting is to insert large power resistors in each line to the motor. Then, as the motor approaches its full speed, the resistors are shorted out and the motor runs normally on full voltage. A major disadvantage with this type of reduced-voltage starting is the bulk of the starting resistors and the problem of mounting them so that the heat can be dissipated. Also, this method suffers from the much higher reduction in starting torque as compared with the reduction in starting current as just outlined. The two preferred methods for reduced-voltage starting of low-voltage motors are the autotransformer and wye–delta types, which overcome these disadvantages.

14.4.1 Autotransformer Starters

The autotransformer starter applies a reduced voltage through taps on the transformer coil. Figure 14.5(a) shows the equivalent single-phase circuit diagram of the connections through the autotransformer to the motor at the instant of starting. The voltage and current relationships are also shown. Assume that the motor is



See Figure 14.2 for protection of control circuit and use of control transformer

S, start contactor

R, run contactor

TR, timing relay

Inst, instantaneously closing contact

TO, time opening contact

TC, time closing contact

(c) Schematic diagram of typical control scheme

FIGURE 14.5

Autotransformer reduced-voltage starter

connected to the 50% tap on the transformer coil. This means that 50% of the full voltage is applied to the motor and therefore the current I_M drawn by the motor is 50% of the full-voltage starting current. However, by transformer action, the line current I_L (the primary current of transformer) is only 50% of the motor current (the secondary current of the transformer). Thus the line current drawn from the system is only $(0.50)^2$ or 0.25 (25%) of the full-voltage starting current. The starting torque with 50% voltage applied to the motor is again $(0.50)^2$ or 0.25 (25%) of the full-voltage starting torque. Therefore, the reduction in the starting current drawn from the line is the same as that for the starting torque. However, this analysis neglects the effect of the magnetizing current drawn by the transformer, which can range from 10% to 20% of the full-load current of the motor. In practice, the reduction in the line current does not quite equal the theoretical reduction as just indicated. Nevertheless, the starting torque efficiency is very high. The *starting torque efficiency* is *the ratio of the starting torque developed per ampere of line current when starting at reduced voltage as compared to the starting torque developed per ampere of line current when starting at full voltage*. The high starting torque efficiency combined with the flexibility provided by the various taps available makes the autotransformer starter a very popular choice when reduced-voltage starting is required.

Manual autotransformer starters are available that accomplish the required switching from the reduced-voltage starting mode to the full-voltage starting mode by means of a manually operated lever. However, most autotransformer starters are the automatic type that use magnetic contactors to do the switching and a pneumatic timing relay to control the start and run sequence. Figure 12.5(b) shows the power connections to the motor, including the main contacts of the magnetic contactors. Note that only two autotransformer coils are used, connected in open delta. This arrangement causes a slight unbalance of the voltages applied to each phase of the motor. Where this unbalance is unacceptable (that is, for large motors), three autotransformers connected in a wye configuration are used instead. It is standard to have transformer taps of 50%, 65%, and 80% so that a range of starting currents and torques can be selected. A permanent connection is then made to one set of taps.

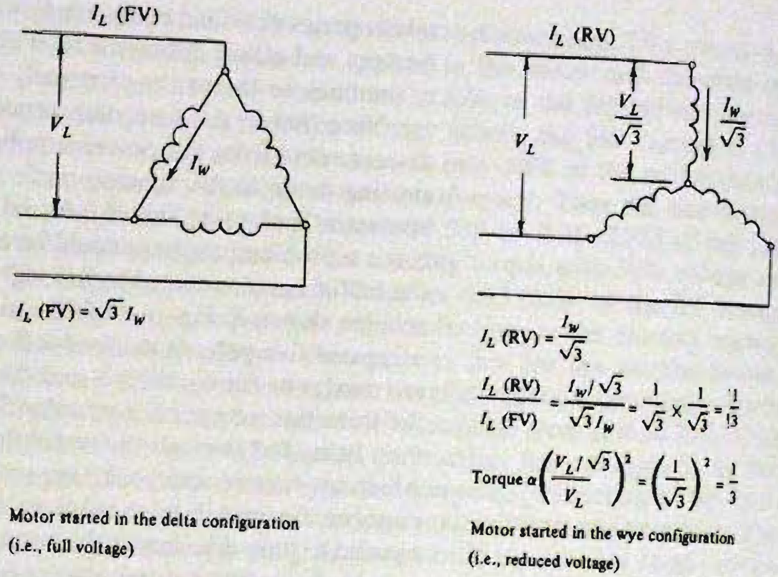
Figure 14.5(c) shows the typical control circuit used to automatically control the necessary switching functions. The sequence of starting is as follows. Operating the start button closes contactor S, which then connects each autotransformer to the line [contacts S and S_1 part (b)] and energizes the motor through the taps. At the same instant, the timing relay is energized to begin its preselected timing cycle. As the motor accelerates toward full speed, the timing relay operates to open contactor S, which disconnects the autotransformers and closes contactor R, which connects the motor directly to the lines so that it runs normally on full voltage.

Note that in the foregoing sequence the motor is momentarily disconnected from the power supply during the transition from the starting mode to the running mode (contactor S must open before contactor R closes). This is referred to as *open transition*. This can cause a problem, as there could be a second inrush of current when the motor is reconnected to full voltage. To avoid this problem, the scheme shown in Figure 14.5(b) can be slightly modified. Instead of using one five-pole contactor for S and S_1, two separate contactors are used, one for contacts S and the other for contacts S_1. Then, in the transition sequence, contactor S_1 is opened first, with the motor then being fed through the remaining part of the transformer coils, which are now in series with the motor. Next, contactor R closes to connect the motor to the full voltage, and finally contactor S is opened to fully disconnect the autotransformer coils from the power supply. Since the motor is always connected to the power supply for the complete starting sequence, this is referred to as *closed transition*. Many manufacturers offer closed transition autotransformer starters as standard.

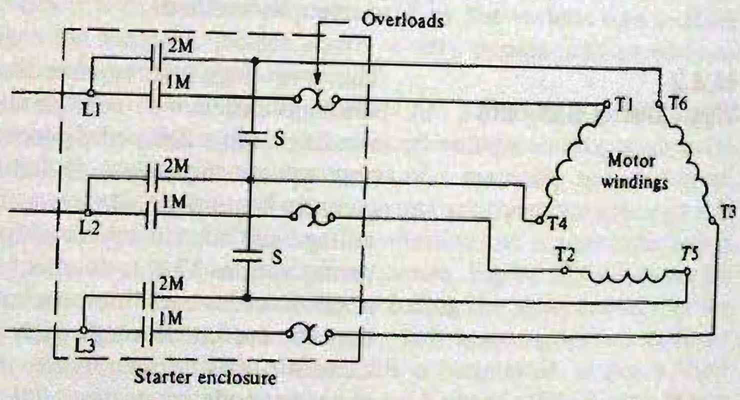
14.4.2 Wye–Delta Starters

The wye–delta starter uses the method of connecting the motor windings into a wye configuration to start and then switching the windings into a delta configuration to run. The reader should at this time review the wye and delta voltage and current relationships given in Section 1.6. Refer next to Figure 14.6(a). First, look at the voltage and current relationships if the motor is started in the delta configuration. This is in effect full-voltage starting, as the voltage applied across each motor winding is the full line voltage. Assume that the current through each phase winding is I_W. Then the line current I_L (FV) drawn by the motor is $\sqrt{3}I_W$. Now let us compare the wye mode of starting. The voltage applied across each motor winding is $1/\sqrt{3}$ or 57% of the line-to-line voltage, thus in effect applying a reduced voltage. This means that the motor winding current is $I_W/\sqrt{3}$, which is also the line current I_L (RV) drawn by the motor. Therefore, if the two line currents drawn by the motor are compared as shown, we see that the line current for the wye starting mode is only one-third that of line current in the delta (full voltage) mode. Also as shown, the starting torque in the wye mode is proportional to the square of the voltage applied across the motor winding and therefore is only one-third that for full-voltage starting. Thus the starting current and torque are both reduced by the same amount.

Figure 14.6(b) shows the power connections for the wye–delta starting. Three contactors are required to complete the start and run



(a) Comparison of starting currents and torques



Note: This diagram shows the power connections only

(b) Power connections for starter and motor

FIGURE 14.6

Wye–delta reduced-voltage starting

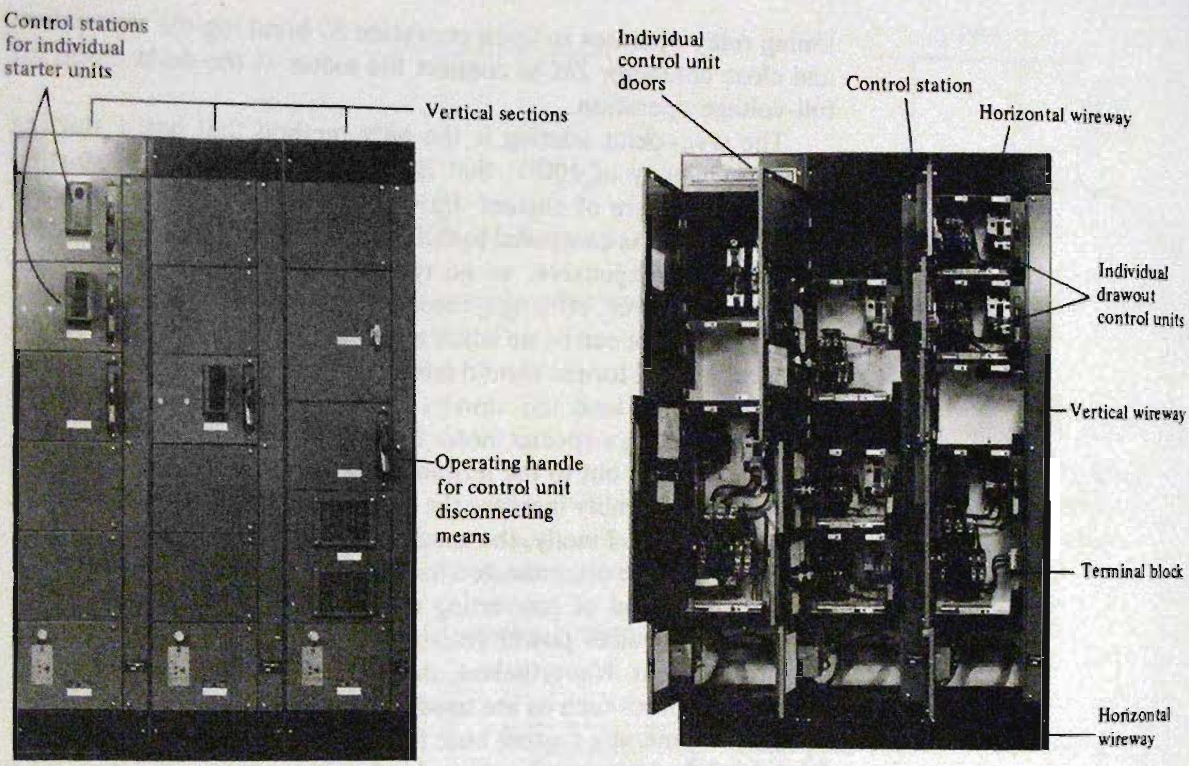
sequence. The control circuit, which is not shown, is similar to that shown for the autotransformer starter in Figure 14.5(c), in that a timing relay is used to control the switching sequence. When the start button is pushed, contactor S closes to establish the wye point for the motor winding (joins terminals T4, T5, and T6) and contactor 1M closes to connect terminals T1, T2, and T3 to the power source. At the same instant, the timing relay is energized to begin its preselected timing cycle. As the motor accelerates toward full speed, the timing relay operates to open contactor S, breaking the wye point, and close contactor 2M to connect the motor in the delta mode for full-voltage operation.

The wye–delta starting is the only method that has a starting torque efficiency of 100%; that is, it maintains the same starting torque per ampere of current drawn from the line during reduced-voltage starting as compared to full-voltage starting. Also the starter is relatively inexpensive, as no resistors or autotransformers are required. However, offsetting these advantages are a few disadvantages. First, there can be no adjustments to the starting torque. If the one-third normal torque should fail to turn the motor over or should it accelerate the load too slowly, nothing can be done about the problem. Second, a special motor is required, one with all six winding leads brought out to the terminal box, as shown in the diagram. This can considerably increase the cost of the motor as compared to a standard motor. Finally, the starter as shown is open transition, as the motor must be disconnected for the transition from wye to delta. There is a method of converting the starter to a closed transition type, but it requires power resistors and extra contactors, which increase the cost. Nevertheless, this type of starter is often used to start large motors such as are used for air-conditioning units. These motors are generally custom built for the compressor units that they drive, and the units can be started unloaded.

14.5 MOTOR-CONTROL CENTERS

Where it is necessary to control a number of motors from one location, the use of a motor-control center is recommended. *Motor-control center* is a term applied to *a grouping of various motor-control units in a series of steel-clad enclosures bolted together to form a continuous structure*, such as shown in Figure 14.7. The standard 600 volt class motor-control center is made up of vertical sections 20 inches wide by 20 inches deep and 90 inches high. A set of main horizontal bus is run across the complete width of the structure, with vertical bus tapped off at each section to supply power to the individual drawout control units. Vertical wireways run the full height of each section, and horizontal wireways run across the total width, both at the top and bottom. These wireways accommodate all the control wiring between control units and to external control devices and power wiring from the control units to the motors. The motor-control center, when in operation, is completely dead-front; that is, no live parts are exposed to a person on the operating side of the equipment.

Motor-control centers are free standing; that is, they are self-supporting and can be floor mounted, allowing access from both the front and rear of the unit if desired. The complete motor-control



(a) Normal view of motor-control center

(b) View shown with control-unit doors open

FIGURE 14.7

Typical motor-control center, 600 volt class

center assembly is available in a variety of configurations, such as L-shaped and U-shaped, and with control units mounted on both the front and the back. However, the most common arrangement is a straight line, with the individual control units mounted on the front only, as shown in Figure 14.7. Motor-control centers can form part or all of the low-voltage distribution section of a unit substation (Section 15.4).

In industrial plants, the trend is to install complete motor-control centers in separate rooms adjacent to the center of the load, thus isolating them from the environment found in the manufacturing area. In commercial buildings, the motor-control centers are usually located in the various mechanical equipment rooms housing the supply and exhaust fans, pumps, and heating and air-conditioning equipment.

The most common control unit used in the motor-control center is the combination magnetic motor starter. However, a variety of other types of units are available. Feeder tap units that contain only a circuit breaker or a fused disconnect switch are used for feeders to remote equipment, such as heaters or motorized equipment that has its own built-in starter and/or control panel. Lighting panels can also be incorporated into the structure, complete with a step-down transformer where required. Thus the motor-control center can serve as the distribution point for all electrical loads within its area if so desired. Motor-control centers can reduce the total costs of electrical systems by keeping the on-site installation time and labor to a minimum. They offer a compact assembly of motor starters and associated equipment. The centralized location of the control units allows for convenient operation and easier maintenance. The modular arrangement provides for future expansion and/or realignment of the individual drawout units.

Each drawout control unit is assembled in its own enclosure, complete with spring-tempered stab fingers for plugging onto the vertical bus. This allows any unit to be easily withdrawn from its space in the motor-control center either for maintenance purposes or for replacement with a working unit. Typical drawout starter units with the unit doors open are shown in Figure 14.7(b). Each unit is complete with its own disconnecting device and magnetic starter. Short-circuit and ground-fault protection for the starter and motor branch circuit (Section 13.1.1) can be provided by either a fusible disconnect switch or a molded-case circuit breaker. The operating handle for the disconnecting means is interlocked with the unit door so that the door cannot be opened when the handle is in the on position. The handle can be padlocked in the off position to satisfy code requirements with regard to the disconnecting means for the motor (see Section 13.2.1 and Figure 13.5).

Each starter unit can be supplied with stop and start push buttons, selector switches, and/or pilot lights in a door-mounted control station for the individual control of the starter. A control transformer, if required, can be mounted within the drawout structure. The magnetic starter and its basic control scheme are all as previously described in Sections 14.2 and 14.2.1. All motor-starting types are available for installation in motor-control centers, including reversing starters (Section 14.3), autotransformer starters (Section 14.4.1) and wye–delta starters (Section 14.4.2).

The drawout control units are constructed on a modular basis; that is, they have standard incremental dimensions to allow for flexibility and variety of use. The smallest unit is normally 12 inches, with larger units increasing in increments of 6 inches (12, 18, 24, 30 inches, and so on). Typical space requirements for the various types of drawout units are shown in Table 14.3. An example of the layout for a motor-control center is given in Section 14.5.3. Although the table and example in this text use 6 inch increments, other modules based on increments such as $4\frac{3}{8}$, $6\frac{1}{2}$, or 7 inches are not uncommon.

TABLE 14.3 Space Requirements for Motor-Control Centers[a]

Starter Size[b]	Combination Starter Units — Number of Space Factors Required: Full Voltage Nonreversing	Full Voltage Reversing	Reduced Voltage Autotransformer	Reduced Voltage Wye–Delta[c]
Circuit Breaker Type				
1	2	3	—	—
2	2	3	6	5
3	4	4	9	6
4	4	4	9	7
5	6	10	12	12[d]
6	12	12[d]	12[e]	—
Fusible Switch Type[f]				
1	2	3	—	—
2	2	3	6	5
3	4	5	10	8
4	6	6	10	12
5	7	12[d]	12	12[e]
6	12	12[d]	12[e]	—

Feeder Tap Units

Circuit Breakers: Amperes	Circuit Breakers: Space Factors	Fusible Switches: Amperes	Fusible Switches: Space Factors
100	2[g]	30	2[g]
150	2[g]	60	2[g]
225	3	100	2
400	4	200	4
		400	6

[a] Based on one space factor = 6 inches. Space factors based on 4⅜, 6½, and 7 inches are also common. All space requirements should be confirmed by manufacturer.

[b] See Table 14.1 for horsepower ratings.

[c] Horsepower ratings are higher than for other types of starters.

[d] Requires structure 24 inches wide.

[e] Requires structure 28 inches wide.

[f] Using UL class J fuses.

[g] Can be dual mounted (two breakers or switches in one drawout unit).

14.5.1 Classifications of Motor-Control Centers

The control schemes required for the motor starters and other control devices housed in the motor-control center can range from very basic (only stop–start push buttons located at each starter unit) to very complex (extensive electrical interlocking between starters and connections to remote pilot devices such as pressure, level, temperature, and speed sensing switches). Therefore, a range of options is available with regards to the degree of control wiring that is done by the manufacturer before the motor-control center is shipped to the site. The National Electrical Manufacturers Association classifications are defined as class I, types A, B or C, and class II, types B or C. A class I motor-control center is primarily a mechanical grouping of starter units requiring only a minimum degree of control wiring. A class II motor-control center is designed as a complete control system requiring system analysis and engineering, as well as interlocking and interwiring between units and provisions for connections to remote pilot devices. The types A, B, and C subclassifications cover the provision of terminal blocks and wiring. With type A, terminal blocks are not provided. Only the internal wiring within each starter control unit is completed. Any field wiring has to be brought into the individual unit for connection. With type B, terminal blocks are provided for each starter control unit [see Figure 14.7(b)] and all internal unit wiring is then connected to the terminal blocks. With type C, in addition to the terminal blocks at each unit, master terminal blocks are provided for each vertical section, mounted either in the top or the bottom horizontal wireway [Figure 14.7(b)]. All internal wiring is completed up to these master terminal blocks. The field wiring need only to be brought to these terminal blocks. The one exception is the power wiring for starters of size 3 and larger, in which case the feeder conductors from the motor have to be terminated at the starter loadside terminals. In summary, a class I, type A motor-control center incorporates very little control wiring, whereas a class II, type C motor-control center is a completely engineered and wired structure requiring only external field wiring to be connected to the master terminal blocks.

14.5.2 Standard Ratings for Motor-Control Centers

All components of motor-control centers are rated for use on systems up to 600 volts nominal. However, the operating coils of all starters and control relays must be rated for the actual control voltage that is used.

Power is distributed from the main incoming feeder lines throughout the motor-control center by three-phase main horizontal bus and by vertical bus at each section. The standard continuous current rating for the horizontal bus is 600 amperes, with optional ratings of 1000, 1200, 1600, and 2000 amperes being available. The vertical bus is available in ratings of 300, 450, and 600 amperes. The bus must also be braced to withstand the maximum available fault current that can exist at the incoming terminals of the motor-control center (see Section 6.2). The standard bus bracing rating is 22,000 amperes symmetrical, with optional ratings of 42,000 and 65,000 amperes being available. These continuous current and bus bracing ratings are typical, and each manufacturer should be consulted for the exact ratings offered. Examples showing the calculations of the available fault current for the purpose of selecting the bus bracing rating are included in Chapter 16.

The combination starter and feeder tap drawout units must also be able to withstand the stresses of the potential fault currents and to safely interrupt any fault currents caused by a short circuit on the feeder that they control. With the combination fusible disconnect type of control unit, the use of high interrupting capacity current-limiting fuses with interrupting ratings of 200,000 amperes rms symmetrical is recommended. Refer to Section 7.3 with regard to current-limiting fuses and Section 7.5 with regard to the classifications of low-voltage fuses.

The combination circuit breaker type of unit is listed for use where the available fault current at the motor-control center is a maximum of 22,000 amperes symmetrical. Reference to Table 8.1 shows that the interrupting rating of the standard molded-case breaker, 150 amperes or less, is only 14,000 amperes at 480 and 600 volts. This discrepancy is explained as follows. NEMA standards specify that the combination starter be tested with its output terminals shorted with minimum-length conductors. Therefore, the impedance of the breaker, starter contacts, overload relay heater elements, and wiring are in series during this test, all of which combine to lower the actual magnitude of the short-circuit test current. Furthermore, the test specifications require that any damage caused by the fault current be contained within the unit involved. This means that the unit may pass the test even though the starter or breaker may require repair or replacement. As an alternative to using the standard breakers, the more costly high-interrupting breakers can be used (see Table 8.1). A second alternative is to use fused circuit breakers (Section 8.7) to increase the interrupting rating up to 200,000 amperes. This arrangement has the advantage of being able to restore power quickly after clearing a low-level fault—the fuses having to be replaced only after clearing a high-level fault, which should be rare.

14.5.3 Layout of Motor-Control Centers

It is important that, early in the design process, the overall size of each motor-control center required for the electrical system be determined so that adequate space is allocated during the preliminary planning of the building. The following example illustrates the method of determining the overall size required for a motor-control center.

EXAMPLE 14.1

A motor-control center is to control the following motors using the type of starters given in Table 14.4. In addition, two 30kW, three-phase heating loads are to be supplied. The source of supply is 480 V, three-phase, and the motors are rated at 460 V, three-phase. The control units are the fusible switch type. Determine **(a)** the overall size of the motor-control center, and **(b)** the ampacity rating of the main bus.

TABLE 14.4

Number	HP	Type of Starter
4	7½	Full voltage, nonreversing (FVNR)
5	10	Full voltage, nonreversing (FVNR)
2	20	Full voltage, nonreversing (FVNR)
2	30	Full voltage, nonreversing (FVNR)
2	40	Full voltage, reversing (FVR)
1	100	Reduced voltage, nonreversing (RVNR; autotransformer type)

Solution

(a) Based on Table 14.3, the space requirements for motor starters are given in Table 14.5.

TABLE 14.5

Motor Starters			No. of Space Factors	
Motor HP	Type of Starting	Starter Size (Table 14.1)	Each Unit	Total
7½	FVNR	1	2	4 × 2 = 8
10	FVNR	1	2	5 × 2 = 10
20	FVNR	2	2	2 × 2 = 4
30	FVNR	3	4	2 × 4 = 8
40	FVR	3	5	2 × 5 = 10
100	RVNR	4	10	1 × 10 = 10
			Total for starters	= 50

Additional space factors are determined.

— Two 30 kW heating loads:

$$\text{load current} = \frac{30 \times 1000}{1.732 \times 480} = 38 \text{ A}$$

which requires two 60 A switches, dual mounted: 2 space factors
— Allowance for main incoming feeder cables: 1 space factor

Total required space factors is found.

$$50 + 2 + 1 = 53$$

— Maximum possible space factors per vertical section = 12
— Minimum number of vertical sections = 53/12 ≈ 5
— Total number of space factors = 5 × 12 = 60
Number used = 53
Number of spare space factors = 7

Figure 14.8 shows a suggested layout for the motor-control center. This example is meant to show the procedure only for laying out an MCC. The manufacturers should be consulted for their exact space requirements.

(b) Table 14.6 gives the calculation for ampacity of main bus. Note that it is the same as that required for the feeder to a group of motors (see Section 13.4).

TABLE 14.6

Motor HP	FLMA (A) (Table 13.2)		
100	123	125% of largest =	1.25 × 124 = 155
7½	11	Plus 100% of remaining	4 × 11 = 44
10	14		5 × 14 = 70
20	27		2 × 27 = 54
30	40		2 × 40 = 80
40	52		2 × 52 = 104
Two 30 kW heaters			2 × 38 = 76
			Minimum ampacity = 583 A

Select the standard main bus rating of 600 A.

It is also necessary to determine the available fault current at the mains of the motor-control center in order to specify the bus bracing. See Sections 16.3 and 16.5 for examples of the necessary calculations. See Section 13.3 for examples of the design of the individual motor branch feeders.

The motor-control center in Figure 14.8 can either be mounted free standing or, since the starters are mounted on the front of the unit only, it can be mounted against a wall. In either case, sufficient clear working space must be provided in front of the enclosure to

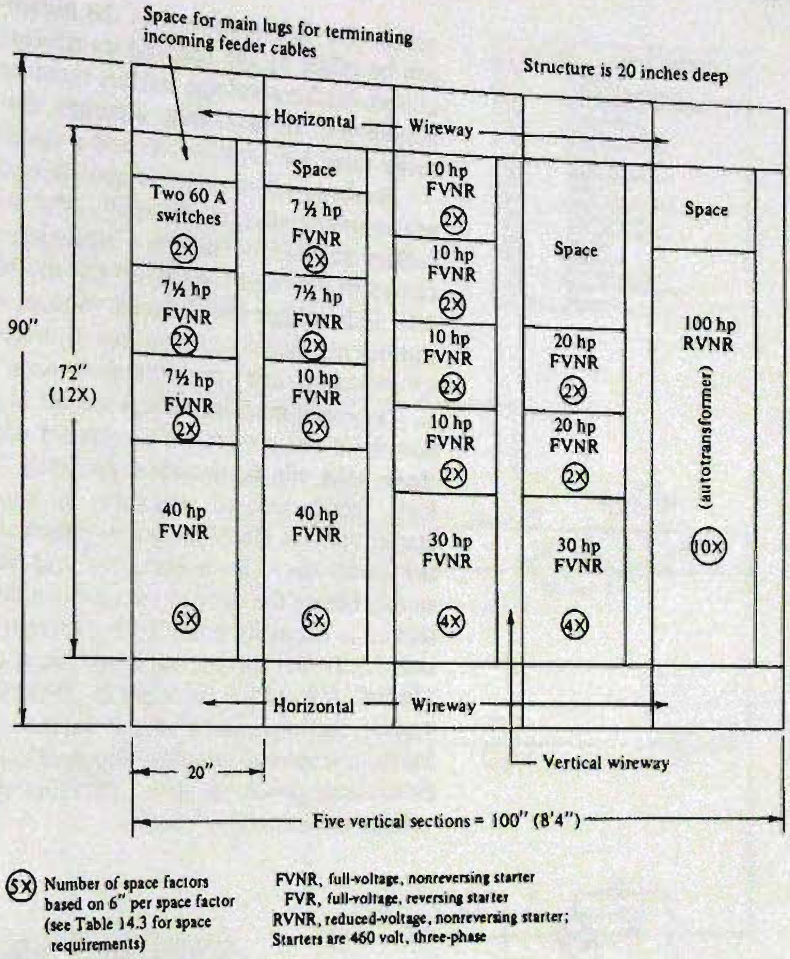


FIGURE 14.8

Layout of motor-control center for Example 14.1

permit ready and safe operation and maintenance of all devices. Section 110-16 of the *National Electrical Code* governs the working space about electrical equipment operating at 600 volts nominal or less. For the motor-control center in the foregoing example operating at 480 volts, there must be a minimum clearance of 3½ feet from the front face of the unit to the nearest grounded surface (concrete, brick, or tile wall). In planning the location of the motor-control center, this working space requirement must be taken into account.

14.6 MEDIUM-VOLTAGE STARTERS

In industrial plants or large commercial buildings that distribute power at voltages above 600 volts, it may be more economical to supply large motors (above 200 hp) directly from the higher-voltage system, rather than step down the power to 480 volts (or even 600 volts). The increased cost of the higher-voltage control equipment can be offset by the reduced transformer and feeder capacities required. Medium-voltage starters rated up to 7.2 kilovolts and 10,000 horsepower are available, although the standard starters are normally rated for 5.0 kilovolts and a maximum of 2500 horsepower.

Medium-voltage starters operate basically the same as low-voltage magnetic starters. Naturally, the starters are much larger and bulkier because of the extra insulation and the need for large arc chutes to interrupt the currents at the higher voltages (see Section 8.1). Full-voltage and reduced-voltage, nonreversing and reversing starters are available to control squirrel-cage induction, wound-rotor induction, and synchronous motors.

A typical medium-voltage starter is made up as a complete assembly of components in a compact drawout unit. Up to three of these units can be mounted vertically in a free standing, 90 inch high, metal-enclosed structure, as shown in Figure 14.9. Each starter unit has electrical and mechanical interlocking to ensure that the starter has to be de-energized and isolated from the main power supply before the door to the unit can be opened. Short-circuit protection is normally provided by current-limiting power fuses (Section 7.8.2) that have a minimum short-circuit interrupting duty of 150,000 kVA at 2500 volts and 250,000 kVA at 5000 volts. Additional vertical sections can be bolted together as required, with the resulting metal-enclosed structure supplied complete with all bus work for distributing power to each individual starter unit, similar to low-voltage motor-control centers.

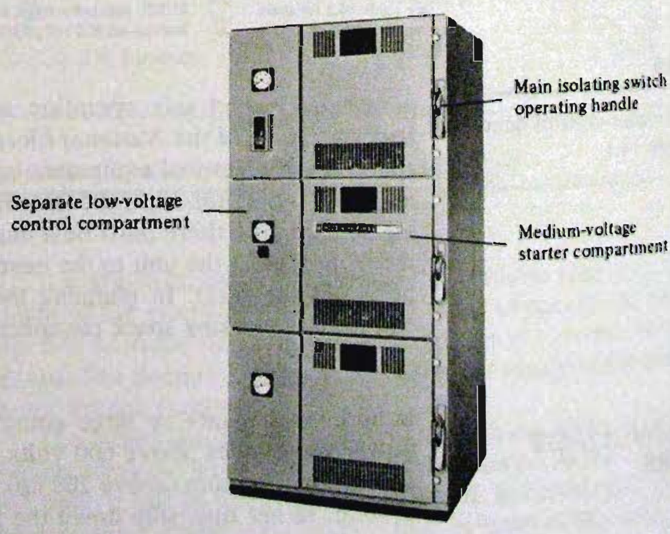


FIGURE 14.9

Typical medium-voltage starter enclosure (three-high construction)

Designation	Device Description
CAP	Capacitor
CPS	Control Power Switch
CPT	Control Power Transformer
CR	Control Relay
CT	Current Transformer
HFU	Fuse for CPT Primary
LB	Late Break
M	Main Line Contactor
MFU	Main Fuse
MIS	Main Isolating Switch
OL	Overload Relay
P1(M)	M Position Interlock
REC	Rectifier
MOV	Suppressor
TSP	Test Source Plug
XFU	Fuse for CPT Secondary
1R, 2R	Resistors

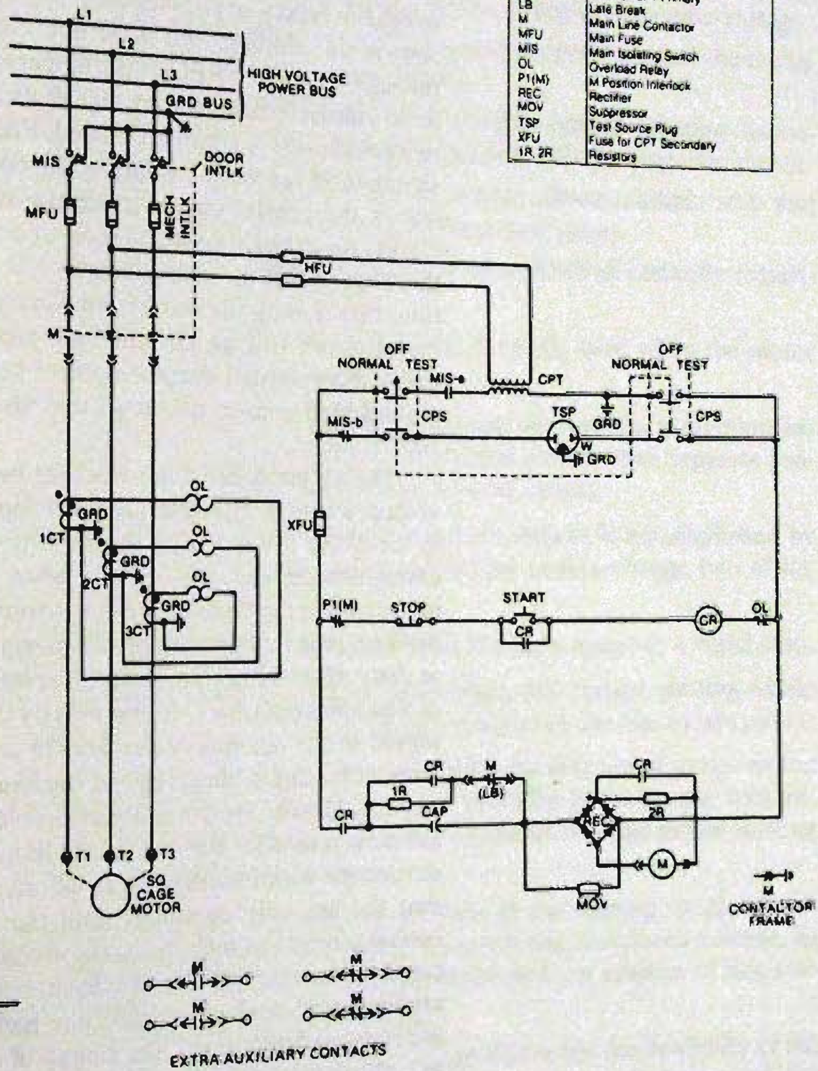


FIGURE 14.10

Typical wiring diagram for a medium-voltage starter

A typical wiring diagram of a medium-voltage starter unit is shown in Figure 14.10. This diagram shows the unit complete with a main isolating switch (MIS). However, the *NEC* permits the draw-out feature of the starter unit to be used as the isolating means, providing that the unit can be locked in the drawout position. The control system for the starter has similar features to those described for the low-voltage starters in Section 14.2.1 in that momentary stop–start pushbuttons are used, which provides the advantages of three-wire control with undervoltage protection. The differences are that a control transformer is always used to step down the motor circuit voltage to a safe level and that the thermal elements of the overload relays are connected through current transformers as shown. In addition, the main line contactor coil M is energized through a rectifier (REC). As compared to ac operation, the use of dc to energize the operating coil gives a much more positive action to force the heavy contactor closed. Finally, there is a control power switch (CPS) at the secondary of the control power transformer that allows the control circuit to be transferred to a test source plug (TSP). An external control power source can then be connected to this plug so that the starter can be safely tested in its drawout position, that is, with the starter completely disconnected from the high motor circuit voltage. Ground-fault protection (Section 10.5) can be easily incorporated into the control scheme with the addition of a ground fault sensor similar to that shown in Figures 10.16(a) and 10.17.

The air break contactor has long been the standard for medium-voltage starters. However, the problem with interrupting a current in air is the distance that the moving contact must travel to fully extinguish the arc. As a result, when the contactor is closed, the impact when the contacts meet is severe. If the starter is required to perform repeated operations, the jarring of the mechanism can lead to early maintenance problems. A solution to this problem is the use of vacuum contactors. As previously discussed in Section 8.1 with regard to the opening of contacts in a vacuum, there can be problems with current chopping and the like. However, modern technology has largely overcome these problems, and vacuum contactors are now available for use in medium-voltage starters. One main advantage with interrupting an alternating current in a vacuum is that the arc only continues until the first current zero, at which instant a region of high dielectric strength is established between the contacts, preventing the arc from being reestablished. Since the arcing period does not exceed one half-cycle and the length of the arc is exceedingly small, the energy of the arc is considerably lower as compared to breaking the arc in air. With the short contact travel, the mechanical stressing on the contactor mechanism as it opens and closes is greatly reduced, leading to far less maintenance problems with repeated operations. Also, with the much smaller magnetic operating mechanism required and the absence of large arc chutes, the vacuum starter can be built as a very compact unit.

SUMMARY

- Manual starters can only be used for the starting and stopping of small motors.

- Full-voltage starting can only be used if the motor starting current does not cause serious disturbances on the electrical system.
- Magnetic starters are designated by their NEMA size number, which sets their maximum horsepower rating at a specific voltage.
- The function of the overload relays is to properly protect the motor against overloads and single phasing.
- Combination starters offer a safe, compact unit, combining disconnecting means and overcurrent protection with the magnetic starter.
- Three-wire control of a magnetic starter allows multiple stop and start points and provides undervoltage protection.
- Undervoltage protection prevents motors from all instantly restarting when power is restored.
- Step-down control transformers are normally used when the motor circuit voltage is 480 or 600 volts.
- If the rating of the motor branch-circuit overcurrent protection exceeds that allowed for the motor control circuit, then separate protection must be provided for the control circuit.
- The reversing of three-phase induction motors is accomplished by adding a second contactor to the starter to interchange two of the three motor leads.
- Reversing starters can also be used to plug a motor to a rapid stop.
- Reduced-voltage starters are used where full-voltage starting would otherwise cause unacceptable disturbances on the electrical system.
- The starting torque of a squirrel-cage induction motor varies as the square of the applied voltage. The resulting lower torque with reduced voltage starting could cause problems with the motor starting and accelerating up to speed.
- Starting torque efficiency is the ratio of the starting torque developed per ampere of line current when starting at reduced voltage, as compared to the starting torque developed per ampere of line current when starting at full voltage.
- The autotransformer reduced-voltage starter has the flexibility of the three tap settings and a very high starting torque efficiency and can easily be made closed transition.
- The wye–delta starter has 100% starting torque efficiency and requires no autotransformers or power resistors. However, it has no adjustments, is basically open transition, and requires a special motor.
- Motor-control centers offer a centralized location for the control of a group of motors.

- Motor-control centers are classified as class I, type A, B, or C, and class II, type B or C, which specifies the amount of internal wiring provided by the manufacturer.
- All components of motor-control centers are rated for a maximum of 600 volts nominal. The standard ratings for the main bus is 600 amperes continuous with 22,000 amperes symmetrical bus bracing. Higher ratings are available when required.
- Motor-control centers use modular plug-in units, allowing for flexibility in arrangement and ease of maintenance.
- Standard plug-in units using circuit breakers are rated for 22,000 amperes symmetrical, and those using current-limiting fuses are rated for 200,000 amperes symmetrical.
- Sufficient space for each motor-control center has to be allowed for in the planning of the building.
- Medium-voltage starters are available for controlling large motors where it is more economical to supply them directly from the higher-voltage distribution system.
- Standard medium-voltage starters are rated for a maximum of 5.0 kilovolts and 2500 horsepower.
- Medium-voltage starters using vacuum contactors offer a compact unit allowing many thousands of operations free of mechanical maintenance problems.

QUESTIONS

1. What are the advantages and disadvantages of manual starters?
2. What are the horsepower limitations of single-phase manual starters?
3. What are the horsepower limitations of three-phase manual starters?
4. When are magnetic starters required?
5. What does FVNR signify?
6. What are the limitations on starting a motor at full voltage?
7. Why must starters be horsepower rated?
8. What is the purpose of the overload relays on the starter?
9. Why are three overload relays used on three-phase starters?
10. What are the several advantages of combination starters?
11. What is a motor control circuit?
12. What is a normally open contact?
13. What is meant by a three-wire control scheme?
14. List the advantages of the three-wire control scheme.
15. When does the two-wire control scheme have to be used?
16. What are the disadvantages of the two-wire control scheme?
17. Why must the two contactors for a reversing starter be interlocked so that only one contactor can be closed at any one time?
18. What is meant by plugging a motor?
19. Explain why the starting torque of a squirrel-cage induction motor is directly proportional to the square of the starting voltage.
20. Why are reduced-voltage starters used?
21. What are the advantages of the autotransformer starter?
22. What are the advantages and disadvantages of the wye–delta starter?

23. What is meant by starting torque efficiency?
24. What is meant by closed transition with regard to reduced-voltage starters?
25. What is a motor-control center?
26. How is power distributed to each control unit in an MCC?
27. What is meant by free standing?
28. What are the advantages of motor-control centers?
29. What is a class II, type B motor-control center?
30. Why is the bus bracing rating of an MCC important?
31. Explain why the standard molded-case breaker with an interrupting rating of only 14,000 A can be used in an MCC rated for 22,000 A available fault current.
32. Why are medium-voltage motors and starters used?
33. How is short-circuit protection usually provided on medium-voltage starters?
34. What are the advantages of using vacuum contactors for medium-voltage starters?

PROBLEMS

1. What size of starter is required for the following motors: (a) 10 hp, 230 V, single-phase; (b) 10 hp, 200 V, three-phase; (c) 60 hp, 200 V, three-phase; (d) 60 hp, 460 V, three-phase.
2. A control circuit for a motor starter consisting of No. 14 copper conductors is contained entirely within the starter enclosure. The motor branch circuit is protected by a 100 A fuse. Does the control circuit require its own separate overcurrent protection? Explain your answer.
3. Repeat Problem 2, except that the control circuit extends beyond the starter enclosure.
4. A motor-control center is to control the following motors using the type of starters noted:

Five 10 hp, FVNR	One 30 hp, FVNR
Three 25 hp, FVNR	One 40 hp, FVNR
One 25 hp, FVR	One 75 hp, FVR

The source of supply is 208 V, three-phase, and the motors are rated at 200 V, three-phase. The control units are the circuit breaker type.
   (a) Determine the overall size and draw a layout of the motor-control center.
   (b) Determine the ampacity rating for the main bus.
5. Repeat Problem 4, except the supply is 480 V, three-phase, and the motors are rated at 460 V, three-phase.

15 Secondary Unit Substations

OBJECTIVES

After studying this chapter, you will be able to:

- Compare the advantages and disadvantages of the radial, secondary selective, and primary selective circuit arrangements.
- Discuss the advantages of the load-center system.
- Explain the operation of a load-interrupter switch.
- Identify primary switchgear using fused load-interrupter switches.
- Estimate the space requirements for dry-type transformers.
- Determine the general arrangement of circuit breakers in the low-voltage distribution section.
- Lay out a unit substation.
- Determine the space requirements for the unit substation.

INTRODUCTION

Secondary unit substations form the heart of all large industrial plant or commercial building electrical distribution systems. They receive the electrical power at the primary level as prescribed by the electrical utility and step it down to the utilization voltage level of 600 volts nominal or less for distribution throughout the building (or portion thereof). Figure 11.1 shows the one-line diagram of a building electrical system that does not include a main step-down transformer. This is the case when the electrical power is purchased from the electrical utility at a low-voltage level and then distributed at this same level throughout the building. This type of arrangement is usually confined to premises with only a few hundred kVA of load or to premises in areas where there is a concentration of loads and the electric utility has an extensive low-voltage secondary network to provide for larger loads (for example, downtown areas of cities). In other cases, the electric power is purchased at higher voltage levels.

requiring a substation to be installed on the customer's premises. Many utilities offer billing savings of as much as 5% to customers who own their own transformers and associated switchgear.

A secondary unit substation consists of primary incoming line, transformer, and low-voltage distribution sections, coordinated in design so that when joined together they form one overall continuous and uniform enclosure complete with all interconnecting buswork. The primary and secondary distribution sections can be made up using different types of switchgear (fused switches or circuit breakers) as required to suit the many variations in the system requirements. The switchgear can also be arranged to suit different power distribution methods.

The unit substation is completely enclosed on all sides with sheet metal (except for the required ventilating openings and viewing windows) so that no live parts are exposed to a person on the operating side of the equipment. Access within the enclosure is provided only through interlocked doors or bolted-on removable panels. The unit is factory assembled and tested according to the appropriate American National Standards Institute (ANSI) and National Electrical Manufacturers Association (NEMA) standards and is designed to require a minimum amount of labor for installation at the site. Large units may have to be divided into smaller sections for the purpose of shipping to the site.

Because of the importance of the unit substation in the electrical system, it is necessary to plan the overall layout of each unit. This planning must be done early in the design process so that, for one thing, adequate space can be allocated in the building. This chapter concludes with an example layout for a unit substation, showing the minimum space requirements for its installation.

The circuit diagrams presented in this chapter use the one-line format. The reader should review the comments in the Introduction to Chapter 11 and Figure 13.1 with regard to one-line diagrams.

15.1 TYPES OF CIRCUIT ARRANGEMENTS

Many types of circuit arrangements can be selected for substations, although only three basic types are discussed here: the radial, the secondary selective, and the primary selective. The choice as to which circuit arrangement to use is usually a compromise between cost and service reliability. The degree to which the extra costs can be justified depends on the reliability of the power source and the characteristics of the load being fed. First, the power supply to the building must be very reliable before the extra cost to increase the reliability of the building system can be justified. Second, the characteristics of the load within the building should be such that any major power outage would result in heavy production losses. As an example, for an industrial plant with a continuous process, short outages may result in the spoilage of considerable material, and it may take many hours to fully restore the process. In this case, extra costs can be justified to increase the reliability of the building distribution system to minimize these production losses.

15.1.1 Radial System

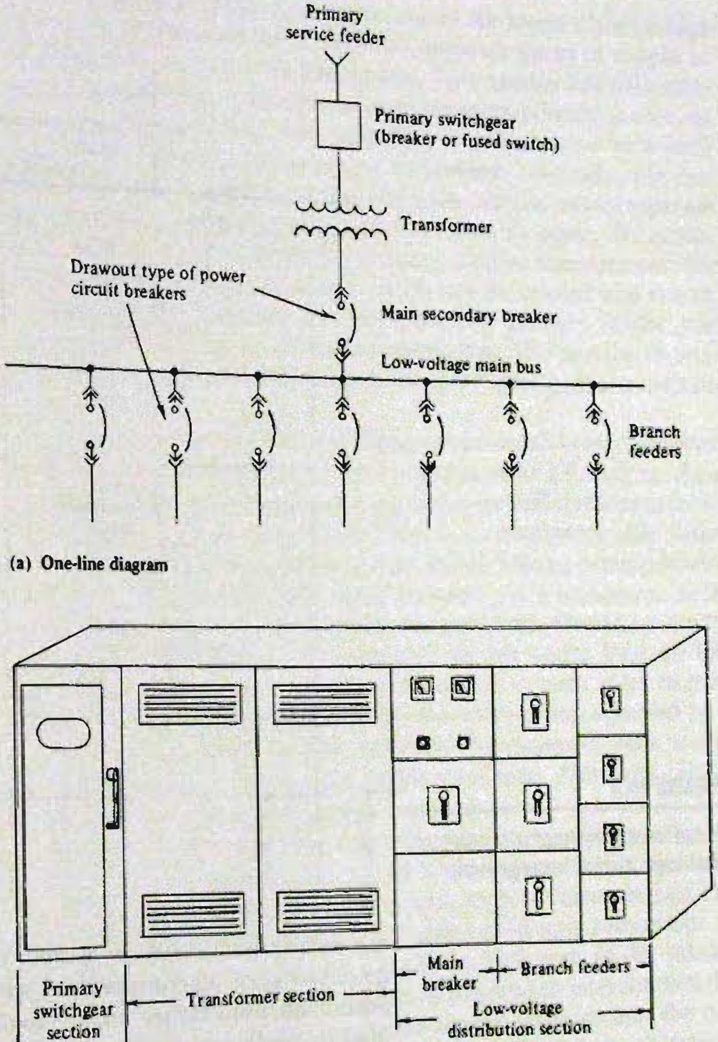
The radial system is the simplest of the circuit arrangements in that there is only one primary feeder and one transformer through which the associated secondary bus is served. Figure 15.1(a) shows the one-line diagram of a typical radial system. This system is the least costly as there is no duplication of equipment and it is the easiest and safest to operate, since there is only the one source of power. However, the obvious disadvantage with this system is that the loss of the primary feeder or a fault on the transformer results in the loss of the entire substation load until the trouble has been cleared. A less obvious drawback is that the maintenance of the system is more difficult, as the substation load must be shut down before any work can be done on the primary feeder or transformer. These planned outages for maintenance may be more of a handicap than the infrequent forced outages.

Figure 15.1(b) shows the physical layout of a typical secondary unit substation using the radial system arrangement. This type is also referred to as a single-ended substation, as there is only a primary incoming line section at the one end of the unit. Note that Figure 15.1 shows drawout-type circuit breakers for the low-voltage distribution section. Fixed molded-case breakers or fused switches could also be used.

15.1.2 Load-Center System

In early radial systems, a single substation, located at the point of the primary service entrance, was used to supply the total load of the building complex. For systems covering a large area, this arrangement required long, large-capacity, and costly low-voltage feeders to distribute the power throughout the building or complex. The modern trend is toward the load-center system using the radial-type circuit arrangement shown in Figure 15.2. The load-center concept allows the power to be distributed at the highest economical voltage level (usually 4.16 or 13.8 kilovolts) to areas of concentrated load where the voltage is transformed down to the utilization level (for example, 480Y/277 volts). The utilization equipment can then be supplied using relatively short low-voltage feeders.

The load-center type of distribution has been made possible by the development of dry-type medium-voltage switchgear and transformers that do not require expensive fireproof vaults and by the development of lower-cost medium-voltage feeder cables [Figure 11.2(d)]. The primary distribution switchgear can be the metal-clad



(b) Layout of single-ended unit substation

FIGURE 15.1

Typical radial system

type using either medium-voltage air circuit breakers (Section 8.10 and Figures 8.19 and 8.20) or load-interrupter switches (Section 15.2.1 and Figure 15.6). Each load center is in itself a radial type of substation, as shown in Figure 15.1.

The added cost of the load centers can be offset by the savings in the cost of feeders. With the older type of single-substation system, the cost of the long low-voltage feeders for distributing the power

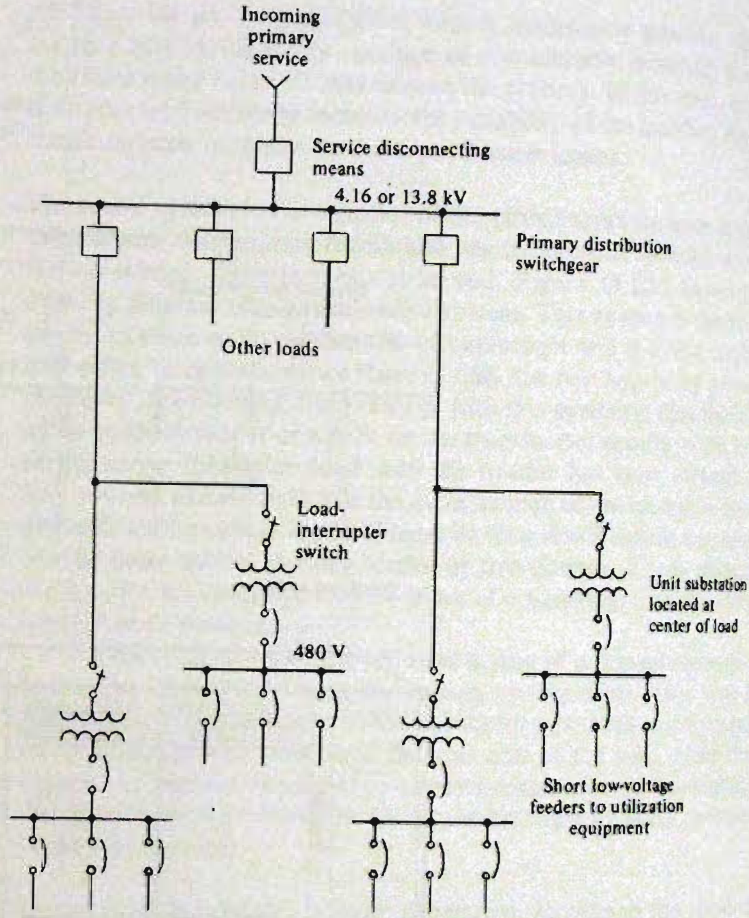


FIGURE 15.2

Load-center system using radial-type circuit arrangement

can be high because of the number of large parallel conductors required to keep the voltage drop within acceptable limits. On the other hand, using higher voltages to distribute power over the longer distances within the building complex substantially reduces the size of the conductors required. Not only are the ampacity requirements per kVA of power transmitted much lower, but also the voltage drop is seldom a problem. Furthermore, the use of a number of smaller substations, rather than one large substation, results in lower available fault current levels at the secondaries of the transformers. Additional savings can be realized because lower interrupting capacity circuit breakers can be used for the protection of the low-voltage feeders. Examples 16.2 and 16.4 show the effect of transformer kVA ratings on the levels of available fault current. The load-center distribution type of radial system should be considered when the total load on a system exceeds 1500 to 2000 kVA, especially if the area to be served is extensive.

15.1.3 Secondary Selective System

The secondary selective system overcomes the major disadvantage of the radial system in that it provides duplicate paths of supply to the secondary bus of each load center. This system has two step-down transformers, each with its own incoming primary feeder, as shown in Figure 15.3(a). The secondary bus associated with each transformer is connected through a tie breaker. Normally, the system is operated with the tie connection open, that is, as two separate radial systems operating independently of each other. However, with the loss of one of the primary feeders and/or transformers, the main secondary breaker for that circuit can be opened and the tie breaker closed, allowing the one remaining primary feeder and transformer to energize all the secondary bus. The service to one-half of the load is momentarily interrupted during this transition period.

The degree to which the total load can be continuously supplied from the one remaining transformer depends on its kVA rating. As a very minimum, each transformer can have just sufficient capacity to handle its own share of the load. Thus, in an emergency only some 50% of the total load can be picked up, the 50% being priority loads, with the less essential loads being dropped. As a maximum, each transformer can be rated to handle the total load. During an emergency, one transformer can then pick up the entire load on the secondary buses with no problem. Naturally, it costs extra to provide this reserve capacity. Usually the kVA rating selected is a compromise between the two extremes; for example, each transformer is sized to handle 75% of the total load. Normally, some loads can be dropped during an emergency.

There are two possible arrangements for the secondary selective system. In the first arrangement, shown in Figure 15.3(a), the total system is enclosed in one complete unit, such as shown in part (c). This arrangement is known as a double-ended unit substation, as there is a primary incoming line section at both ends of the substation. Only one tie breaker, as shown, is required to interconnect the two sections of secondary bus. In the second arrangement, the two sections of the system are actually two single-ended substations located some distance apart and then interconnected through a tie feeder. This arrangement requires a tie breaker at each end of the tie feeder, as shown in part (b).

The tie breaker(s) is normally interlocked with the two main breakers so that the tie connection cannot be made unless one main breaker is open. This prevents the two transformers from being operated in parallel, a condition that would almost double the amount of fault current available at the secondary bus and would materially increase the cost of providing the higher interrupting capacity secondary feeder breakers. Therefore, it is preferable to interlock the system so that the maximum fault current available

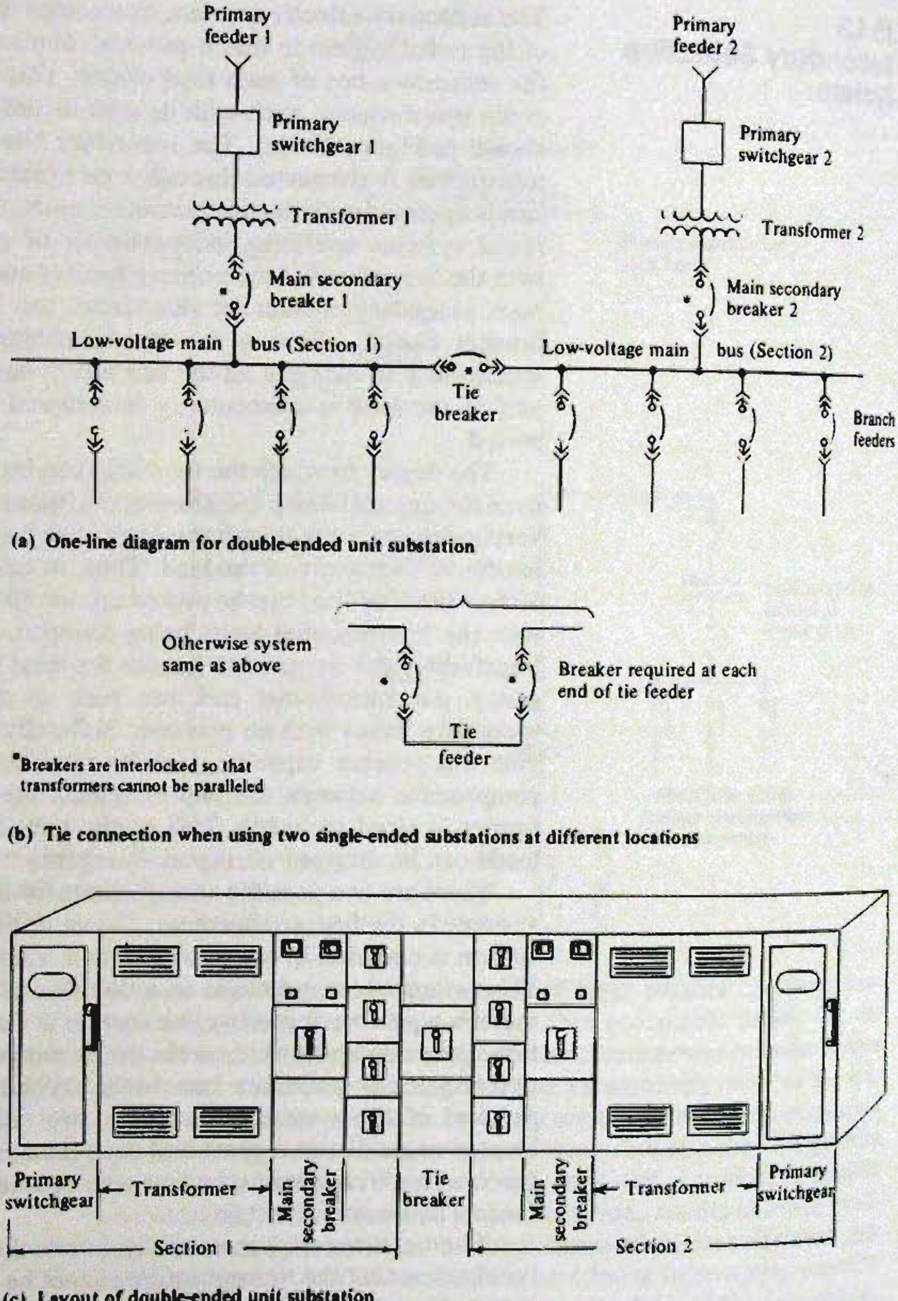


FIGURE 15.3

Typical secondary selective system

under any condition is only the current that can be provided through the one feeder and transformer.

The closing of the tie breaker under emergency conditions can be done either manually or automatically, depending on how urgent it is to pick up the lost load. With automatic operation, voltage sensing relays are connected to each section of the secondary bus. Upon sensing the loss of voltage on one section, these relays initiate the tripping of the associated main secondary breaker, the closing of the tie breaker(s), and, if necessary, the shedding of any nonessential loads. This automatic scheme must, however, have an overriding feature that blocks the transfer of power if one of the main secondary breakers has been tripped due to a fault on its section of the low-voltage bus.

The obvious advantage of the secondary selective system is the increased service reliability provided to the system. A less obvious, but equally important, advantage is the extra flexibility that it allows for maintenance. Work can now be scheduled without the necessity of a prolonged power outage, at least to the essential loads. Naturally, the system costs more than the radial system, especially if reserve capacity is provided in each transformer. Also, the system is more complex to operate because of the possibility of incorrectly interconnecting the two sources of power.

15.1.4 Primary Selective System

The primary selective system also offers duplicate paths of supply, but only as far as providing two primary feeders to each substation, as shown in Figure 15.4. The complete system normally incorporates a number of substations supplied through two primary feeders, with the substations equally distributed between the two. In the event that one feeder is out of service, the system is designed so that the remaining feeder has sufficient capacity to carry the entire load.

As with the secondary selective system, service to one-half of the load is interrupted when a fault occurs on one of the primary feeders. The transformers normally supplied from the faulted feeder then must be switched over to the good feeder to restore service. The use of two circuit breakers at each substation to perform the transfer from one feeder to the other is the safest method. However, the relatively high cost of the breakers often precludes their use unless an automatic transfer scheme is required. The normal practice is to use two load-interrupter switches (Section 15.2.1) interlocked so that only one switch can be closed at any one time.

As with the secondary selective system, the primary selective system offers increased service reliability. It also provides flexibility in allowing scheduled outages for maintenance on the primary feeders. Its major drawback is that the loss of a transformer still means that all the load connected to that substation is shut down until

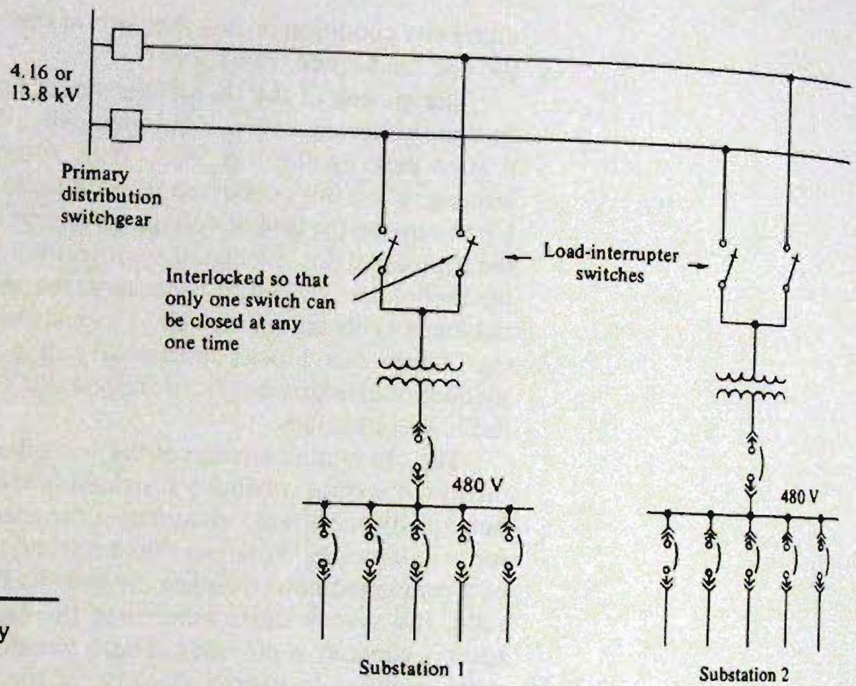


FIGURE 15.4

One-line diagram of primary selective system

temporary connections can be made to an alternative secondary source. However, transformer faults usually happen much less frequently than feeder faults.

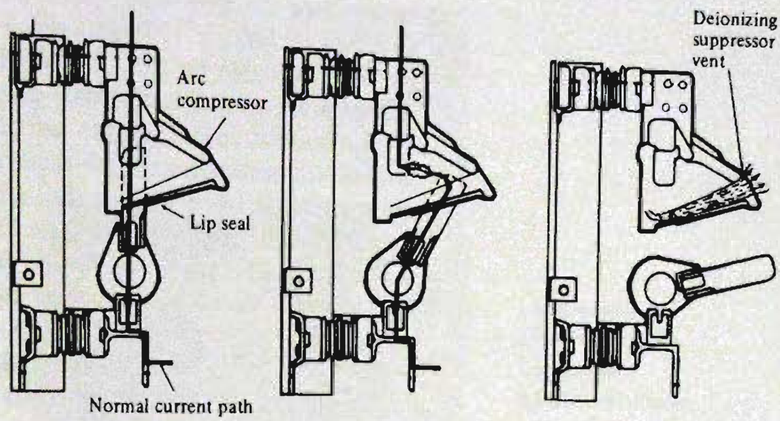
The physical layout of a typical unit substation using the primary selective system is similar to that shown in Figure 15.1(b), except there are two primary incoming line sections located side by side at one end of the enclosure.

15.2 PRIMARY INCOMING LINE SECTION

The primary incoming line section incorporates the terminations for the primary feeder cables and the primary switchgear all housed in one metal-clad enclosure. The switchgear used can range from load-interrupter switches, fused or unfused, to drawout circuit breakers. The latter, as described in Section 8.10, provide the ultimate in primary protection and flexibility in operation and maintenance. However, because of the high cost of breakers, the medium-voltage load-interrupter switch offers an acceptable alternative.

15.2.1 Load-Interrupter Switches

A load-interrupter switch (sometimes referred to as a load-break switch) is designed to safely interrupt a current up to the continuous ampere rating of the switch. Figure 15.5 shows one method of providing this load-interrupting capability. Part (a) shows the switch in the closed position, with the load current flowing through the main



(a) Switch in closed position (b) Switch blade separates from main contact at high-speed; arc compressor provides controlled circuit interruption without external arc or flame (c) Unique lip seal wipes blade as blade exits arc compressor, keeps the arc under compression, and directs controlled arc gases through the deionizing suppressor vent

FIGURE 15.5

Opening sequence of medium-voltage load-interrupter switch

contacts and switch blade. Parts (b) and (c) detail the opening sequences. By combining high-speed opening action with arc suppression, the current is interrupted without any external arc or flame. The switches are normally gang operated; that is, all three blades are opened and closed simultaneously. This quick-make, quick-break mechanism uses the stored-energy method, which incorporates springs to rapidly force the switch blades open and closed. The speed of operation of the switch blade is not dependent on the speed with which the operating handle is moved.

It must be emphasized that load-interrupter switches can safely interrupt currents only up to their continuous ampere rating and can therefore be used only for switching under normal load conditions. They cannot be used to interrupt fault currents. However, as part of its switching functions, the switch could inadvertently be closed in on a faulted feeder. The switch mechanism must therefore have the ability to safely withstand the tremendous mechanical forces created by the fault currents as the switch contacts touch to make the circuit. The operating handle must not kick back and endanger the operator. This is known as the *make rating* of the switch. When the load-interrupter switch is combined with fuses to provide for overcurrent protection of a circuit, the switch must also be able to withstand the peak fault current that occurs during the first cycle until the fuse blows to clear the fault. This is known as the *momentary* *rating* (see Section 6.6). Standard ratings for load-interrupter switches are 600 and 1200 amperes, 5 and 15 kilovolts, although they are also available up to 34.5 kilovolts. The make and momentary ratings are a minimum of 40,000 amperes rms symmetrical.

Load-interrupter switches are also used in applications where only disconnecting means are required at the unit substation. Such an application occurs when the substation forms part of a load-center system, as shown in Figure 15.2. Overcurrent protection for the primary of each substation is provided by the branch feeder device in the primary distribution switchgear. The load-interrupter switch allows each unit substation to be shut down and isolated without interfering with the other loads on the same primary feeder.

In smaller plants or commercial buildings where only one secondary unit substation is required to supply the entire load, the primary switchgear must provide overcurrent protection for the primary of the transformer, as well as serve as the service entrance disconnecting means. In this case, the load-interrupter switch is combined with power fuses. Figure 15.6 shows a typical metal-enclosed switchgear cubicle complete with a three-pole, gang-operated load-interrupter switch and three power fuses. Interlocks are provided so that access to the fuses is only possible when the switch operating handle is in the off position. For details and ratings of power fuses, see Section 7.8.1 and Table 7.4. As an alternative, the new electronic fuses as described in Section 7.8.3 can be used.

Incoming line section cubicles containing fused load-interrupter switches are typically 36 inches wide, 90 inches high, and 54 inches deep to match the adjoining transformer cubicle. When primary metering is required, the necessary potential and current transformers can also be mounted within the cubicle. The cubicle comes complete with all necessary interconnecting bus work, starting from the point of termination for the incoming feeder cables.

15.2.2 Lightning Protection

In many instances, lightning protection is also required at the primary switchgear location. If the premises are supplied from a distribution system, any part of which runs overhead, protection from lightning surges should be provided. Lightning discharges can produce excessive voltages on electrical systems either by direct stroke or by induction. Protection against direct strokes at outdoor substations is provided by overhead ground wires that intercept the lightning strokes and deflect them to ground. However, the majority of lightning surges are caused by induction. A lightning stroke sets up a tremendous electrostatic field. When the field collapses, it induces high voltages into adjacent overhead power lines. These voltage surges then travel at high speeds along the lines away from the point of origin. Service entrance equipment inside buildings should there-

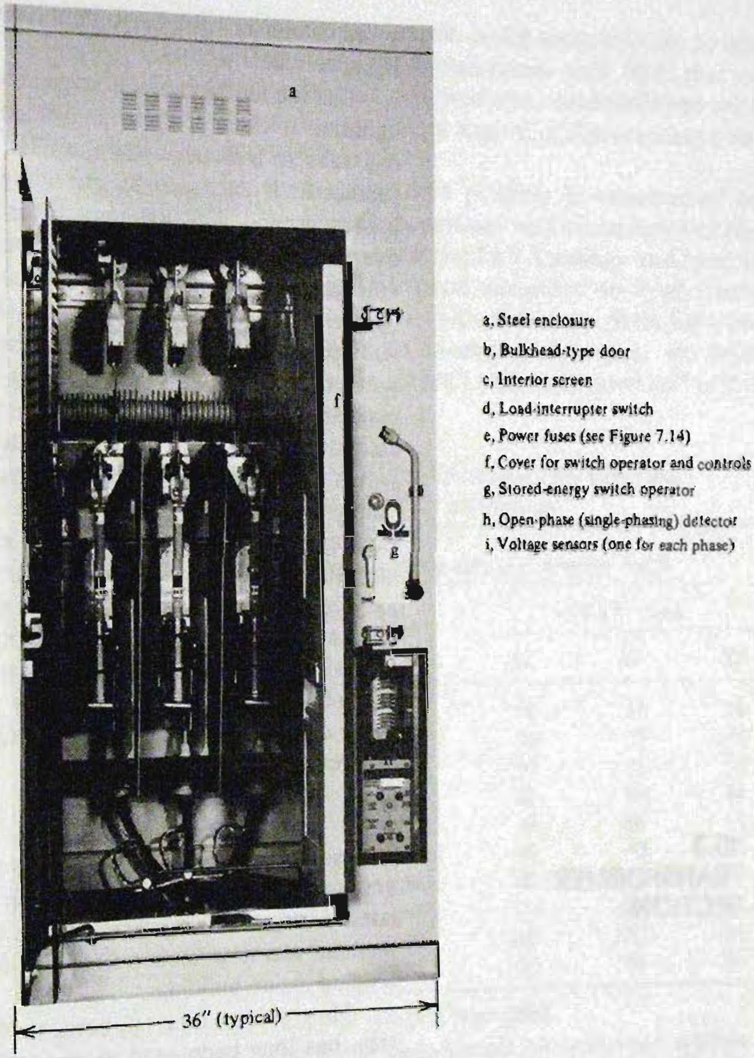


FIGURE 15.6

Typical metal-enclosed medium-voltage fused load-interrupter switch

fore be protected against these traveling voltage waves, which enter the system through the service entrance cables.

It is characteristic of most insulations that the voltage stressing that they can successfully withstand varies inversely with time. Power distribution equipment is required to withstand two different types of voltage stressing tests. The first is a test at low frequency (60 hertz) with a moderate overvoltage for a duration of 1 minute. The second is an impulse test to prove that the insulation will not break down on voltage surges of high magnitude but extremely short duration (on the order of microseconds). The peak value of the maximum voltage surge that the equipment can successfully withstand establishes the basic impulse level (BIL) for the equipment being tested.

It is the function of the surge arrester (formerly referred to as a lightning arrester) to limit the overvoltage from any induced traveling wave to a value below the BIL rating of the equipment being protected. It does this by providing a low-impedance conducting path to ground. This low-impedance path must not exist before the overvoltage appears, and it must be immediately broken after the voltage returns to normal. This is accompanied in the surge arrester by an enclosed air gap that can withstand the normal operating voltage, but will spark over and become conducting at a higher voltage. In series with the spark gap is a column of material whose resistance varies inversely as some power of the voltage. This column, known as a valve, has a low resistance at high voltages (when the surge arrester is discharging) and a high value at low voltages (when voltage returns to normal). This valve aids in interrupting the arc in the gap, which prevents any power-frequency current from flowing to ground after the surge has passed.

The application of surge arresters requires a thorough knowledge of their characteristics and ratings. The reader should consult the reference listed in the Bibliography for a more detailed discussion of lightning protection. Article 280 of the *National Electrical Code* covers the general requirements for surge arresters installed on premises wiring systems.

15.3 TRANSFORMER SECTION

This section houses the transformer for stepping down the primary voltage to the low-voltage utilization level (see Section 1.7). Ventilated dry-type transformers using air as the insulating and cooling medium are now universally used for secondary unit substations located inside buildings.

Mineral insulating oil, because of its superior dielectric properties, has long been used as an insulating and cooling medium for transformers. However, oil-filled transformers create a severe fire and explosion hazard and as such either have to be mounted outdoors or in expensive fireproof and explosion-proof vaults if installed indoors. To overcome this requirement, askarel-filled transformers were developed some years ago. The synthetic askarel has the same excellent insulating qualities as mineral oil, but it will not burn or explode. However, askarel contains polychlorinated biphenyls and can therefore cause severe environmental problems. Because of great concern in the past few years regarding contamination from polychlorinated biphenyls, this type of transformer has rapidly lost favor. As a result, the dry-type transformer, which does not constitute any fire, explosion, or environmental hazard and which requires little if any maintenance, is the accepted type to use for indoor installations. Dry-type transformers with 80°C rise or higher ratings and of completely enclosed and ventilated-type construction do not have to be installed in a room of fire-resistant construction (*NEC* Section 450-21).

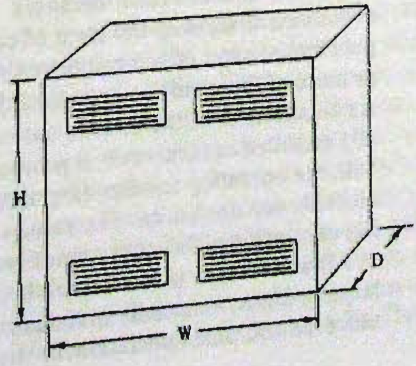
The transformer enclosure where possible is constructed to match the overall dimensions of the primary and secondary switchgear sections. Table 15.1 shows standard kVA ratings and typical cubicle dimensions for 5 and 15 kilovolt ventilated dry-type transformers up to 2500 kVA as used for unit substations. With the continued development of solid-type insulating materials, dry-type transformers are now also available with primaries rated up to 34.5

TABLE 15.1 Ratings and Typical Cubicle Dimensions for Dry-Type Transformers Used with Unit Substations

kVA Rating[a]	Dimensions of Transformer Cubicle (in.) 5 kV Class H	W	D[b]	15 kV Class H	W	D[b]
112½	90	30	54	90	30	54
150	90	30	54	90	30	54
225	90	30	54	90	42	54
300	90	42	54	90	90	54
500	90	42	54	90	90	54
750	90	90	54	90	90	54
1000	90	90	54	90	100	54
1500	90	100	54	90	100	54
2000	90	100	54	100	100	54
2500	90	100	54	100	100	54

[a] Some manufacturers offer additional ratings to those listed.

[b] Depth can be increased to match other sections of unit substation where required.



kilovolts and ratings up to 5000 kVA. See Section 16.2 with regard to the effect of the transformer kVA rating on the level of available fault current.

15.4 LOW-VOLTAGE DISTRIBUTION SECTION

The low-voltage distribution section provides the protection and control for the low-voltage feeder circuits. This switchboard section may consist of fusible switches, molded-case circuit breakers, power circuit breakers, or any combination of these devices. Motor-control center assemblies (Section 14.5) can also form part or all of the low-voltage section.

The selection of the type of device to use for a particular application should take into account functional requirements, economic factors, and safety requirements. Refer to Chapters 7 and 8 for a complete discussion and comparison of the use of fuses, molded-case circuit breakers, and low-voltage power circuit breakers, including the combination fused circuit breakers and the new type of encased breaker. Since these low-voltage encased breakers offer most of the same ratings and operating characteristics as the standard type of power circuit breakers, for the purposes of the discussions in this chapter they are assumed to be included with power circuit breakers. From purely economical considerations, fused switches generally have the lowest initial cost, followed by molded-case circuit breakers, with the power circuit breakers having the highest initial cost. All these devices are completely safe when properly applied and maintained.

When fused switches are used for the low-voltage switchboard section, the form of construction usually incorporates the panelboard type of arrangement shown in Figure 7.12(b), with one or more of these vertical panelboard sections being used as required. The standard ratings of general-use fusible switches are listed in Table 7.2. On all but the smallest ratings of unit substations, a power circuit breaker is usually used for the main secondary protection and disconnecting means ahead of the fused switches.

When molded-case breakers are used for the low-voltage switchboard section, the form of construction may incorporate the panelboard type of arrangement shown in Figure 8.10(b), with one or more of these vertical panelboard sections being used as required. As an alternative, the molded-case circuit breakers can be individually mounted in their vertical position, either singularly or in groups, with the operating handles extending through the front panels of the switchboard enclosure. The ratings of standard and high-interrupting capacity molded-case circuit breakers are listed in Table 8.1.

Drawout-type power circuit breakers are normally preferred on large systems, especially in industrial plants, because of the importance of the unit substation in the overall system. Power circuit breakers offer a wide selection of operating characteristics and adjustments, making it possible to obtain excellent coordination with other protective devices in the system. A typical drawout type of power circuit breaker is shown in Figures 8.11 and 8.12. The ratings of power circuit breakers are listed in Table 8.2, and those of the newer encased type of circuit breakers are listed in Table 8.3.

Individual power circuit breakers are installed in separate compartments so that the breakers are isolated from each other and from the bus. The breaker cubicles are designed on a modular basis so that combinations of cubicles and instrument panels can be mounted in 90 inch high vertical sections. These vertical sections are then joined together to form the overall switchboard unit. A typical cross section through a low-voltage switchboard is shown in Figure 15.7, indicating three breakers mounted one above the other and with an instrument panel at the top. Instruments can be ammeters, voltmeters, watt-hour meters, and so on. Also, where protective relays are used to control breakers (Chapter 9), these relays are also mounted in the instrument panel. This cross section shows a breaker in the connected position (compartment B), in the test position (compartment C), and in the disconnected position (compartment D). The test position allows the operation of the breaker to be checked without repeatedly making and breaking the power circuit to the branch circuit load.

Note the separate secondary contacts shown at the top of the breaker. These contacts are included on any electrically operated breaker where the control circuit has to be extended to remotely located control devices. The secondary contacts are still engaged in the test position, even though the main power disconnecting contacts have separated. Refer also to Figure 8.11, which shows a picture of a power circuit breaker in the fully connected position [part (a)] and in the fully withdrawn position [part (b)]. Figure 8.12 shows the disconnecting contacts on the rear of the breaker that engage with the fixed contacts in the breaker cubicle.

Figure 15.7 also shows the bus compartment, which contains the horizontal main bus that electrically ties the vertical sections together and the vertical bus that connects to the lineside of each individual breaker. There is then space at the rear of each section for the outgoing feeder cables. The main bus and tap connections usually consist of bare tin-plated aluminum bars. Copper bus with silver-plated connections, which is more expensive, is available as an option. Standard continuous current ratings for the main horizontal bus are 1600, 2000, 2500, 3000, and 4000 amperes. All the switchgear and bus work is rated for a maximum of 600 volts nominal. The main bus must also be properly braced to withstand the maximum possible fault current (see Section 6.2). The standard bus bracing rating is

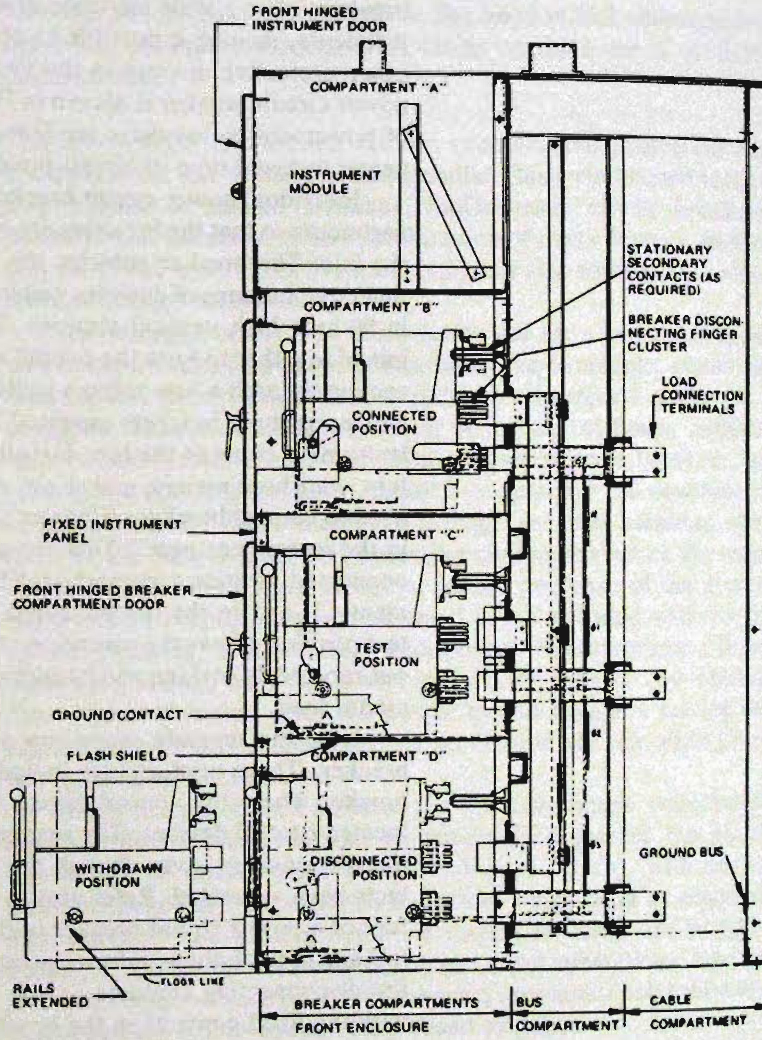
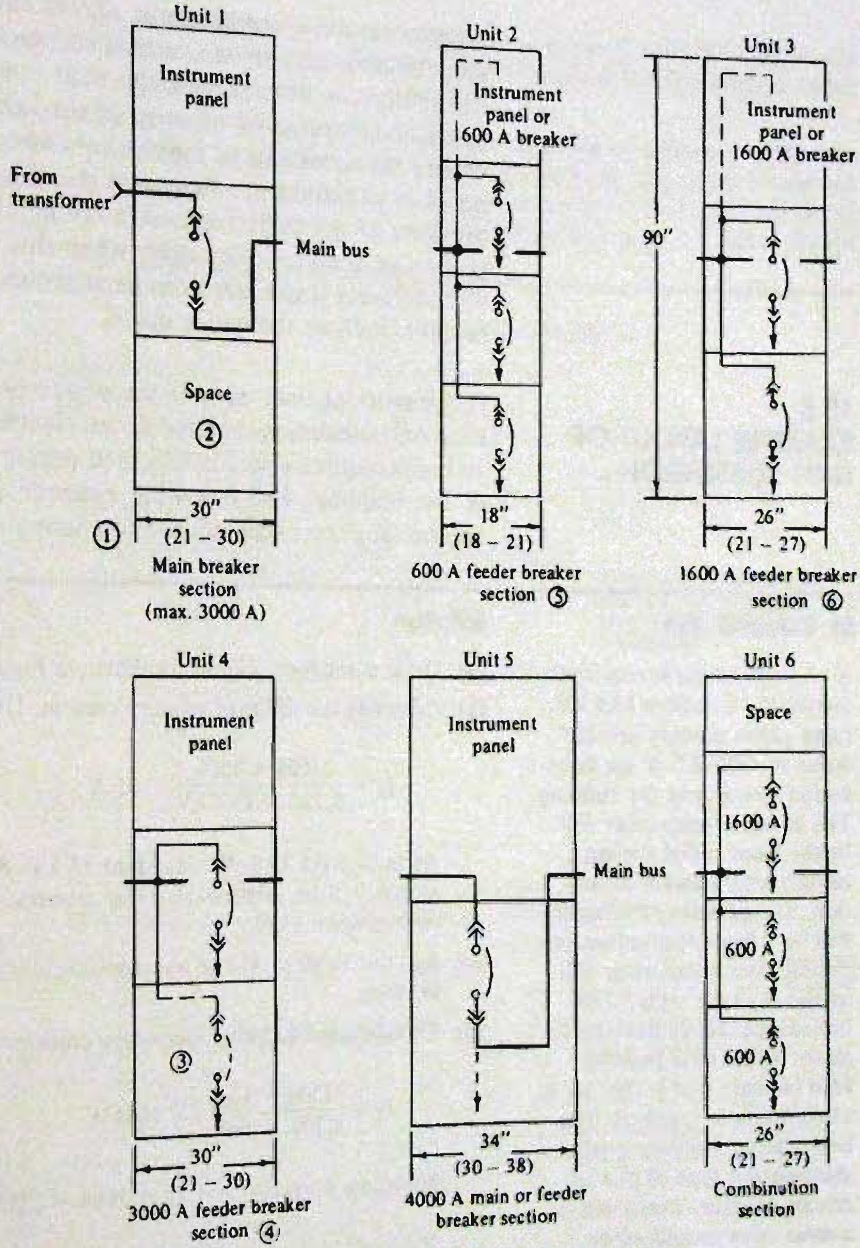


FIGURE 15.7

Cross section through typical low-voltage switchboard (refer also to Figure 8.11)

42,000 amperes symmetrical, with optional ratings of 65,000 and 85,000 amperes symmetrical being available. These continuous current and bus bracing ratings are typical, and each manufacturer should be consulted for the exact ratings that are offered.

A few of the possible modular stacking arrangements for the low-voltage power circuit breakers and associated instrument panels are shown in Figure 15.8. These diagrams are meant only to be representative arrangements, as there are variations in requirements between manufacturers. For example, unit 3 shows the 1600 ampere frame size breakers as being mounted in a three-high vertical ar-



Note: ① Dimensions in parentheses ( ) are possible ranges of section widths
② Some manufacturers may permit a feeder breaker in this space
③ Some manufacturers may permit only one 3000 A breaker per section
④ For 21 inch wide section, 3000 A breaker cubicle is 45 inches high
⑤ Also 800 A frame
⑥ Also 2000 A frame

FIGURE 15.8

Modular stacking arrangements for low-voltage circuit breaker switchboards rangement. One manufacturer allows this size of breaker to be mounted four high in one vertical section, providing that their total trip settings do not exceed a specified amount (1800 amperes). This restriction is required because of the accumulated heat produced under load conditions by the breakers when stacked four high. Other possible variations are shown on the diagram. Wherever possible, breakers of the same frame size are mounted in the same vertical section or sections. However, when this is not possible, breakers with different frame sizes can be accommodated in the one vertical section, such as shown for unit 6.

15.5 EXAMPLE LAYOUT OF UNIT SUBSTATION

It is important that, early in the design process, the overall size of each unit substation required for an electrical system be determined so that adequate space is allocated during the preliminary planning of the building. The following example illustrates the method of determining the expected size of a unit substation.

EXAMPLE 15.1

A unit substation is required to step the incoming 13.8 kV, three-phase primary service down to 480Y/277 V for distribution throughout the building. The circuit arrangement will be the basic radial system using a single-ended substation. The primary switchgear will be a fused load-interrupter switch. The transformer will be the dry-type with 5.75% impedance. Preliminary estimates of the total building load indicate that a 1500 kVA transformer is required. The low-voltage switchgear will be the drawout type of power circuit breaker. There will be a main breaker and seven feeder breakers to distribute the power throughout the building. The continuous loading on any one feeder breaker will be a maximum of 500 A. The calculated available fault current at the main secondary bus is 37,000 A symmetrical, which includes the contribu-

Solution

(a) Draw a one-line diagram as shown in Figure 15.9(a).

(b) Calculate the full-load primary current: Using Equation 1.14,

$$I_p = \frac{1500 \times 1000}{1.732 \times 13.8 \text{ kV}} = 63 \text{ A}$$

As in Section 15.2, the standard 15 kV, 600 A fused load-interrupter switch will be satisfactory. The primary switchgear cubicle is 36 in. wide (Figure 15.6).

(c) Refer to Table 15.1. The transformer cubicle for 15 kV, 1500 kVA is 100 in. wide.

(d) Calculate the full-load secondary current:

$$I_s = \frac{1500 \times 1000}{1.732 \times 480 \text{ V}} = 1804 \text{ A}$$

Minimum ampacity = 1.25 × 1804 = 2255 A (See Section 16.5)

Main bus: select standard rating of 2500 A (minimum).
Main breaker: from Table 8.2, select 3000 A frame with interrupting rating of 65,000 A symmetrical.
From Figure 15.8, select unit 1, 30 in. wide.

(e) Branch breakers: Referring to Table 8.2, it is noted that the 600 A frame breakers (as required for the expected continuous loading on each feeder) have an interrupting rating of only 30,000 A symmetrical at 480 V, whereas 37,000 A is available. Therefore, all branch breakers will have to be the 1600 A frame size with an interrupting rating of 50,000 A symmetrical and with trip ratings to suit feeder full-load currents. From tion from the motors. (Section 16.5 shows a complete example of the calculation of the available fault current.) Determine the layout of the unit substation.

Figure 15.8, three vertical units similar to unit 3, each 26 in. wide, are required for the seven 1600 A feeder breakers, leaving two spaces for future breakers.

(f) Draw the overall outline of the unit substation as in Figure 15.9(b). The overall depth of the unit is estimated to be 66 in. This depth is required for the low-voltage section to accommodate the 2500 A main bus and to provide sufficient space at the rear for the outgoing branch feeder cables.

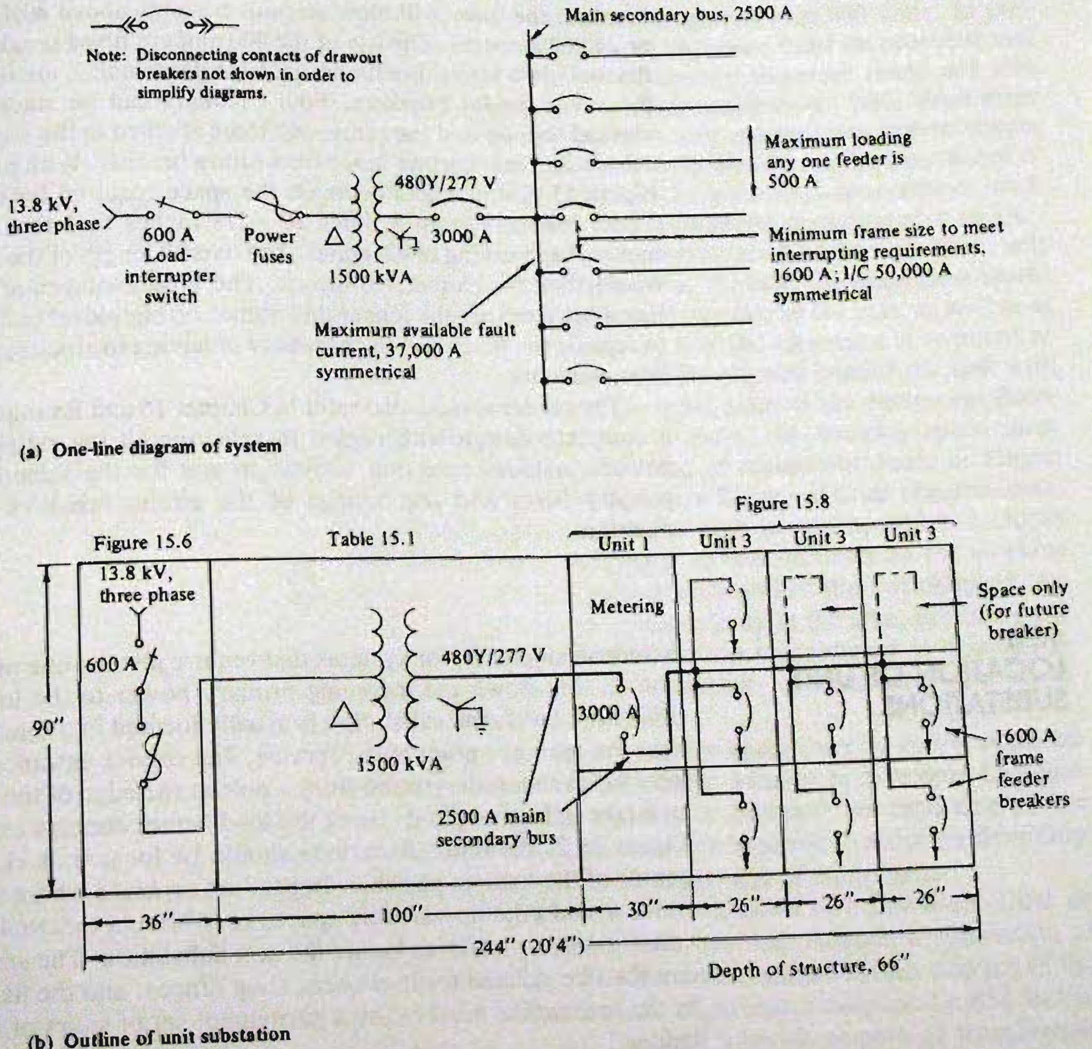


FIGURE 15.9

Layout of unit substation for Example 15.1

In the foregoing example layout of the unit substation, in place of using the 1600 ampere frame standard breakers, the combination fused circuit breakers could be selected. As described in Section 8.7, the addition of the current-limiting fuses increases the interrupting capacity of a breaker unit to 200,000 amperes, thus allowing the 600 ampere frame breakers to be used for the branch feeders. As shown in Figure 8.16, the breaker and fuse are coordinated so that the fuses blow to clear fault currents above approximately 80% of the interrupting rating of the breaker itself. Thus, with the 600 ampere breaker, the fuses will blow on fault currents above 80% of 30,000, or 24,000 amperes. The use of the 600 ampere fused breakers means that only two vertical sections, each similar to unit 2, are required for the seven feeder breakers. Four breakers can be stacked in one vertical section and the remaining three stacked in the second vertical section, leaving one space for a future breaker. With reference to Figure 15.9, this would decrease the space required for the branch feeder breakers from 3 times 26 = 78 inches to 2 times 18 = 36 inches, for a saving of 42 inches. The overall length of the substation would then be 16 feet, 10 inches. The disadvantages of using the fused breakers are the longer downtimes on high-level faults in order to replace the fuses and the necessity of having to stock replacement fuse elements.

The reader should also refer to Chapter 16 and Example 16.5 for a complete design with regard to selecting all the ratings for the devices installed in a unit substation and for the selection of the primary fuses and trip ratings of the circuit breakers for coordination.

15.6 LOCATION OF UNIT SUBSTATIONS

In industrial plants, for systems that require just the one unit substation to step down the incoming primary power to the low-voltage utilization level, the substation is usually located in a separate room near the entrance point of the service. The service entrance feeder is very often run underground from a pole at the edge of the property. In larger industrial plants using the load-center concept as shown in Figure 15.2, the unit substations should be located as close to the center of the load as possible. In production areas where a separate room would take up valuable space, very often a mezzanine area is constructed on which to locate the unit substation. The space below can then be utilized for tool cribs, shop offices, and the like. Access to the mezzanine must be by a permanent set of stairs or by a fixed ladder.

In larger commercial buildings that receive their power at above utilization levels (4.16 or 13.8 kilovolts) the unit substation is normally located in a separate room in the basement near the point of entry of the service feeder. In very tall office buildings, a second unit substation is usually located in the mechanical penthouse at the top of the building; some extremely tall buildings have additional units located at intermediate floors, again in mechanical equipment areas. These unit substations are then fed by medium-voltage feeders (4.16 or 13.8 kilovolts) from the primary switchgear located in the basement.

Sections 110-30 to 110-34 of the *National Electrical Code* govern the installation of electrical equipment over 600 volts. In particular, sufficient access and working space must be provided and maintained about all electrical equipment to permit ready and safe operation and maintenance of such equipment. With dead-front equipment, which is normal with unit substations, the minimum clear working space that must be maintained from the front panel of the unit to any adjacent vertical grounded surface (concrete or brick wall, metal fencing) is 5 feet for equipment operating at 4.16 kilovolts) and 6 feet for equipment operating at 13.8 kilovolts. Since unit substations have removable panels at the rear, the same clear working space must also be maintained at the rear of the unit, as well as at each end to provide access. Note that the clearance is required at both ends so that a person cannot be trapped behind the unit with only one way out should trouble arise, such as the equipment flashing over and arcing to ground. Finally, the working space must permit at least a 90-degree opening of equipment doors or hinged panels. See Appendix A for Canadian Electrical Code requirements.

For switchboards exceeding 6 feet in width, which includes most unit substations, there must be one entrance to the working space around the unit located at each end of the switchboard. An exception to this allows one entrance only to the area, providing the required working space in front of the switchboard is doubled or where the switchboard location permits a continuous and unobstructed way of exit travel.

Figure 15.10 shows the minimum space (size of room) required to accommodate the unit substation detailed in Example 15.1 and Figure 15.9. It would be prudent to increase the final size of the room or area above the minimum size required to allow for flexibility in design and space for future expansion of equipment.

The unit substation should be located in a dry area. Dust or corrosive atmospheres should be avoided. Adequate ventilation of the substation area must be provided to ensure proper cooling of the dry-type transformer. A typical requirement calls for 3 cubic feet of air movement per minute for each kilovolt-ampere of transformer capacity. Thus, for the unit substation in Example 15.1 and Figure 15.10, the minimum air movement for the substation area is three

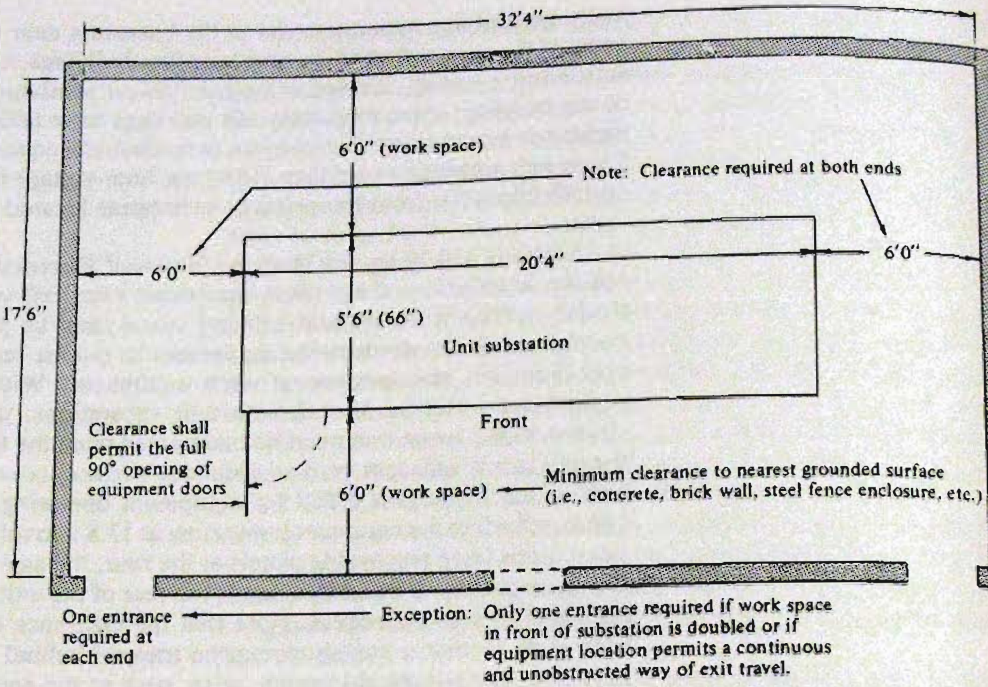


FIGURE 15.10

Space requirements for unit substation in Example 15.1

times 1500, or 4500 cubic feet per minute. Forced ventilation (a fan) is usually required to provide this air movement.

SUMMARY

- Unit substations offer a coordinated and integrated switchgear and transformer package, factory assembled and tested, requiring a minimum amount of labor for installation at the site.
- The radial system is generally the least expensive of the circuit arrangements and the easiest to operate, but it is the least reliable.
- The secondary selective system is more reliable and offers flexibility with regard to scheduled maintenance, but it costs more and is more difficult to operate.
- The primary selective system also is more reliable, but it costs more and a fault on the single substation transformer shuts down all load on that substation.
- The modern trend for large electrical systems is the use of the load-center system, which allows the power to be distributed at the highest economical voltage level.
- The load-interrupter switch and fuse assembly are widely used for the primary switchgear of unit substations.

- The load-interrupter switch can interrupt currents only up to its continuous current rating, normally either 600 or 1200 amperes.
- Lightning protection should be provided if the unit substation is supplied from a distribution system, any part of which runs overhead.
- Dry-type, air-cooled transformers are universally used in unit substations as they do not require any special fireproof vault construction.
- The low-voltage distribution section can utilize fusible switches, molded-case circuit breakers, power circuit breakers, or a combination of these devices.
- The fused switches generally have the lowest initial cost, followed by molded-case circuit breakers, with the power circuit breakers being the most expensive.
- The drawout power circuit breakers are normally preferred on large systems because of their wide range of operating characteristics.
- The overall size of the unit substation should be estimated early in the design stages so that adequate space can be allocated for its installation.
- Adequate working space must be provided around each unit substation to permit ready and safe operation and maintenance of the equipment.
- The substation area should be dry, free of dust and corrosive atmospheres, and adequately ventilated.

QUESTIONS

1. What are the advantages and disadvantages of the radial system?
2. What are the advantages of the load-center system?
3. Describe the secondary selective system.
4. What are the advantages and disadvantages of the secondary selective system?
5. With the secondary selective system, why must the tie breaker(s) be interlocked with the main secondary breakers so that the tie connection cannot be made unless one of the main breakers is open?
6. When is it necessary to block the automatic transfer of power in a secondary selective system?
7. What are the advantages and disadvantages of the primary selective system?
8. How much current can a load-interrupter switch safely interrupt?
9. Why is the load-interrupter switch referred to as being quick make, quick break?
10. Explain the make rating of a load-interrupt switch.
11. Why must the load-break switch have a momentary rating?
12. What is the significance of the BIL rating of equipment?
13. What is the basic function of a surge arrester?
14. Why are dry-type transformers normally used for indoor unit substations?
15. Why is the test position provided for drawout-type low-voltage circuit breakers?
16. What are the standard continuous current ratings and bus bracing ratings for the main bus of

the low-voltage distribution section of a unit substation?

17. What are the basic space requirements with regard to installing a unit substation in a room?

18. What is the requirement with regard to ventilation of the room housing a unit substation?

PROBLEMS

1. A unit substation has a 4.16 kV-480 V, three-phase, 1000 kVA transformer. Available fault current at the main secondary bus is 25,000 A symmetrical. Calculate the rated secondary current of the transformer and select the frame size of the main secondary breaker.
2. For the unit substation in Problem 1, select the frame size of a branch feeder breaker (low-voltage power type) if the continuous load on the feeder is 400 A.
3. A unit substation has a 4.16 kV-208Y/120 V, three-phase, 750 kVA transformer. Available fault current at the main secondary bus is 37,500 A symmetrical. Calculate the rated secondary current of the transformer and select the frame size of the main secondary breaker.
4. For the unit substation in Problem 3, select the frame size of a branch feeder breaker (low-voltage power type) if the continuous load on the feeder is 900 A.
5. Repeat Example 15.1, except that the incoming primary service is 4.16 kV, the secondary voltage is 208Y/120 V, the transformer is 1000 kVA, the number of feeder breakers is 10, the maximum loading on any one feeder is 400 A, and the available fault current is 50,800 amperes symmetrical.
6. Determine the minimum length and width of room required to house the unit substation of Problem 5.
7. Repeat Problems 5 and 6, except that combination fused circuit breakers will be used for the branch feeders.

16 Fault Calculations and System Coordination

OBJECTIVES

After studying this chapter, you will be able to:

- Calculate the per unit impedance of the utility system source.
- List the sources of short-circuit currents.
- Include the motor contribution to available fault currents.
- Calculate the equivalent system fault impedance.
- Calculate the effect of system components on fault currents.
- Calculate the per unit impedance of a feeder.
- Use rules of thumb to simplify fault calculations.
- Calculate fault currents at specific points on the system.
- Select the heater elements for motor starter overload relays.
- Coordinate the motor branch-circuit protective device with the overload relays.
- Follow the design of a complete system.
- Select the necessary settings for circuit breakers.
- Follow the coordination of a complete system.

INTRODUCTION

As discussed in the Preface, the primary function of the electrical system is to provide electrical energy to each piece of utilization equipment at the correct voltage and phase relationship and with sufficient capacity to supply the required current on a continuous basis, without any component overheating or causing unacceptable voltage drops. If only the normal operation of the system had to be considered, then the design of the system would be much simpler. However, since nothing that is manufactured can be deemed to be perfect, the system must also be capable of safely handling any abnormal situation that can arise. Therefore, an equally important aspect of the design of the system is the proper selection, application, and coordination of those devices that operate to protect the system when an abnormal condition does occur. The proper coordination of these protective devices ensures that any power outages due to faults on the system are restricted to as small a section of the system as possible and that any resulting damage is kept to an absolute minimum.

So far in this text, we have generally been looking at individual parts of the electrical system, such as substations, feeder cables, circuit breakers, fused disconnect switches, motor starters, panelboards, and branch circuits. In this last chapter, we will now concentrate on looking at the electrical system as a whole with respect to its ability to continuously handle the normal loads and to properly protect itself when an abnormal condition arises.

The reader should review Chapter 6 with regard to the priorities of system protection, the problems associated with electric faults, and the functions of protective devices in dealing with these faults. The reader should also review Section 7.7 on the coordination of low-voltage fuses and Section 8.6 on the coordination of circuit breakers, as these introduce the reader to the first applications of system coordination. The examples in this chapter expand on the basic methods of calculating fault currents and obtaining coordination between protective devices.

16.1 CALCULATION OF FAULT CURRENTS

The first step in providing adequate protection to a system is to calculate the magnitude of the available fault current at specific locations in the system. Protective devices such as fuses and circuit breakers must have sufficient capacity to safely interrupt the largest possible fault current that can occur at their location in the system. Other parts of the system, such as switches, feeder cables, bus duct, and bus bars, must be capable of withstanding the mechanical and thermal stresses associated with these large fault currents (Section 6.2).

The term *available fault current* means *the maximum current that can flow under the worst possible fault conditions*. Important assumptions in the fault calculations are that the fault itself is *bolted;* that is, it has zero impedance (see Section 6.3) and that it is a three-phase fault. These assumptions not only simplify the calculations but also add a margin of safety, as they result in the maximum possible fault current. Actual fault currents are usually less than the calculated three-phase bolted value. Bolted line-to-line fault currents are approximately 87% of the three-phase values. In industrial and commercial systems, bolted line-to-ground faults rarely exceed the three-phase values. Furthermore, absolutely zero impedance bolted faults seldom happen. Any degree of fault impedance will act to reduce the magnitude of the fault current. In fact, many faults involve arcing, which reduces the magnitude of the fault currents because of the relatively high resistance of the arc. Arcing faults and ground-fault protection are discussed in detail in Sections 10.4 and 10.5.

The reader is first introduced to fault current calculations in Chapter 6 and in particular in Section 6.4, where the concept of per unit values is developed. We will now expand on the examples in Section 6.4 to show how more complete fault calculations are done.

In Example 6.2, the primary utility feeder to the transformer is assumed to have an impedance of 1.0% (0.01 per unit). This value is obtained by comparing the system kVA with the maximum three-phase short-circuit kVA that the utility system can produce at the service entrance location. The equivalent per unit impedance of the utility system connection can then be obtained as follows:

$$Z_U = \frac{\text{base kVA}}{\text{short-circuit kVA}} \tag{16.1}$$

where Z_U = per unit impedance of the utility system.

base kVA = chosen system three-phase kVA (usually the transformer kVA)

short-circuit kVA = utility system three-phase symmetrical short-circuit capability

The short-circuit kVA value is provided by the local electric utility company.

EXAMPLE 16.1

Refer to Example 6.2 and Figure 6.2. The kVA rating of the transformer is 500 kVA. Assume that the utility system short-circuit capability is 50,000 kVA. Calculate the per unit impedance of the utility system.

Solution

The base kVA = 500 (the transformer rating). From Equation 16.1,

$$Z_U = \frac{500}{50{,}000} = 0.01 \text{ p.u.}$$

which agrees with the value used in Example 6.2.

16.1.1 Sources of Short-Circuit Currents

In the example calculations for the available fault current previously presented in Chapter 6, the only source considered was the electric utility system. However, other sources must also be considered, for example, in-house generators and all motors, both synchronous and induction types. As indicated in Figure 16.1, the available fault cur-

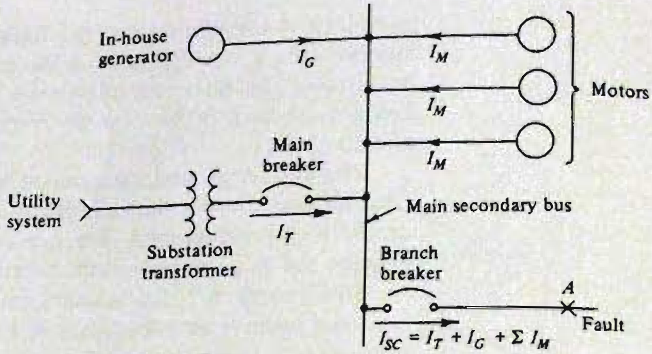


FIGURE 16.1

Sources of short-circuit currents

rent at point A is the total of the current I_T supplied from the utility system through the substation transformer, the current I_G supplied by the in-house generator (or generators), and the sum of all currents ΣI_M supplied by the motors. The feeder breaker protecting the faulted feeder must be able to safely interrupt the total current I_{SC}.

Large in-house generators are usually found only on very complex industrial systems. Their inclusion into the fault calculations is beyond the scope of this text. Small emergency standby generators are often included in building electrical systems. However, these generators usually serve only as a power source during power outages on the utility system connection. Then they only pick up emergency lighting and other such essential loads through throw-over switches. As such, they are never run in parallel with the substation transformer and therefore do not contribute to fault currents.

It would be easy to overlook motors as a source of power during fault conditions. The motor is normally thought of as a power user, not as a power source. At the instant that a bolted fault occurs on a system, the system voltage at that point collapses. Thus the voltage at the motor terminals also collapses. However, the inertia of the motors and their driven equipment keeps them turning, at least for a short time. In the case of synchronous motors, which have separate dc fields (see Section 2.4), the motor turns into a generator and begins to pump power back into the system. Induction motors do not have a separate dc field, but instead their excitation is provided by the main armature winding (see Section 2.5). However, the magnetic field that existed just prior to the collapse of the voltage cannot decrease to zero instantly, but takes several cycles to do so. Thus an induction motor becomes a generator for these few cycles. In the case of low-voltage systems, the circuit breakers interrupt the current within two cycles, and therefore the contributions from the induction motors must be included.

The precise calculations necessary to include the contribution from each motor are complex. Studies on typical low-voltage systems have indicated that the following rule-of-thumb method is satisfactory for most system fault calculations, probably erring on the side of safety. This method assumes that *the motor contribution to the fault current will be four times the full-load running current of each motor*. It is further assumed that, in the case of 480 and 600 volt systems, the connected motor load equals 100% of the system kVA. In effect, this means that the sum of the full-load running currents of all the motors equals the rated secondary current of the system transformer. In the case of 208Y/120 volt systems, it is not logical to assume a 100% motor load. This system is normally selected because a substantial part of the load is lighting and other nonmotor loads requiring 120 volt circuits. Therefore, for a 208Y/120 volt system, it is assumed that the motor load is 50% of the system kVA, meaning that the sum of the full-load running currents of all the motors is equal to 50% of the rated secondary current of the system transformer.

The following examples illustrate the application of these rule-of-thumb methods to calculating the available fault current. Because these calculations are based on assumptions, the results need not be taken to too many significant figures. All calculated values of fault current used in the examples in this chapter are rounded out to the nearest 100 amperes.

EXAMPLE 16.2

Power is supplied over a primary utility feeder to a 1000 kVA, 5.75% impedance transformer that steps down the voltage to 480Y/277 V for distribution throughout the building, as shown in Figure 16.2(a). The utility system short-circuit kVA capability is 250,000. Feeder 1 has a continuous load of 400 A. Determine the available short-circuit current at the main secondary bus and select the frame size for the feeder breaker (power type).

Solution

The base kVA = 1000 (rating of substation transformer). The rated voltage = 480 V (line-to-line), 277 V (line-to-neutral). Using Equation 1.14,

$$\text{rated secondary current} = \frac{1000 \times 1000}{1.732 \times 480\ \text{V}} = 1203\ \text{A}$$

Draw the equivalent single-phase fault circuit diagram [Fig. 16.2(b)]. From Equation 16.1,

$$Z_U = \frac{1000}{250{,}000} = 0.004\ \text{p.u.}$$

The total impedance of the source through the substation is:

$$Z_{UT} = Z_U + Z_T = 0.004 + 0.0575 = 0.0615\ \text{p.u.}$$

The current I_T through the transformer is

Using Equation 16.3, $I_T = \dfrac{E}{Z_{UT}} = \dfrac{1.0}{0.0615} = 16.26$ p.u.

Using Equation 16.4, $I_T = 1203 \times 16.26 = 19{,}600$ A

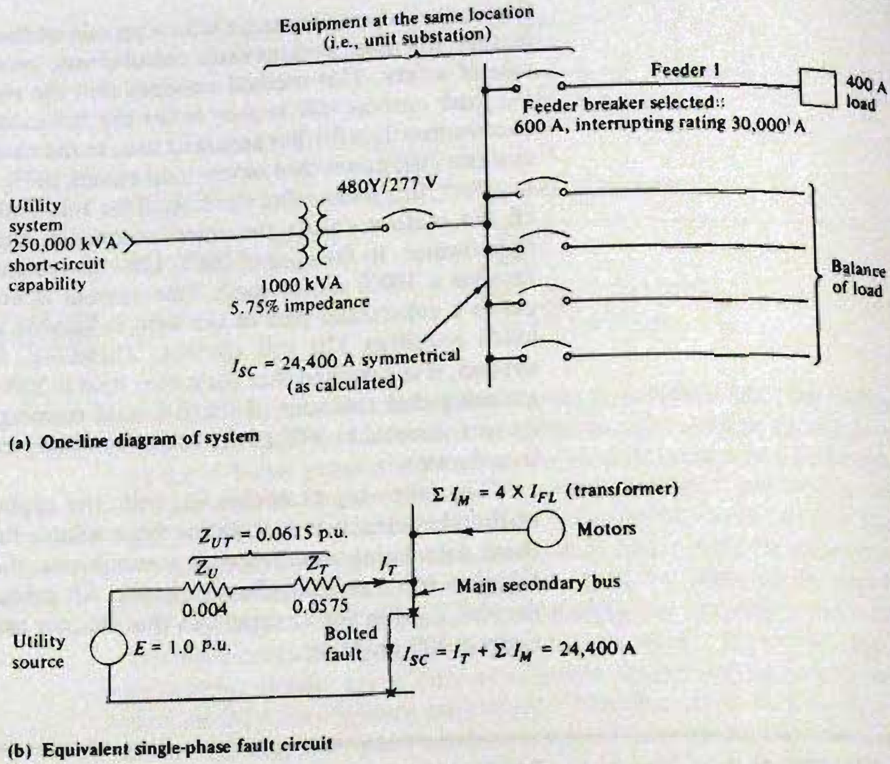


FIGURE 16.2

Diagrams for Example 16.2

The motor load is assumed to be 100%. The sum of all motor contributions is:

$$\Sigma I_M = 4 \times \text{rated current} = 4 \times 1203 = 4800 \text{ A}$$

Therefore, the total fault current is:

$$I_{SC} = I_T + \Sigma I_M = 19{,}600 + 4800 = 24{,}400 \text{ A symmetrical}$$

Refer to Table 8.2 for the ratings of the power type of circuit breaker. Select a 600 A frame size for the branch breaker since it can carry the 400 A continuous load on the feeder, and it has an interrupting rating of 30,000 A symmetrical at 480 V.

With respect to the foregoing example, assume that one of the branch feeders requires a 225 ampere rating for the continuous load, and molded-case circuit breakers are to be used. Refer to Table 8.1. for the ratings of molded-case breakers. The interrupting rating of the standard 225 ampere frame breaker is only 22,000 amperes symmetrical and would not be satisfactory on the basis of the preceding calculations. Had the motor contribution not been included, the standard 225 ampere breaker would appear to be satisfactory. As it is, either the 225 ampere high-interrupting capacity breaker (interrupting rating 25,000 A) or the 400 ampere standard breaker (interrupting rating 30,000 A) has to be used, both of which cost more.

EXAMPLE 16.3

Repeat Example 16.2 except that the secondary voltage is 208Y/120 V.

Solution

The per unit current supplied through the transformer is the same as previously calculated: $I_T = 16.26$ P.U.

$$\text{Rated secondary current} = \frac{1000 \times 1000}{1.732 \times 208 \text{ V}} = 2780 \text{ A}$$

$$I_T = 2780 \times 16.26 = 45{,}200 \text{ A}$$

The motor load is assumed to be 50%:

$$\Sigma I_M = 4 \times (0.5 \times 2780) = 5600 \text{ A}$$

$$I_{SC} = 45{,}200 + 5600 = 50{,}800 \text{ A symmetrical}$$

From Table 8.2, the smallest frame size that can be used is 1600 A, which has an interrupting rating of 65,000 A symmetrical at 208 V (if instantaneous tripping of the breaker is used).

Note the significant increase in the available fault current in Example 16.3 as compared to Example 16.2. Another characteristic of 208Y/120 volt systems is the problem with high available fault currents, indicating again the desirability of keeping the voltage level at which power is distributed throughout a building as high as possible. Where 208Y/120 volts is required for utilization equipment, substations should be kept down to a reasonable size.

16.2 EFFECT OF SYSTEM COMPONENTS ON FAULT CURRENTS

The kVA rating of the substation transformer has a significant effect on the magnitude of the available fault current on the low-voltage system. This can best be illustrated by the following example.

EXAMPLE 16.4

Repeat Example 16.2, except that the transformer rating is 2000 kVA.

Solution

Base kVA = 2000

$$\text{Rated secondary current} = \frac{2000 \times 1000}{1.732 \times 480 \text{ V}} = 2405 \text{ A}$$

$$Z_U = \frac{2000}{250{,}000} = 0.008 \text{ p.u.}$$

$$Z_{UT} = 0.008 + 0.0575 = 0.0655 \text{ p.u.}$$

$$I_T = \frac{1.0}{0.0655} = 15.27 \text{ p.u.}$$

$$I_T = 2405 \times 15.27 = 36{,}700 \text{ A}$$

$$\Sigma I_M = 4 \times 2405 = 9600 \text{ A}$$

$$I_{SC} = 36{,}700 + 9600 = 46{,}300 \text{ A symmetrical}$$

Note that the available fault current has nearly doubled as compared to that calculated in Example 16.2. This means that the 600 ampere frame size for the feeder breaker is no longer satisfactory, as it does not have sufficient interrupting capacity. A 1600 ampere frame breaker with an interrupting rating of 50,000 amperes has to be used, even though the load on the breaker remains at 400 amperes. A minimum frame size of 1600 amperes must be used for all branch breakers in the substation at a considerable increase in cost. Once again the alternative is to consider the use of the combination fused circuit breakers with current-limiting fuses (Section 8.7).

The selection of circuit breakers involves two ratings, the frame size and the trip rating. Refer to Section 8.3.1 for an explanation of these ratings. The frame size of the breaker is selected to satisfy both the continuous (load) current and the fault interrupting requirements, as shown in the previous examples. On the other hand, the trip rating of the breaker is selected to provide proper overcurrent protection for the feeder, and it remains the same regardless of the change in frame size. See Section 11.8 on the overcurrent protection of feeders.

Examples 16.2 and 16.4 show the significant effect that the substation transformer kVA *rating* has on the available fault current on the low-voltage system. Note that the magnitude of the load on feeder 1 has no effect on the magnitude of the available fault current at the location of the feeder circuit breaker. Conversely, the size of the transformer has no effect on the feeder load. It will draw 400 amperes regardless of whether it is fed through a 1000 or 2000 kVA transformer. Indirectly, the load on each feeder does of course have an effect in that these loads in total dictate the size of the transformer required.

The selection of kVA ratings of substation transformers is very critical in establishing the levels of available fault current on the secondary side of the substation. In large systems, it may be advantageous to split up the loads between several smaller substations to reduce the available fault current levels (see Section 15.1.2 on load-center systems).

Referring again to the previous examples of fault current calculations, note that the impedance of the transformer is the main factor in limiting the magnitude of the fault current available on the low-voltage section of the system, especially at points close to the substation. If the impedance of the transformer is materially reduced, the level of available fault current rises accordingly, as shown in the following example.

EXAMPLE 16.5

Repeat Example 16.2, with the exception that the impedance of the transformer is 3.0%.

Solution

$$Z_{UT} = 0.004 + 0.030 = 0.034 \text{ p.u.}$$

$$I_T = \frac{1.0}{0.034} = 29.4 \text{ p.u.}$$

$$I_T = 1203 \times 29.4 = 35{,}400 \text{ A}$$

$$\Sigma I_M = 4800 \text{ A} \quad \text{(no change)}$$

$$I_{SC} = 35{,}400 + 4800 = 40{,}200 \text{ A symmetrical}$$

Note the significant increase in the available fault current as compared to Example 16.2. This means that the interrupting capacity of the 600 A frame breaker is insufficient, and the 1600 A frame has to be used, considerably increasing the cost of the breakers.

Because of the importance of the transformer impedance in limiting the available fault current, substation transformers are designed on purpose to have impedances of at least 5.0%, with a typical value being 5.75%. This high impedance is obtained by increasing the leakage reactance of the transformer windings, rather than their resistance. Higher-resistance windings would increase the heat losses in the transformer, which is not desirable. Refer to Example 6.3, which shows the typical ratio of the reactance to the resistance of transformer windings. Note that the reactance is by far the more important parameter of the total impedance of the transformer. The impedance of the transformer, however, cannot be made too high; otherwise, its secondary voltage would vary excessively under normal loading conditions because of internal voltage drop. The expected percentage impedance of each substation transformer to be installed on a system should always be specified as part of the ordering information.

16.3 EFFECT OF FEEDER IMPEDANCES ON FAULT CURRENTS

The previous examples calculated the available fault current immediately adjacent to the secondary terminals of the substation transformer. At that location, the only limiting factors for the fault current are the impedance of the primary feeder and the substation transformer. It is necessary to also calculate available fault currents at other locations on the system that are some distance from the substation, such as at power panels and motor-control centers. The impedance of the feeder cables acts to further limit the available fault current at these locations and therefore must be included in calculating the total impedance up to the point of the fault.

Table 16.1 lists the ac resistance and inductive reactance of three-phase feeders consisting of three single 600 volt copper conductors installed in one run of conduit. As with the impedances of other system components previously included in the fault calculations, the resistance and reactance of the conductors must be converted into per unit values. The reader at this time should review

TABLE 16.1 AC Resistance and Inductive Reactance of 600 V Cables, Three-Phase, 60 Hz, 75°C, Three Single *Copper* Conductors in Conduit

Wire Size, AWG or MCM	Ohms per 1000 Feet, Line to Neutral			
	AC Resistance (R_{ac})		Inductive Reactance (X_L)	
	Aluminum Conduit	Steel Conduit	Aluminum Conduit	Steel Conduit
2	0.20	0.20	0.045	0.057
1	0.16	0.16	0.046	0.057
1/0	0.13	0.12	0.044	0.055
2/0	0.10	0.10	0.043	0.054
3/0	0.082	0.079	0.042	0.052
4/0	0.067	0.063	0.041	0.051
250 MCM	0.057	0.054	0.041	0.052
300 MCM	0.049	0.045	0.041	0.051
350 MCM	0.043	0.039	0.040	0.050
400 MCM	0.038	0.035	0.040	0.049
500 MCM	0.032	0.029	0.039	0.048

For a complete set of values, including those for aluminum conductors, see *NEC* Table 9, Chapter 9.

Section 6.4 with particular reference to the term *base impedance*. Equation 6.1 shows how the base impedance of a system is calculated. Note that the rated line-to-neutral voltage of the system must be used in this calculation. This is necessary as the fault calculations for a three-phase system are simplified by equating it to a single-phase system and using phase-to-neutral values. Note that in Table 16.1 the heading indicates that the values of the resistances and reactances are *line to neutral*. Equation 6.2 shows how the actual value in ohms is changed to a per unit value. Using these equations, the following example shows how to calculate the per unit values for a feeder.

EXAMPLE 16.6

A three-phase feeder consisting of three 250 MCM copper conductors in a steel conduit is 100 ft in length. The capacity of the transformer supplying the feeder is 1000 kVA and the system is 480 V. Calculate the per unit resistance and reactance of the feeder.

Solution

Base kVA = 1000 kVA

Rated voltage = 480 V (line to line), 277 V (line to neutral)

Rated secondary current = 1203 A (see Example 16.2)

From Table 16.1, the resistance and reactance of 250 MCM copper conductors in steel (magnetic) conduit are:

$$R_{ac} = 0.054\ \Omega/1000\ \text{ft}, \qquad X_L = 0.052\ \Omega/1000\ \text{ft}$$

The resistance and reactance for 100 ft are then:

$$R_{ac} = \frac{0.054 \times 100}{1000} = 0.0054\ \Omega, \qquad X_L = \frac{0.052 \times 100}{1000} = 0.0052\ \Omega$$

Using Equation 6.1,

$$\text{Base impedance} = \frac{277}{1203} = 0.23\ \Omega$$

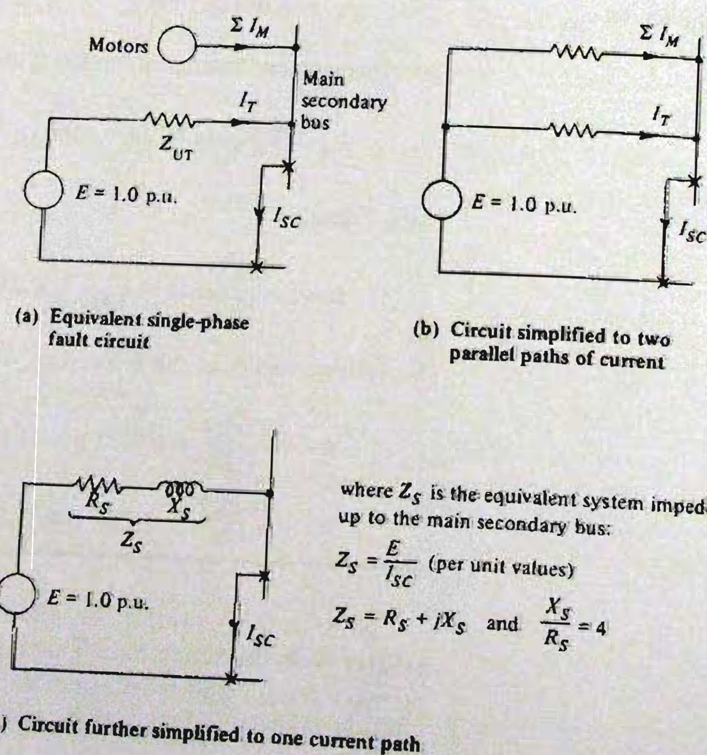
The per unit values of the feeder are, using Equation 6.2,

$$R_F = \frac{0.0054}{0.23} = 0.0235\ \text{p.u.} \quad (2.35\%)$$

$$X_F = \frac{0.0052}{0.23} = 0.0226\ \text{p.u.} \quad (2.26\%)$$

Note in this example that the resistance of the feeder is slightly greater than the reactance. This is contrary to the situation with the primary feeder and substation transformer, in which case the reactance is many times that of the resistance. In previous examples, the total system impedance was calculated by simply adding the numerical value of each impedance. While this is not strictly correct, the error introduced is small. Now, however, if the impedance of the feeder, with its high component of resistance, is simply added arithmetically to the system impedance, which is largely reactive, a significant error will occur, unfortunately in the wrong direction. It would give a larger value of overall impedance than is actually the case, resulting in a calculated value of available fault current that is low. Therefore, account must now be taken of the resistance of the system up to the source of the feeder. The following rule of thumb is adopted as a satisfactory means of adjusting to this problem. This rule assumes *that the resistance of the system is 25% that of the reactance of the system.*

An equivalent impedance of the system has to be determined so that it can be broken down into its respective resistance and reactance components. Refer to Figure 16.3. Part (a) shows the typical equivalent single-phase circuit as previously used to solve for the fault current at the main secondary bus of the substation. The path for the current I_T and the path for the current ΣI_M can be considered to be in parallel, as shown in part (b). This then permits the two parallel paths to be combined into one equivalent system impedance



where Z_S is the equivalent system impedance up to the main secondary bus:

$$Z_S = \frac{E}{I_{SC}} \quad \text{(per unit values)}$$

$$Z_S = R_S + jX_S \quad \text{and} \quad \frac{X_S}{R_S} = 4$$

FIGURE 16.3

Reducing system to one equivalent fault impedance

Z_S, as shown in part (c), such that:

$$\text{per unit } Z_S = \frac{E(\text{p.u.})}{I_{SC}(\text{p.u.})} \tag{16.2}$$

From the previously stated rule-of-thumb:

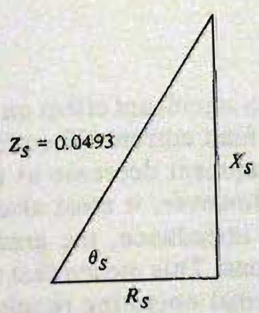
$$Z_S = R_S + jX_S, \qquad \text{where } X_S/R_S = 4 \tag{16.3}$$

(The reader should review Section 1.4.3).

The following example illustrates the method of including the effect of a feeder in the calculations for the available fault current.

EXAMPLE 16.7

Combine Example 16.2 with Example 16.6 as shown in Figure 16.4. Determine the available fault current at the power panel being supplied by the feeder.



Solution

From previous calculations in Example 16.2, the available fault current at the main secondary bus is 24,400 A and the rated current is 1203 A. Therefore, the per unit fault current is:

$$I_{SC} = \frac{24{,}400}{1203} = 20.3 \text{ p.u. (at main secondary bus)}$$

Using Equation 16.2,

$$Z_S = \frac{1.0}{20.3} = 0.0493 \text{ p.u.}$$

From Equation 16.3,

$$R_S + jX_S = 0.0493 \quad \text{and} \quad X_S/R_S = 4$$

$$\text{Tan } \theta_S = 4/1, \quad \theta_S = 76°$$

$$R_S = 0.0493 \times \cos 76° = 0.0119 \text{ p.u.}$$

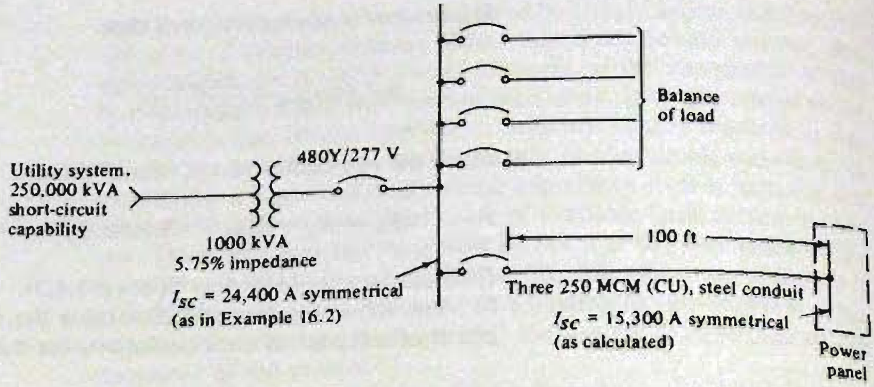
$$X_S = 0.0493 \times \sin 76° = 0.0478 \text{ p.u.}$$

From Example 16.6, the values for the feeder are:

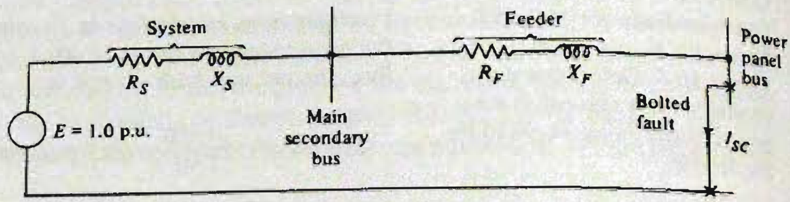
$$R_F = 0.0235 \text{ p.u.} \quad \text{and} \quad X_F = 0.0226 \text{ p.u.}$$

$$\begin{aligned} Z \text{ (total)} &= (R_S + R_F) + j(X_S + X_F) \\ &= (0.0119 + 0.0235) + j(0.0478 + 0.0226) \\ &= 0.0354 + j0.0704 = 0.0788 \text{ p.u.} \end{aligned}$$

$$\begin{aligned} I_{SC} &= \frac{1.0}{0.0788} = 12.7 \text{ p.u.} \\ &= 1203 \times 12.7 = 15{,}300 \text{ A symmetrical} \quad \text{(at power panel)} \end{aligned}$$



(a) One-line diagram



(b) Equivalent single-phase fault circuit

FIGURE 16.4

Diagrams for Example 16.7

Note that the 100 feet of feeder has a significant effect on further limiting the magnitude of the available fault current. Therefore, the short-circuit duty requirements for equipment decrease as the distance from the substation increases. However, it must also be remembered that the greater the feeder impedance, the greater the voltage drop under normal load conditions. This means that there is always a compromise between the normal operating requirements and the desire to limit the available fault currents.

16.4 SELECTION AND COORDINATION OF MOTOR PROTECTION

The purpose of this section is to outline the method of selecting the proper rating of the thermal sensing (heater) elements of the overload relays for a motor starter and then to show how the motor branch circuit protective device (fuse or breaker) is coordinated with this overload protection. The operation of magnetic starters is described in Section 14.2. Figure 14.2(a) shows the connection diagram for a three-phase full-voltage starter, including the three overload relays. Figures 14.2(b) and (c) show how the relay contacts are connected in series with the starter coil such that the release of any overload contact de-energizes the coil and opens the starter to stop the motor.

The most common thermal-responsive relays are the bimetallic and the eutectic-solder types. The bimetallic relay has a bimetal strip that is heated by the passage of the motor current through the heater element. If the current is excessive, the heat eventually deflects the bimetal strip to the point where it releases the normally closed relay contact. The eutectic-solder relay uses an alloy that melts at a specific temperature. The alloy is heated by the passage of the motor current through the heater element. When the alloy melts, because of an excessive motor current, it allows a ratchet to turn, thus releasing the normally closed relay contact.

Both types of relays have an inverse time–current characteristic (Section 6.7). Industry standards designate an overload relay by a class number indicating the maximum time in seconds at which it will trip when carrying 600% of its rated current. A class 10 relay will trip in 10 seconds or less, a class 20 in 20 seconds or less, and a class 30 in 30 seconds or less. The class 20 relay is used for general applications where the accelerating time of the motor is normal. Figure 16.5 shows the typical time–current curves of class 20 and class 30 overload relays. The curves are plotted with the time in seconds on a log scale against the percentage of current of the relay on a linear scale.

Table 16.2 lists typical ratings for overload relay heater elements. The heater type number is selected using the full-load amperes nearest to the actual full-load current shown on the nameplate of the motor. The rated current of the relay in amperes at 40°C is 115% of the full-load amperes listed for the heater type number. Note that the heater type numbers shown in the left column are the manufacturer's designation. Each manufacturer has his own form of heater designation and ranges of heater ratings. The precise current ratings of the heater elements depend on many factors, such as the number of heater elements in a starter, type of starter enclosure, and whether the starter is a combination type using circuit breakers or fuses. It is necessary to follow the manufacturer's complete set of recommendations before the final heater selection is made.

The following example illustrates the method recommended by the manufacturer for the selection of the correct heater element from Table 16.2 for the situation where the ambient temperature is the same for both the starter and the motor.

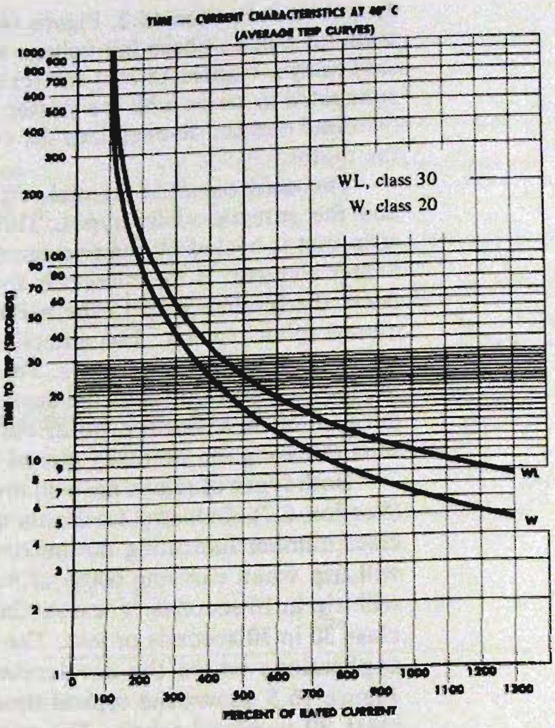


FIGURE 16.5

Typical time–current characteristic curves for motor overload relays

■ EXAMPLE 16.8

Refer to Example 13.1, which shows the design of a motor branch circuit for a 40 hp, 460 V, three-phase motor, service factor 1.15, and with a nameplate full-load current of 50 A. Select the heater type number and calculate its rated current.

Solution

From Table 14.1, a size 3 starter is required. From Table 16.2, select the manufacturer's heater type No. W69, listed for full-load amperes of 52.0 (nearest to 50 A). The rated current of overload relay is $1.15 \times 52.0 = 59.8 \approx 60$ A. Note that this is less than the maximum allowed by code as calculated in part (3) of Example 13.1.

We will next show how the motor branch-circuit protective device should coordinate with the overload relay just selected. Previous examples of coordination between protective devices have been for devices with similar characteristics (see Section 7.7 for fuses and Section 8.6 for circuit breakers). The following is then an example of coordination between devices with different response characteristics.

First, however, review Section 13.1.1 with regard to the func-

TABLE 16.2 Typical Ratings of Overload Heater Elements for Three-Phase Magnetic Motor Starters

Heater Type Number	Full Load Amps.				
	Size 0	Size 1	Size 2	Size 3	Size 4
W40	3.04	3.04			
W41	3.34	3.34			
W42	3.68	3.68			
W43	4.04	4.04			
W44	4.46	4.46			
W45	4.94	4.94	5.13		
W46	5.46	5.46	5.64		
W47	6.03	6.03	6.22		
W48	6.65	6.65	6.85		
W49	7.33	7.33	7.56		
W50	8.13	8.13	8.45		
W51	8.95	8.95	9.32		
W52	9.90	9.90	10.3	10.4	
W53	10.7	10.7	11.3	11.4	
W54	11.7	11.7	12.3	12.5	
W55	12.8	12.8	13.4	13.7	
W56	14.0	14.0	14.5	15.1	
W57	15.3	15.3	15.8	16.7	
W58	16.2	16.2	16.7	18.4	19.0
W59	17.5	17.5	18.0	20.3	21.0
W60	19.4	19.4	19.9	22.5	23.1
W61	....	21.3	21.9	24.8	25.5
W62	....	23.3	24.2	27.2	28.0
W63	....	25.5	26.8	30.0	31.0
W64	....	27.2	28.7	33.0	34.0
W65	....	....	31.0	36.0	37.0
W66	....	....	33.5	39.5	40.0
W67	....	....	36.0	43.5	44.0
W68	....	....	38.5	47.5	48.5
W69	....	....	41.5	52.0	53.0
W70	....	....	45.0	56.0	57.0
W71	....	....	....	60.0	62.0
W72	....	....	....	65.0	67.0
W73	....	....	....	69.0	72.0
W74	....	....	....	74.0	77.0
W75	....	....	....	79.0	82.0
W76	....	....	....	85.0	87.0
W77	....	....	....	91.0	93.0
W78	....	....	....	....	99.0
W79	....	....	....	....	105
W80	....	....	....	....	112
W81	....	....	....	....	117
W82	....	....	....	....	123
W83	....	....	....	....	129
W84	....	....	....	....	135
W85	....	....	....	....	....

Heater Type Number	Full Load Amps.				
	Size 5	Size 6	Size 7	Size 8	Size 9
W29	74	144	240	360	600
W30	81	157	261	390	650
W31	88	171	285	430	710
W32	97	186	310	465	780
W33	106	209	340	510	850
W34	115	222	370	555	920
W35	126	242	405	610	1020
W36	138	268	445	670	1120
W37	151	294	490	740	1220
W38	165	325	540	810	1350
W39	180	355	590	890	1480
W40	197	390	650	970	1620
W41	215	430	710	1070	1780
W42	235	470	780	1170	1960
W43	256	515	860	1290	2150
W44	281	560			2360

Ratings from 0.18 A to 2.76 A for size 1 and 2 starters are not shown.

Ratings apply to starters mounted in standard enclosures.

For size 5 starters and above, overload relays are connected through current transformers.

Consult manufacturer for complete listing of heater ratings and for complete set of recommendations with regard to selection of heater type number.

tion of motor branch-circuit short-circuit and ground-fault protection and Section 13.1.2 with regard to motor overload protection. In particular, Figure 13.4 shows the relationship between the overload device and the motor starting and running currents. The overload relay in the motor starter should operate first to shut down the motor for any excess currents up to the locked-rotor (starting) current of motor. This locked-rotor current is typically 600% of the full-load running current of the motor. Any current in the motor circuit that exceeds 600% can only be as the result of a fault in the motor windings or the circuit itself, in which case the circuit should be interrupted as soon as possible. Thus, the response of the circuit protective device should be such that it operates first to clear any current in excess of the 600%.

For a coordination study, the response curves of the various devices must be copied on one common graph so that they may be compared at all current and time points. The best way to do this is to use the industry standard log–log graph paper, such as shown in Figure 16.6 (which is reduced to approximately 60% of its actual size). A typical log–log graph sheet is K and E No. 48-5258, which is available in drafting supply outlets. The vertical axis represents time and consists of a five-decade scale ranging from 0.01 to 1000 seconds. The horizontal axis represents current and consists of a four-and-a-half-decade scale ranging from 0.5 to 10,000 amperes. The current scale can be shifted for a particular graph by modifying the current scale by a factor of times 10, 100 ($\times 10$, $\times 100$), and so on. Time–current characteristic curves of fuses and circuit breakers, prepared on full-size transparencies, are available from most manufacturers of the devices. An overlay can then be made by tracing the manufacturer's curves onto one single sheet, making sure that both the time and current scales are lined up properly. The following example shows the method of plotting various devices on the one graph to check their coordination.

EXAMPLE 16.9

Select the minimum rating for the following overcurrent devices when used for the motor branch circuit as in Examples 13.1 and 16.8:

(a) Nontime-delay fuses

(b) Time-delay dual-element fuses

(c) Circuit breaker with inverse time-delay element

Solution

The characteristic curve for the overload relay as selected in Example 16.8 must first be plotted on the standard log–log graph paper using the curve shown in Figure 16.5. Since this particular set of curves is not drawn on the industry standard form of graph, points must be selected from this graph for plotting on the standard log–log graph. Also, since the horizontal scale is in percent of rated current, the actual current for each point must be calculated on the basis that the 100% rating of the W69 heater element in Example 16.8 is 60 A. The following table shows the points selected from the curve for the type W (Class 20) heater element:

Percent of Rated Current	Actual Current (A)	Time (s)
100	60	Infinity
200	120	85
300	180	40
400	240	24.5
500	300	16.8
600	360	12.8
800	480	8.3

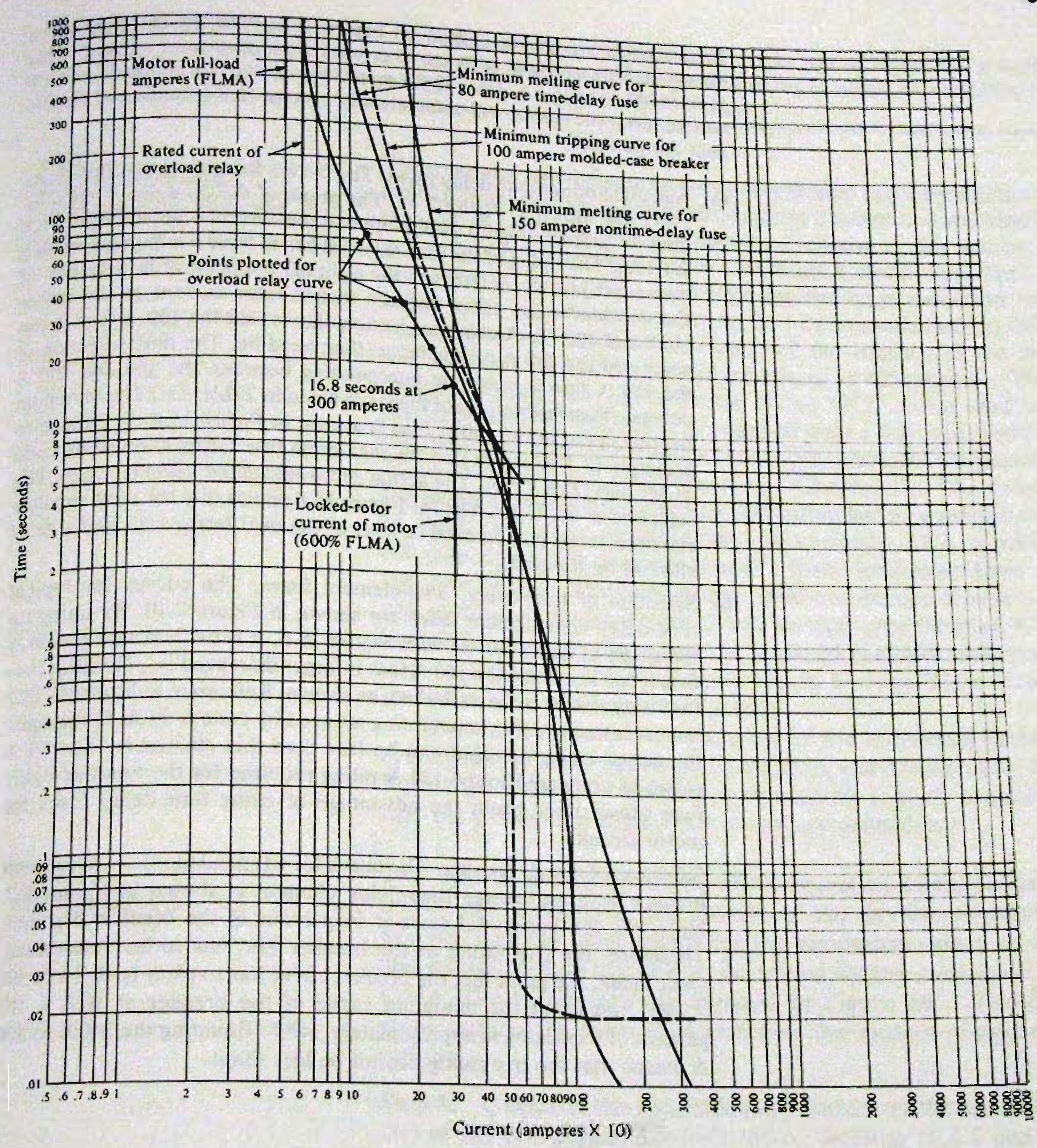


FIGURE 16.6

Time–current curves for motor branch-circuit protection as outlined in Example 16.9

These points are shown plotted on Figure 16.6, with the resulting curve drawn in. This overload relay curve crosses the locked-rotor current of the motor (300 A) at 16.8 s. Thus, if the motor fails to start (is jammed so that it cannot turn), the starter will automatically open in 16.8 seconds and disconnect the power.

(a) Selection of nontime delay fuses: The curves for typical nontime-delay fuses are shown in Figure 7.11. The graph of these curves is lined up with the graph in Figure 16.6. Note that the current scale in Figure 16.6 is (×10). The rating of the fuse selected has to have a minimum melting curve that just clears (stays to the right of) the point of intersection of the overload relay curve and the locked-rotor current of the motor (16.8 s at 300 A). A quick inspection shows that the 100 A fuse is too small and the 200 A fuse is larger than need be. The final selection of the 150 A fuse is made by interpolating between the 100 and 200 A curves. (Standard ratings of fuses are listed in Table 7.1.) The minimum melting curve of the 150 A fuse is shown in Figure 16.6. Reference to Example 13.1 indicates that the maximum fuse rating allowed by code as per part (2) is 175 A. The actual 300% calculated value is 156 A. The selection of the 150 A fuse for Figure 16.6 shows that the next smallest standard rating can be used instead of the next larger standard size as allowed by the code.

(b) Selection of time-delay, dual-element fuses: The curves for typical time-delay dual-element fuses are shown in Figure 7.10. By lining up the graph of these curves with Figure 16.6, it is evident that the 60 A fuse is too small and the 100 A fuse is larger than need be. The 80 A fuse (as interpolated) is then selected, as shown. Reference to Example 13.2 indicates that the maximum rating allowed by code is 90 A. Once again the actual rating selected can be less than this maximum. The 80 A rating as compared to the 150 A rating required for the nontime-delay fuse shows once again the advantage of using time-delay fuses for motor circuits.

(c) Selection of circuit breaker: The curve for a typical molded-case circuit breaker with an inverse time-delay element is shown in Figure 8.7. Note that the horizontal scale is in percent of the breaker trip unit. Therefore, the trip rating of the breaker first has to be determined. Once again, the point that the breaker curve has to clear is 16.8 s at 300 A. By looking at the minimum curve of the breaker at 16.8 s, the percent of trip rating is approximately 340%. Equating the 340% to 300 A means that the trip rating cannot be less than:

$$\frac{300}{3.4} = 88 \text{ A}$$

From Table 8.1, the next highest trip rating is 90 A, but to be on the safe side a rating of 100 A is selected, as reference to Example 13.3 indicates that the maximum rating permitted by code is 150 A. The method of plotting breaker curves on a current basis is shown in Section 8.6 and

Figure 8.14. For Figure 16.6, the 100% line of Figure 8.7 is lined up with the 100 A line (the trip rating of the breaker). The resulting minimum curve of the breaker is shown.

16.5 DESIGN OF AN ELECTRICAL SYSTEM

The example now presented covers the design and coordination of a system starting from the branch circuit of a motor and working back through the system to the primary switchgear at the source. The system is shown in Figure 16.7. The branch circuit supplies a 150-horsepower, three-phase, 460 volt squirrel-cage induction motor, which is the largest motor fed from the motor-control center (MCC). The sum of the full-load currents from the balance of the motors connected to the MCC has been calculated at 425 amperes. With all motors running, the power factor of the MCC motor load is estimated to be 85%. The MCC is supplied over a 200 foot feeder from the main unit substation which has a 1500 kVA, 5.75% impedance, 13,800-480Y/277 volt transformer (see Chapter 15). The balance of the feeders connected to the unit substation has a combined demand of 1000 kVA. The utility system short-circuit kVA capability is 500,000. The primary switchgear is a fused load-interrupter switch (Section 15.2.1). The low-voltage main and feeder breakers at the unit substation are the power circuit breaker type (Section 8.5). The branch breaker for the motor circuit is the molded-case type (Section 8.4). The feeder conductors are to be type THW copper installed in steel conduit above grade.

The design procedures for most of the individual parts of the system are covered in preceding sections and examples in the text. Reference to the relevant section or example is made at each step so that the reader can review the necessary procedures.

16.5.1 Calculations

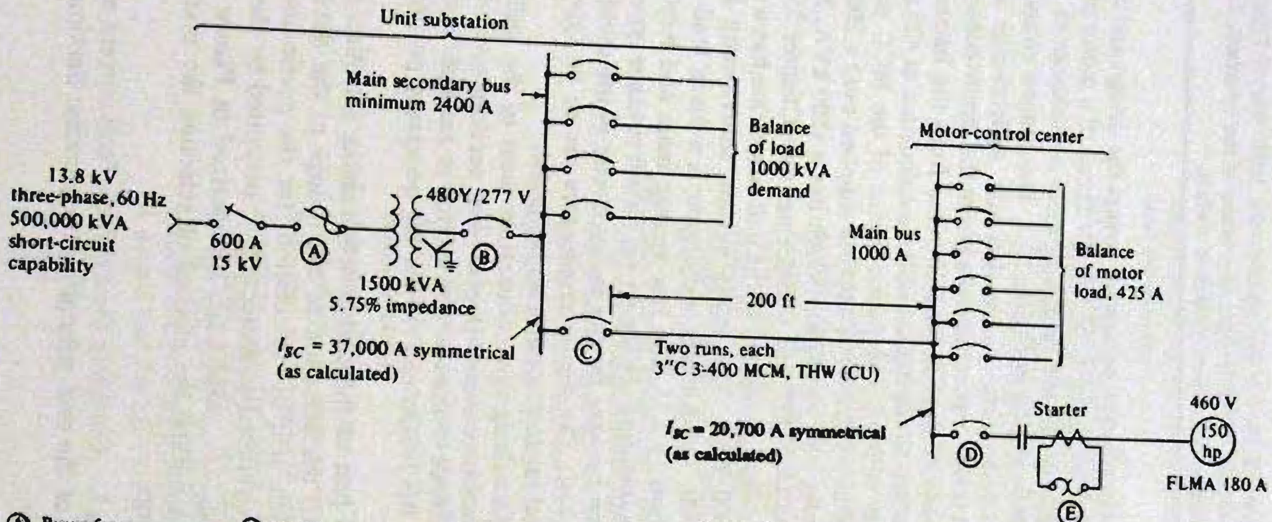
This part of the design involves the selection of the feeder to the MCC, the selection of the ratings of the devices required in the system, and the calculations for the maximum values of overload and overcurrent protection as permitted by the *National Electrical Code*. The results are summarized in Figure 16.7. The following steps outline the method of selecting the system components and ratings.

Step 1. Calculate the available fault current at the secondary main bus of the unit substation (references: Section 16.1.1 and Example 16.2):

Base kVA = 1500

Rated voltage

= 480 V (line to line), 277 V (line to neutral)



Ⓐ Power fuses
Fuse assembly, 400 A
I/C, 600,000 kVA*
Fuse unit, 150E A

Ⓑ Power circuit breaker
Frame, 3000 A
I/C, 65,000 A
Sensor, 2400 A
LDPU, 2160 A

Ⓒ Power circuit breaker
Frame, 1600 A
I/C, 50,000 A
Sensor, 1200 A
LDPU, 840 A

Ⓓ Molded-case breaker
Frame, 400 A
I/C, 30,000 A
Trip, 350 A

Ⓔ Overload relay
Rated 207 A
(motor amperes)

*Equivalent three phase
I/C, interrupting capacity, symmetrical
LDPU, long delay pickup

FIGURE 16.7

One-line diagram for system as outlined in Section 16.5

$$\text{Rated secondary current} = \frac{1500 \times 1000}{1.732 \times 480\ \text{V}} = 1804\ \text{A}$$

$$Z_U = \frac{1500}{500{,}000} = 0.003\ \text{p.u.}$$

$$Z_{UT} = 0.003 + 0.0575 = 0.0605\ \text{p.u.}$$

$$I_T = \frac{1.0}{0.0605} = 16.53\ \text{p.u.}$$

$$I_T = 1804 \times 16.53 = 29{,}800\ \text{A}$$

$$\Sigma I_M = 4 \times 1804 = 7200\ \text{A}$$

$$I_{SC} = 29{,}800 + 7200 = 37{,}000\ \text{A symmetrical}$$

Step 2. Select the feeder to the motor-control center (references: Section 11.7 and Examples 11.11 to 11.16; Section 13.4 and Example 13.4):

a. Minimum size required for ampacity. From Table 13.2, the full-load motor amperes (FLMA) of a 150 hp, 460 V motor is 180 A.

Sum of FLMA of remaining motors (as given) = 425 A

Minimum ampacity = 125% of largest + 100% of remainder
= (1.25 × 180) + 425 = 650 A

From Table 11.1, minimum size is 1750 MCM, THW. This is too large a size; recommend paralleling (Section 11.6).

Minimum ampacity per conductor = 650/2 = 325 A

Minimum size of each conductor = 400 MCM, THW (rated 335 A based on two runs of conduit)

b. Minimum size required for short-circuit current. From step 1, I_{SC} = 37,000 A symmetrical. From Table 11.4, K_0 is 1.3 and clearing time is 2 cycles.

$$I_{ASY} = 1.3 \times 37{,}000 = 48{,}100\ \text{A}$$

From Figure 11.5, the minimum size is No. 3/0.

c. Minimum size required for voltage drop.

Current per conductor = 325 A

Ampere-feet = 325 × 200 = 65,000 = 65 × 1000

$$\text{Maximum allowable volts drop} = 2\% \text{ of } 277 = 5.54 \text{ V}$$

$$\text{Maximum volts drop/1000 AF} = 5.54/65 = 0.085$$

From Table 11.5, the minimum size is No. 4/0 THW for each conductor (interpolate between 80% and 90% power factor).

Final selection of feeder (as dictated by ampacity) is

two runs, each 3″ C, 3-400 MCM, THW (CU)

(conduit size from Table 11.6).

Step 3. Calculate the available fault current at MCC (references: Section 16.3 and Examples 16.6 and 16.7):

a. Per unit resistance and reactance of system up to main secondary bus:

From step 1, $I_{SC} = 37{,}000$ A, rated current = 1804 A

$$\text{per unit } I_{SC} = \frac{37{,}000}{1804} = 20.5 \text{ p.u.}$$

$$Z_S = \frac{1.0}{20.5} = 0.049 = R_S + jX_S$$

$$\text{where } \frac{X_S}{R_S} = 4 \text{ and } \theta_S = 76°$$

$$R_S = 0.049 \cos 76° = 0.012 \text{ p.u.}$$

$$X_S = 0.049 \sin 76° = 0.048 \text{ p.u.}$$

b. Per unit resistance and reactance of feeder. From Table 16.1, for 400 MCM copper in steel conduit:

$$R_{ac} = 0.035\ \Omega/1000 \text{ ft}, \qquad X_L = 0.049\ \Omega/1000 \text{ ft}$$

For 200 ft:

$$R_{ac} = \frac{0.035 \times 200}{1000} = 0.070\ \Omega$$

$$X_L = \frac{0.049 \times 200}{1000} = 0.0098\ \Omega$$

$$\text{Base impedance} = \frac{277}{1804} = 0.1535\ \Omega$$

$$R_F = \frac{0.0070}{0.1535} = 0.046 \text{ p.u.}, \qquad X_F = \frac{0.0098}{0.1535} = 0.064 \text{ p.u.}$$

The foregoing are the values for each conductor. For two conductors in parallel:

$$R_F = \frac{0.046}{2} = 0.023 \text{ p.u.}, \qquad X_F = \frac{0.064}{2} = 0.032 \text{ p.u.}$$

c. Total impedance up to MCC:

$$Z\text{ (total)} = (0.012 + 0.023) + j(0.048 + 0.032)$$
$$= 0.035 + j(0.080) = 0.087 \text{ p.u.}$$

d.

$$I_{SC} = \frac{1.0}{0.087} = 11.5 \text{ P.U.} = 1804 \times 11.5$$
$$= 20{,}700 \text{ A symmetrical}$$

e. Ratings of MCC main bus (Section 14.5.2):
Bus bracing: standard 22,000 A symmetrical
Continuous current: 1000 A (minimum 650 A, step 2)

Step 4. Select overload protection Ⓔ for motor (references: Section 16.4 and Example 16.8). From Table 13.2, FLMA = 180 (assume nameplate amperes are the same). From Table 14.1, a size 5 starter is required. From Table 16.2, select the manufacturer's heater type W39 listed for 180 amperes (the 180 amperes is the equivalent rating as the heater is connected through a current transformer):

$$\text{Rated current of overload relay} = 1.15 \times 180 = 207 \text{ A}$$

Step 5. Select the motor branch breaker Ⓓ (references: Section 13.1.1 and Example 13.3).

$$\text{Maximum rating of trip unit} = 250\% \text{ of } 180 = 450 \text{ A}$$

From Table 8.1, the nearest standard trip rating is 450 amperes. From step 3, the available fault current is 20,700 amperes symmetrical. From Table 8.1, both 400 and 600 ampere standard frames have interrupting ratings of 30,000 amperes symmetrical at 480 volts. (*Note:* See step 11, Section 16.5.2, for final selection of breaker ratings as required for coordination.

Step 6. Select the feeder breaker Ⓒ (references: Section 13.4 and Example 13.5). From step 1, the available fault current is 37,000 amperes symmetrical.

$$\text{Maximum setting of trip unit} = (250\% \text{ of } 180) + 425$$
$$= 875 \text{ A}$$

From step 2, the minimum ampacity is 650 amperes. From Table 8.2, select 1600 ampere frame with interrupting rating of 50,000 amperes symmetrical at 480 volts (note that the 800 ampere frame does not have sufficient interrupting capacity). Select a 1200 ampere sensor (next rating above 875 amperes). See step 12 for trip unit settings for coordination.

Step 7. Select the main secondary breaker Ⓑ and main bus.

Transformers are capable of sustaining from 15% to 25% overloads. Section 450-3 of *NEC* limits the maximum setting of the secondary overcurrent device to 125% of rated current.

$$\text{Rated secondary current (from step 1)} = 1804 \text{ A}$$

$$\text{Maximum setting of trip unit} = 1.25 \times 1804 = 2255 \text{ A}$$

From Table 8.2, select a 3000 ampere frame with interrupting rating of 65,000 amperes symmetrical at 480 V. Select a 2400 ampere sensor. See step 13 for trip unit settings for coordination.

Ratings of substation main secondary bus (Section 15.4) are

— Bus bracing: standard 42,000 A symmetrical
— Continuous current: 2400 A (minimum)

Step 8. Select the primary fuse Ⓐ.

$$\text{Rated primary current} = \frac{1500 \times 1000}{1.732 \times 13{,}800} = 63 \text{ A}$$

Section 450-3 of *NEC* limits primary fusing to a maximum of 300% of rated current of transformer.

$$\text{Maximum rating of fuse unit} = 3 \times 63 = 189 \text{ A}$$

$$\text{Short-circuit kVA capability (as given)} = 500{,}000 \quad (500 \text{ MVA})$$

From Table 7.4, select a 400 ampere fuse assembly with equivalent three-phase symmetrical interrupting capacity of 600 MVA. Note that the 200 ampere fuse assembly has insufficient interrupting capacity even though it is large enough for the fuse unit. See step 10 for the final selection of the rating of the fusible element as required for coordination.

16.5.2 Coordination

This part of the design involves the selection of the time–current characteristics of the breakers and the rating of the primary fuse element to provide coordination of the system protection. The curves of devices Ⓐ through Ⓔ are plotted on an overlay as in Figure 16.8 (see Section 16.4 for the method of making overlays). Note that the current scale on the overlay is times 100 (that is, 1 on scale = 100 A) and that it is with reference to the secondary currents (at the 480 volt level).

Step 9. Plot the overload relay curves Ⓔ (reference: Example 16.9).

Rated current of overload relay (from step 4) = 207 A

Therefore, in applying Figure 16.5, the 100% line is equal to 207 amperes. Using the same procedure as in Example 16.9 (200% = 414 A, time is 85 seconds, and so on), points are plotted and the curve for the overload relay is established in Figure 16.8. The full-load and 600% locked-rotor (starting) currents of a 150 horsepower motor are also marked on the graph.

Note: The overload relay curve is plotted first, as it is set by the motor full-load amperes and cannot be adjusted. It therefore establishes the low current (downstream) boundary of the curves for the five overcurrent protective devices that are in series.

Step 10. Plot the primary fuse curves Ⓐ. The primary fuse curves are plotted next as they set the high current (upstream) boundary of the set of curves. The main purpose of the primary fuses is to provide short-circuit protection to the transformer. The fuse must operate in response to a fault before the magnitude and duration of the fault current exceed the short-time limits recommended by the transformer manufacturer. A typical transformer through-fault protection curve is first drawn on Figure 16.8. This curve is based on the requirement that transformers must be designed to withstand the stresses caused by short circuits on their external terminals within the following limitations;

—25 times rated current for 2 s
—20 times rated current for 3 s
—16.6 times rated current for 4 s
—14.3 times rated current for 5 s

The reader is referred to Chapter 10 of ANSI/IEEE Std 242-1986 (see Bibliography) for a more detailed discussion on the protection of transformers and the application of transformer through-fault protection curves.

The fuse also must be able to carry the inrush current that occurs when the transformer is energized. This current, which is assumed to be 12 times the rated current of the transformer with a

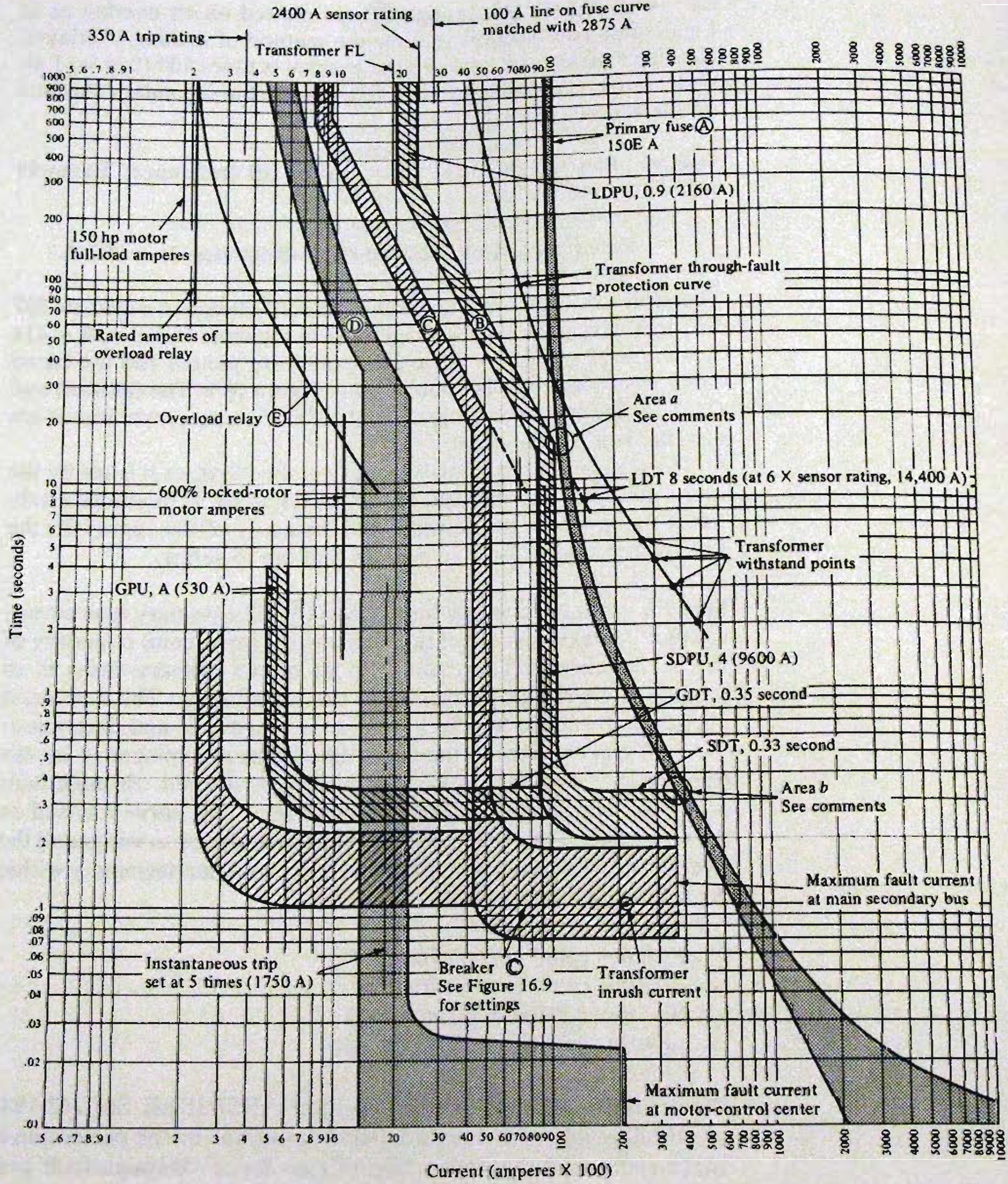


FIGURE 16.8

Time–current curves for devices in system as shown in Figure 16.7

duration of 0.1 seconds, must not blow the fuse. This point is plotted on Figure 16.8.

The transformer through-fault protection curve, the current inrush point, and the primary fuse curves are plotted with reference to the rated secondary current of the transformer. Otherwise, these points and curves would not have the correct relationship with the curves drawn for the other four devices that are on the secondary side of the transformer. The fuse curves used are shown in Figures 7.15 (minimum melting) and 7.16 (total clearing). See Section 7.1 and Figure 7.1 with regard to the meaning of minimum melting and total clearing times of fuses. The fuse curves are copied onto the overlay (Figure 16.8) by matching a particular current on the fuse curve with its equivalent secondary current, taking into account the turns ratio of the transformer. The turns ratio of a transformer is the ratio of the rated primary to secondary voltages.

$$\text{Turns ratio} = \frac{13{,}800}{480} = 28.75$$

The fuse curves are traced by matching the 100 ampere line on the fuse curves with the (100 × 28.75) = 2875 ampere line on the overlay. The rating of the fuse unit selected is 150 E amperes. This is below the maximum of 189 amperes as permitted by the *NEC* code (see step 8). Note that the minimum melting line of the fuse is well clear of (to the right of) the transformer inrush current point. The total clearing time curve of the fuse crosses the transformer through-fault protection curve at approximately 12,000 amperes or 660% of the rated current of the transformer. Therefore, the fuse provides protection against short circuits, but not against overloads on the transformer. More is stated about this in the conclusions in Section 16.5.3.

Step 11. Plot the motor branch circuit breaker curves Ⓓ [reference: Example 16.9, part (c)]. As previously determined in step 5, both a 400 and 600 ampere frame breaker can be used. The breaker curve for a 400 ampere frame molded-case circuit breaker is shown in Figure 8.8. By matching up the 100% line on the breaker curve with the possible trip ratings (400, 350 amperes, and so on) on the overlay, a trip rating of 350 amperes is selected, since the minimum line for this trip rating stays clear of the curve for the motor overload relay Ⓔ up to the locked-rotor motor amperes.

The 400 ampere frame molded-case breaker also has a magnetic (instantaneous) trip that is adjustable from 500% to 1000% (see Sections 8.4.2 and 8.6). The 500% setting is chosen (5 × 350 = 1750 A). The ±25% tolerance lines (1750 − 25% = 1315 A and 1750 + 25% = 2185 A) are also plotted, as the actual instantaneous pickup can occur anywhere between these extremes. The low limit of the pickup still clears the locked-rotor current of the motor (1080 A). Since the 350 ampere trip unit is satisfactory, the 400 ampere frame can be used. Note that the 350 ampere trip rating is below the maximum of 450 amperes as permitted by the *NEC* code (step 5).

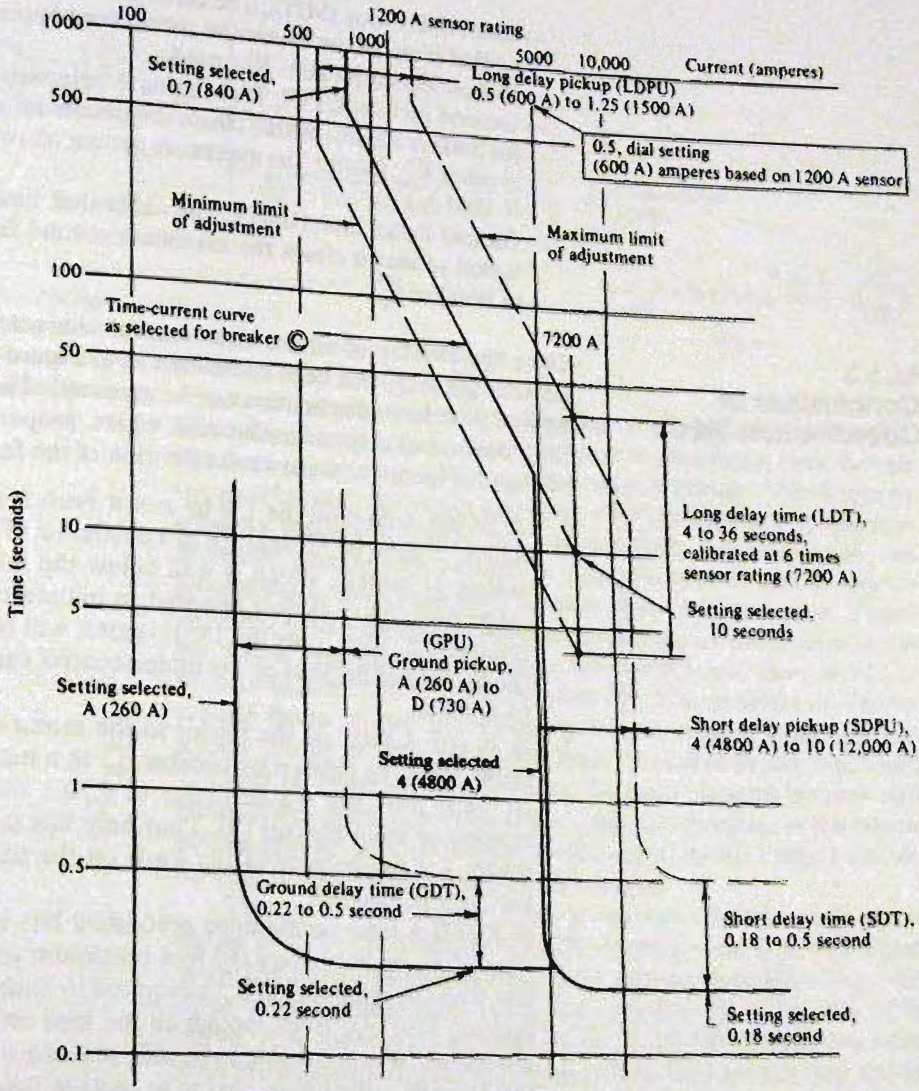
Step 12. Plot the curves for the feeder breaker Ⓒ. The type of device specified for this and the main breaker have solid-state trip units. The reader should review Section 8.5.1 and Figure 8.13, which outline all of the adjustments that can be made to the breaker time–current characteristics. Note that the adjustments are continuous, with calibration points marked on the dial as indicated. The ranges of adjustments and the final selection of each setting with the resulting time–current curve for breaker Ⓒ are shown in Figure 16.9. The selection of these settings is summarized below:

- —Long delay pickup (LDPU). From step 6, the sensor rating is 1200 A and the maximum setting of the trip unit is 875 A. The setting selected is 0.7 ($0.7 \times 1200 = 840$ A).
- —Long delay time (LDT). By inspection of breaker curves, a setting of 10 seconds is selected so that the minimum line clears the maximum line of breaker Ⓓ. Note that the dial setting of 10 represents the time in seconds for the breaker to operate at six times the sensor rating (even though this point ultimately falls outside the selected breaker curve).
- —Short delay pickup (SDPU). The minimum setting of 4 is selected, as it clears breaker Ⓓ and allows space for breaker Ⓑ.
- —Short delay time (SDT). The minimum setting of 0.18 s is chosen, as this clears the instantaneous tripping time of breaker Ⓓ.
- —Instantaneous pickup. Not used.
- —Ground pickup (GPU). Since this is the first device with ground-fault protection in the upstream direction, it is set to the lowest point: dial setting A, pickup of 260 A for a 1200 A sensor (see table at the bottom of Figure 8.13).
- —Ground delay time (GDT). Set to lowest setting: 0.22 s.

Figure 16.9 shows the center line only of the resulting breaker response curve. In Figure 16.8, breaker Ⓒ is shown with the tolerance allowances included.

Step 13. Plot the curves for main secondary breaker Ⓑ.

- —Long delay pick-up (LDPU). From step 7, the sensor rating is 2400 A and the maximum setting of the trip unit is 2255 A. The setting selected is 0.9 ($0.9 \times 2400 = 2160$ A).



Note: Tolerance limits not shown on this diagram. Refer to Figure 8.13.

FIGURE 16.9

Summary of settings and resulting time–current curve for breaker ©

— Long delay time (LDT). By inspection of breaker curves, a setting of 8 s is selected so that the minimum line clears the maximum line of breaker © and so that the maximum line is below the transformer through-fault protection curve.

— Short delay pickup (SDPU). The minimum setting of 4 is selected so that the maximum line is clear of the minimum melting line of the primary fuse.

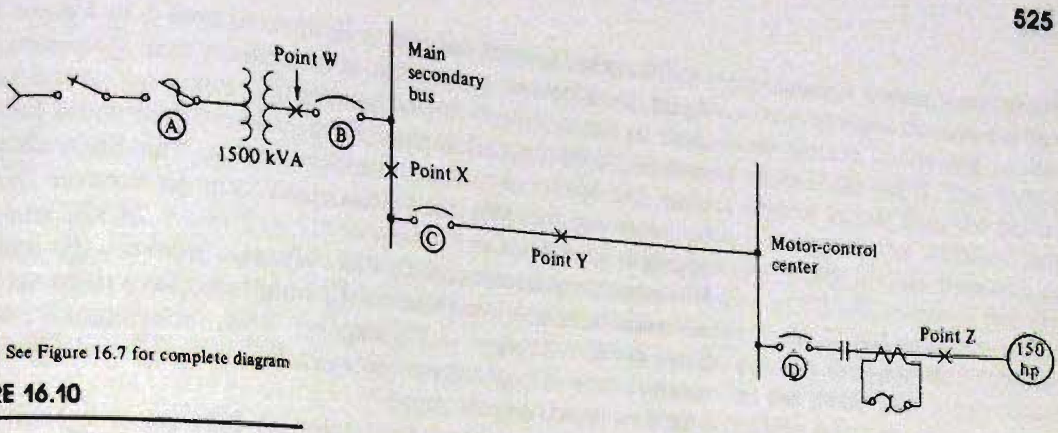
—Short delay time (SDT). The calibrated time of 0.33 s is selected so that it clears the maximum short-time tripping of breaker Ⓒ.
—Instantaneous pickup: Not used.
—Ground pickup (GPU). Dial setting A selected, pickup of 530 A for 2400 A sensor, which clears the maximum ground pickup of breaker Ⓒ. (*Note:* The maximum setting allowed by *NEC* code is 1200 A.)
—Ground delay time (GDT). The calibrated time of 0.35 s is selected so that it clears the maximum ground fault tripping time of breaker Ⓒ.

16.5.3 Conclusions of Coordination Study

Once the overlay of all the time–current characteristic curves for devices Ⓐ to Ⓔ has been completed as in Figure 16.8, the coordination or lack of coordination can be assessed. The following are a few selected examples to illustrate where proper coordination is obtained. Figure 16.10 shows the location of the faults as analyzed.

1. A 10,000 A fault on the 150 hp motor branch circuit at point Z will be cleared by breaker Ⓓ in a maximum of 0.024 s (approximately 1½ cycles), which is well below the minimum of 0.07 s (approximately 4 cycles) required to initiate tripping of feeder breaker Ⓒ. Thus, only the 150 hp motor will be shut down, and the balance of the load on the motor-control center can continue to operate.
2. A 20,000 A fault on the feeder to the motor-control center at point Y will be cleared by breaker Ⓒ in a maximum of 0.18 s, which is less than the minimum of 0.20 s required to initiate tripping of main breaker Ⓑ. Thus only this feeder will be shut down, and the balance of the loads on the unit substation can continue to operate.
3. A 30,000 A fault on the main secondary bus at point X will be cleared by main breaker Ⓑ in a maximum of 0.33 s, which is less than the minimum of 0.5 s required to initiate the blowing of primary fuse Ⓐ. Even though all the load on the substation is shut down, it is preferable to be able to restore power by closing the breaker, rather than having to replace fuse units in the primary fuse assembly.
4. An overload of 3000 A on the feeder to the motor-control center will trip breaker Ⓒ in a maximum of 60 s, which is less than the minimum of 120 s required to initiate tripping of main breaker Ⓑ.

There is, however, one case where proper coordination is not obtained. A line-to-ground fault of 1200 amperes on the 150 horsepower motor branch circuit at point Z will trip breaker Ⓒ in a maximum of 0.22 second, which is well before the minimum time of



See Figure 16.7 for complete diagram

FIGURE 16.10

Location of faults as analyzed in Section 16.5.3

43 seconds required to initiate tripping of the branch breaker Ⓓ. Thus, the complete motor-control center is shut down even though the fault is only on the one motor branch circuit. This happens because breaker Ⓓ is not equipped with ground-fault protection, whereas breaker Ⓒ does have ground-fault protection and can therefore discriminate between a line-to-line fault and a line-to-ground fault, as explained in Section 10.5.1 and shown in Figure 10.16(b). A 1200 ampere line-to-line current (an overload), for example, would take 240 seconds to trip breaker Ⓒ, and there would be no coordination problem with breaker Ⓓ. This problem on line-to-ground faults on the motor branch feeder, ranging from approximately 230 up to 1300 amperes (a high resistance arcing type fault) can only be overcome by equipping the motor branch breaker with ground-fault protection. This is an economic decision, as the cost of adding ground-fault protection to the many motor branch circuits throughout the system could be substantial.

There are also two fault areas where coordination could possibly be lost. The first area of concern is designated area *a* in Figure 16.8. The minimum melting line of the primary fuse Ⓐ comes very close to the maximum line of the main breaker Ⓑ at the *knee* of the curve. Any shifting of the fuse curve to the left (which can occur with preloading of fuse) could result in both the fuse blowing and the main breaker tripping for faults at point X (Figure 16.10) in the 10,000 ampere range. The short time pickup of breaker Ⓑ is set at its minimum value of four times (9600 amperes) and cannot be decreased. However, some models of circuit breakers permit the short time pickup to be set as low as two times the sensor rating, rather than the four times shown in Figure 8.13. If this model of breaker is used, then the short time pickup of breaker Ⓑ could be set down to a lower value, for example, three times or 7200 amperes, which would eliminate the possibility of lack of coordination with the primary fuse.

The other area of concern is designated area *b* in Figure 16.8. Again, the minimum melting line of the primary fuse Ⓐ comes very close to the maximum line of breaker Ⓑ. For a maximum bolted fault of 37,000 amperes at point X, the primary fuse could possibly blow, in addition to the main breaker tripping. This possibility can be overcome by using the instantaneous trip on breaker Ⓑ and setting it to pick up at 12 times or (12 × 2400) = 28,800 amperes. However, to maintain coordination between breakers Ⓑ and Ⓒ, the instantaneous trip on breaker Ⓒ would also have to be set at 12 times or (12 × 1200) = 14,400 amperes. This, unfortunately, would result in loss of coordination between breakers Ⓒ and Ⓓ in the 14,400 to 20,600 ampere range.

Finally, a comparison of the primary fuse curve Ⓐ with the transformer through-fault protection curve shows that the fuse only properly protects the transformer from internal faults from a point above approximately (12,000/1804) or 6.6 times its full-load rating. Any low-current arcing faults of less than this magnitude that occur ahead of the main breaker (point W in Figure 16.10) or internally within the transformer will not initially be detected by the fuse. The fault will persist until the current builds up to the point where the fuse will eventually blow, thus increasing the damage. It should be noted that the 150 ampere rating of the fuse is below the maximum of 300% permitted by the *NEC* code. This situation can be improved somewhat by selecting a lower rating for the fuse unit (for example, 125 amperes). But then coordination with breaker Ⓑ could only be maintained if the short delay pickup of the breaker can be set below 4 times and the instantaneous trip is set at 12 times, as previously discussed. Improved coordination may be possible through the use of the new electronic fuses discussed in Section 7.8.3.

The foregoing discussion is presented primarily to show that complete coordination is not always possible, at least not at a reasonable cost. It also shows that many options are available to the system designer and it takes experience to determine which set of options is best for a particular system, balancing the economics of the system costs against the costs of unnecessary shutdowns. Simply complying with the provisions of the *National Electrical Code* does not necessarily mean that the system will be properly coordinated. The primary function of the *NEC* is to ensure safety, which must always have a higher priority than coordination.

With regard to the calculations shown for the fault currents, the method employed assumed the rules of thumb as outlined. Also, the impedances of such system devices as switches, circuit breakers, and substation bus have not been included, as they have a very minor effect, and, in any event, would act to further decrease the available fault current. In step 3, the calculations for the available fault current at the mains of the motor-control center were made using the assumption that all the motor contributions occurred at the main switchboard when, in fact, those motors connected to the MCC would contribute directly at the mains of the MCC. This would tend to make the actual fault current slightly higher than the calculated value. However, for motor-control centers the standard bus bracing and interrupting rating for the motor circuit breakers is 22,000 amperes. The calculated value of 20,700 amperes for the available fault current is some 6% below the 22,000 amperes, and it is highly unlikely that the degree of error in the simplified calculations would approach this amount. In the event that a calculated value is very close to the standard ratings for equipment, a more precise set of calculations would be in order.

The one example design shown is not meant to show all the problems inherent in designing an electrical system nor all the possible solutions to obtaining a good design. However, it is hoped that the example has introduced the reader to the fundamentals of system design and that it can act as an introduction to further study on the principles of system design and coordination.

There is now a growing use of computers in the design and study of electric power systems. There are programs that can materially aid in the calculations of available fault currents. Also, computer graphic routines allow the user to construct time–current curves quickly and systematically to arrive at a final set of coordinated curves. However, it should always be remembered that the computer is just another tool. The designer should first have a thorough understanding of the principles involved before applying the computer to solve the various problems.

SUMMARY

- The magnitude of available fault currents must be calculated for each section of a system to ensure the proper selection of feeders and protective devices.
- On low-voltage systems, calculations are done on the basis of three-phase bolted faults, as these generally result in the maximum possible fault current.
- The per unit impedance of the utility system is calculated as follows:

$$Z_U = \frac{\text{base kVA}}{\text{short-circuit kVA}}$$

- All motors on the system contribute to the available fault current. The contribution is assumed to be four times the full-load current of each motor.

- With 480 and 600 volt systems, it is assumed that the motor load is 100% of the system kVA.
- With 208Y/120 volt systems, it is assumed that the motor load is 50% of the system kVA.
- The kVA rating and the percentage impedance of the substation transformer have a significant effect on the magnitude of the available fault current.
- When the impedance of a feeder is to be included in the fault calculations, the equivalent system impedance up to the source of the feeder is assumed to have an inductive reactance to resistance ratio of 4.
- There are three classes of motor overload relays: classes 10, 20, and 30. The number specifies the maximum time in seconds for the relay to operate at 600% of its rating.
- Proper coordination on motor circuits is obtained when the overload relay opens the starter on all excess currents up to 600% and the overcurrent device clears all currents above 600% of the motor rated current.
- The rating of the primary protection of a transformer operating at more than 600 volts should not exceed 300% of the transformer rated primary current.
- The rating of the secondary protection of a transformer operating at more than 600 volts should not exceed 125% of the transformer rated secondary current.
- The coordination of a system is studied by preparing an overlay of the time–current characteristic curves of the protective devices, with all curves properly lined up on a common current scale.

QUESTIONS

1. Why is it necessary to calculate the available fault current at specific locations in an electrical system?
2. What does the term available fault current mean?
3. In calculating the available fault current on a low-voltage system, why is the fault assumed to be a three-phase bolted type?
4. List the possible sources of fault current in a building electrical system.
5. Explain why induction motors are a source of fault current for the first few cycles after a fault occurs.
6. What is the assumption with regard to the motor contribution to the available fault current for 208Y/120 V systems?
7. What are the two types of ratings with regard to circuit breakers that must be specified when applying them to protect a feeder?
8. Explain why it is desirable to select power transformers with impedances of at least 5.0%.
9. Explain why the short-circuit duty requirements for equipment decrease as the distance from the substation increases.
10. Why is it undesirable to increase the system impedance to a high value to keep fault currents to a low value?

11. Describe the two most common types of thermal-response motor overload relays.
12. What does class 20 designate with regard to overload relays?
13. What factors affect the precise current rating of a motor overload heater element?
14. Why should the motor circuit protective device (fuse or circuit breaker) operate first to clear any current above 600% of the full-load current of motor?
15. In the design procedure covered in Section 16.5.1, why is the calculation of the available fault current at the secondary main bus the first step?
16. Why is it necessary to calculate the available fault current at the motor-control center as in step 3, Section 16.5.1?
17. The minimum ampacity required for the feeder to the motor-control center is 650 A. Explain why an 800 A frame breaker cannot be used for breaker Ⓒ.
18. Explain why the primary fuse Ⓐ (Figure 16.7) does not adequately protect the substation transformer for fault currents less than approximately 660% of the full-load current of the transformer.

PROBLEMS

1. The utility short-circuit capability is 100,000 kVA. The transformer rating is 750 kVA. Calculate the per unit impedance of the utility system connection.
2. Power is supplied over a primary feeder to a 13,800-208Y/120 V, 500 kVA unit substation. The impedance of the transformer is 5.0%. The utility system short-circuit capability is 150,000 kVA. Assume 50% of the load is motors. Calculate the available short-circuit current at the main secondary bus of the substation.
3. Repeat Problem 2, except the secondary voltage is 480Y/277 V and motor load is 100%.
4. A three-phase feeder consists of three No. 4/0 copper conductors in a steel conduit and is 150 ft in length. The feeder is connected to a 750 kVA unit substation, and the system voltage is 208Y/120 V. Calculate the per unit resistance and reactance of the feeder.
5. In Problem 4, the utility short-circuit capability is 250,000 kVA and the transformer impedance is 5.75%. Assume a 50% motor load on the substation. The feeder is connected to a power panel. Calculate the available fault current at the mains of the power panel.
6. Repeat Problem 4, except the system voltage is 480Y/277 V.
7. Repeat Problem 5, except the system voltage is 480Y/277 V and motor load is 100%.
8. Select the overload heater elements from Table 16.2 for the magnetic starters for the following three-phase squirrel-cage induction motors with service factors of 1.15: (a) 10 hp, 200 V; (b) 10 hp, 460 V; (c) 25 hp, 460 V; and (d) 60 hp, 460 V. Assume that the nameplate full-load current ratings of the motors are the same as the values listed in Table 13.2.
9. Calculate the rated current of each overload heater element selected in Problem 8.
10. Express the rated current of each overload relay selected in Problem 8 as a percentage of the full-load current of the motor it is protecting. Does your selection satisfy the code requirements with regard to overload protection of motors (see Section 13.1.2 of this text).
11. Determine the response time for each overload heater element selected in Problem 8 at 600% of the motor full-load amperes (at locked-rotor amperes). Use the curve for class 20 relays in Figure 16.5.
12. A motor-control center controls the following 460 V, three-phase squirrel-cage induction motors: five 5 hp, two 7½ hp, two 10 hp, two 15 hp, two 25 hp, and one 60 hp. The motor-control center is supplied over a 300 ft feeder from a 13,800-480Y/277 V, 2000 kVA unit substation. The transformer impedance is 5.75%. The utility system short-circuit kVA capability is 150,000. The feeder conductors are to be type THW copper installed in steel conduit above grade. The voltage drop on the feeder is not to exceed 3%. Assume the power factor of the motor load is

85%. Select the feeder to the motor-control center.

13. Select the feeder breaker for the feeder to the motor-control center in Problem 12, including the sensor rating and the setting on the long delay pickup (based on the maximum permitted by the code). The breaker will be the low-voltage power type as in Section 8.5 in this text.

14. Select the main secondary breaker for the substation in Problem 12, including the sensor rating and the setting of the long delay pickup.

15. The primary switchgear for the substation in Problem 12 is a fused load-interrupter switch. Select the primary fuse and indicate the maximum rating of the fuse unit permitted by the code.

Appendix A

REFERENCES TO 1986 CANADIAN ELECTRICAL CODE

General

The *Canadian Electrical Code* (CEC) is published by the Canadian Standards Association (CSA), 178 Rexdale Boulevard, Rexdale, Ontario. The code is divided into two parts: Part I, CSA Standard C22.1-1986, covers safety standards for electrical *installations*, and Part II covers safety standards for electrical *equipment*. The list of Part II standards is shown in Appendix A of the Canadian Electrical Code, Part I.

The general arrangement of the Canadian Electrical Code, Part I, is shown on page 30 of the 1986 edition of the code. It is divided into numbered sections, with each section further divided into numbered rules. Rules applicable to a specific subject are grouped together under 100, 200, and so on, numbered series. As an example, Rules 10-100, 10-102, 10-104, and so on, are in Section 10, Grounding and Bonding, and are grouped under the heading *System and Circuit Grounding*. The tables and diagrams are shown separately after the sections and are numbered 1, 2, and so on.

The objective of the Canadian Electrical Code, as stated in Section 0, Object, Scope, and Definitions, is *to establish safety standards for the installation and maintenance of electrical equipment and for the prevention of fire and shock hazards*. The CEC requirements are generally consistent with the *National Electrical Code* requirements. The following is a list of those rules in the 1986 Canadian Electrical Code that are applicable in place of the National Electrical Code rules mentioned in the main text of this book. The related comments indicate any differences between the two codes.

Chapter 1

1.8 Voltage Terminology and Standards

- Table 1.1, Voltage standards for building electrical systems.
- Reference: CSA Standard CAN3-C235-83. Preferred voltage levels for ac systems, 0 to 50,000 volts

Comments: The CSA method of designating three-phase, four-wire wye systems differ slightly from that shown in Table 1.1. For example, CSA designates a system as 120/208Y, rather than 208Y/120.

The major difference in CSA voltage standards less than 750 volts is that the 277/480Y system is not a preferred standard, whereas the 347/600Y system is a preferred standard. The 240/416Y system is an additional preferred standard.

Chapter 6

- Introduction
- Reference: Section 0, Object

6.1 Types of Abnormal Conditions

- Reference: Section 14 and Rule 14-100

Chapter 7

7.2 Categories of Low-Voltage Fuses

- Reference: 14-000 series of rules and CSA Standard C22.2 No. 59-M1984; Fuses (both plug and cartridge-enclosed types)

7.5 Classifications of Low-Voltage Fuses

- Reference: CSA Standard C22.2 No. 106-M1985; HRC Fuses

Comments: The CSA has the additional classifications of form I and form II fuses. Form I fuses must meet the 135% and 200% maximum allowable clearing times as required for standard code fuses (see Table 7.1). Form II fuses must meet specified clearing times at only 160% of their rating, and these times are similar to those specified at 135% for the standard code fuses. For example, a 100 A form II fuse has a maximum clearing time of 120 minutes at 160% of its rating, as compared to 120 minutes at 135% for a standard fuse. Therefore, form II fuses applied at their rated current provide only short-circuit protection and must be used in conjunction with other means of providing overload protection. A typical application is to use form II fuses for motor branch circuit protection, with the overload protection being provided by the overload relays in the motor starter. An example of a CSA designation is HRCI-J, which signifies that the fuse is a high rupturing capacity type, form I, class J.

Rule 14-212 governs the use of form I and form II high rupturing capacity (HRC) fuses.

7.6 Fusible Switches

- Reference: Rule 14-402

Chapter 10

- Reference: Section 10, Grounding and bonding

Comments: The 1986 edition of the CEC clearly differentiates between grounding and bonding (see definitions in Section 0). Grounding means a permanent and continuous conductive path to earth. Bonding means a low-impedance path obtained by permanently joining all noncurrent-carrying metal parts to assure electrical continuity of the equipment grounding circuit.

10.2 Grounded Systems

- Reference: 10-100 and 10-200 series of rules

  Comment: Rule 10-106(b) does not specify a voltage and therefore both the 240/416Y and the 347/600Y volt, three-phase, four-wire systems in which the neutral is used for a circuit conductor are included in the system grounding requirements.

10.2.1 Selection of System Grounding Points

- Reference: Rule 10-206, Grounding connections for isolated systems

  Comment: The CEC uses the term *isolated* system rather than *separately derived* system, but the intent is the same.
- Reference: Rule 10-200, Current over grounding and bonding conductors

10.3.1 Impedance of Equipment Grounding Circuit

- Reference: Rule 10-504, Common grounding electrode

  Comment: This rule states that the same electrode *may* be used, rather than making it mandatory (which it should be).

10.3.3 Summary of *National Electrical Code* requirements

- References with regard to Canadian Electrical Code:
  - —Rules 4-028 and 030, Identification of insulated neutral conductors
  - —Rule 4-036(1), Identification of insulated grounding conductor
  - —10-300 series, Conductor enclosure bonding
  - —10-400 series, Equipment bonding
  - —10-500 series, Methods of grounding
  - —10-600 series, Bonding methods
  - —10-700 series, Grounding electrodes
  - —10-800 series, Grounding and bonding conductors
  - —10-900 series, Grounding and bonding conductor connections
  - —36-300 series, High voltage installations, grounding
  - —Table 16, Minimum size of conductors, metal conduit, or electrical metallic tubing for bonding raceways and equipment
  - —Table 17, Minimum size of grounding conductor for ac systems or common grounding conductor
  - —Table 18, Minimum size of grounding conductor for service raceway and service equipment

  Comments: Table 17 is based on ampacity of largest service conductor rather than on size. Table 18 covers grounding of raceways and equipment where the ac system is not grounded at the premises. Note that aluminum conductors are not approved for use as grounding conductors.
- *Example 10.1* RW90(XLPE) is CSA equivalent of type XHHW. Ampacity of conductors from CEC Table 2 = 395 amperes. Two parallel runs (separate conduit) = 2 × 395 = 790 amperes. From CEC Table 17, No. 3/0 (000) copper ground wire is required.

- *Example 10.2* CEC Table 16 also requires No. 3 copper as indicated.

10.5 Ground-Fault Protection

- Reference: Rule 14-102

  Comment: This rule also requires ground-fault protection for systems of 150 volts or less to ground (120/208Y) and 2000 A or more.

10.6 High-Resistance Grounded Systems

- There is no reference in the CEC to this type of system.

Chapter 11

- References: Section 4, Conductors; Section 12, Wiring methods

11.1 Continuous Current Rating of Conductors

- References: Rule 4-004, Tables 2 (copper) and 4 (aluminum).

  Comment: Tables 2 and 4 are used in lieu of Table 11.1 (*NEC* Table 310-16) as shown in this text. The CEC and *NEC* tables are for the most part compatible with the following major exceptions:

  — AWG sizes 14, 12, and 10 copper and 12, 10, and 8 aluminum have the same ampacities for 60°, 75°, and 90°C rated conductors.
  — CEC ampacities for 90°C rated conductors tend to be lower.
  — kcmil instead of MCM and 0, 00, etc. instead of 1/0, 2/0, etc.

  There is no CEC equivalent for Table 11.2 (*NEC* Table 310-27). Tables 2 and 4 are also used for conductors run in underground raceways.

11.1.4 Ambient Temperature

- Reference: Table 5A, Ampacity correction factors for ambient temperatures above 30°C

  Comment: There are no correction factors listed for ambient temperatures below 30°C and values for 90°C conductors are not the same.

11.1.5 Conductors Installed in Raceways

- Reference: Rule 4-004

  Comment: There is no mention in the CEC that the neutral of a three-phase, four-wire circuit, where the majority of the load consists of electric-discharge lighting, data-processing, or similar equipment, must be considered as a current-carrying conductor. However, at least one provincial inspection authority (British Columbia) requires that the neutral for such loads shall be considered as a fourth current-carrying conductor (Bulletin 4-1-0).

11.1.6 Determining the Ampacities of Conductors

- *Example 11.1* From CEC Tables 2 and 5A, ampacity same as shown.

- *Example 11.2* From CEC Table 2 and Rule 4-004(1)(c), ampacity = 345 × 0.80 = 276 amperes.
- *Example 11.3* From CEC Tables 4 and 5A and Rule 4-004(2)(d), ampacity same as shown.
- *Example 11.4* CEC Table 2 is used and no allowance is made for 20°C ambient earth temperature nor any correction for two ducts. Ampacity = 230 amperes.

11.3 Maximum Allowable Voltage Drop

- Reference: Rule 8-102

11.4 Letter Designation of Cables

- Differences in CSA designations (see Table D1):

  — Separate designation XLPE used to indicate cross-linked synthetic polymer (polyethylene) insulation.
  — Temperature ratings above 60°C designated by 75 or 90.

Examples: TW75 is equivalent of *NEC* type THW. RW90(XLPE) is equivalent of *NEC* type XHHW.

11.5 Raceways

- Reference: Section 0, Definition of raceways

11.5.1 Types of Conduit

- References: 12-1000 to 12-5000 series, Use and installation of conduit and tubing; Rule 12-010, Wiring in ducts and plenum chambers; Rule 10-510(3), Separate grounding conductor for liquid-tight flexible metal conduit

  Comment: Intermediate conduit and electrical nonmetallic tubing is not mentioned.

11.5.2 Number of Conductors Permitted in Conduit

- Reference: Rule 12-1116 and Table 6
- *Example 11.10* The CSA equivalent for THW is TW75. From CEC Table 6, 2½ inch conduit required (no change).

11.6 Conductors in Parallel

- References: Rules 12-108 and 12-1004(1)

11.7 Examples of Feeder Design

- References: Section 8, Circuit loading and demand factors; Rule 8-104(3), Continuous and noncontinuous loads

Comment: For loads of 225 amperes or less, the time is reduced to 1 hour.

- Reference: Rule 8-104(5) and Appendix B

  Comment: Unless the fusible switch or circuit breaker is marked as being suitable for 100% operation, a feeder can only be continuously loaded to 80% of its ampacity rating, which is the same as saying that its ampacity rating must be 125% of the continuous load.

- *Example 11.11* Equivalent CSA conductor type is TW75. **(a)** Minimum size required for ampacity; From CEC Table 2, ampacity of No. 1/0 TW75 is 150 amperes. **(e)** From CEC Table 6, conduit size required is 2 inch. Therefore, there is no change to solution as shown.

- *Example 11.15* Equivalent CSA conductor types are TW75 and RW90(X-LPE). **(a)** Minimum size required for ampacity: Derating factor of 80%, see Rule 4-004(1)(c). From CEC Table 2, No. 4/0 TW75 rated at 230 amperes; No. 3/0 RW90 rated at 210 amperes. **(e)** From CEC Table 6, four No. 3/0 RW90(XLPE) requires 2 inch conduit. Therefore, there is no change to solution as shown.

- *Example 11.16* **(d)** From CEC Table 6, four No. 4/0 RW90(XLPE) requires 2½ inch conduit.

11.8 Overcurrent Protection of Feeders

- References: 14-000 series and Rules 14-100 and 104, Requirements and locations of overcurrent protection; Rule 8-104 for continuous loading of devices

- *Example 11.17* From CEC Table 2, ampacity of No. 3/0 RW90 is 210 amperes. Ampacity of four No. 3/0 in conduit = 0.80 × 210 = 168 amperes, which is satisfactory (see CEC Table 13).

11.9 Cable Trays

- References: Section 0, Definition of cabletrough; 12-2200 series, Installation of cabletroughs

  Comment: CEC uses term cabletrough for cable tray.

11.10 Busways

- References: Section 0, Definition of busyway; 12-2000 series, Installation of busways

Chapter 12

- References: Section 8, Circuit loading and demand factors; Section 12, Wiring methods; Section 14, Protection and control; Section 30, Installation of lighting equipment

12.1 Branch Circuit Conductors See comments for Sections 11.1 through 11.5.2 in this appendix

- *Example 12.1* Ampacity of No. 12 R90 copper from CEC Table 2 is 20 amperes. Temperature correction factor from CEC Table 5A is 0.90. Derating factor from Rule 4-004(1)(c) is 80% for six conductors. Ampacity = 20 × 0.90 × 0.80 = 14.4 amperes. Therefore, ampacity is not sufficient and No. 10 R90 copper (rated for 30 amperes) has to be used.

- References: Rule 30-312, Temperature rating of conductors for ballasts in lighting fixtures

  Comment: RW75 is not approved for 90°C use in fixtures. Rule 4-002, Minimum size of conductors

12.2 Branch Circuits for Lighting

- References: Section 30, Installation of lighting equipment; Rule 30-104, Protection of lighting circuits

  Comments: The CEC requirements are summarized as follows:

  — Branch circuits for incandescent medium-base luminaires shall have a maximum rating of 15 A.
  — Branch circuits for incandescent mogul-base luminaires shall have a maximum rating of 40 A.
  — Branch circuits for metal-enclosed fluorescent and medium-base HID luminaires shall have a maximum rating of 20 A.
  — Branch circuits for mogul-base HID luminaires shall have maximum ratings of (i) 40 A at 120 V, (ii) 20 amperes up to 277 volts, and (iii) 15 A above 277 V.

- Reference: Rule 30-102, Voltage

  Comments: The CEC requirements are as follows:

  — Circuit voltages shall not exceed 150 volts-to-ground in any dwelling unit.
  — In industrial and commercial establishments where a trained and qualified maintenance staff is available, the voltage-to-ground shall not exceed that of a nominal 347/600Y system.

The fact that 347 volt (line-to-ground) branch circuits are permitted means further savings in branch circuit and feeder wiring as compared to 277 volt circuits. The ballasts necessary for operating fluorescent and HID luminaires on 347 volts are CSA approved.

- *Example 12.2* Add the following: **(c)** 347/600Y volts. Ballast has a line current of 0.75 amperes at 347 volts.
- *Solution:* Maximum loading of each circuit is again 16 amperes. **(c)** 347/600Y volt system (ballasts connected to 347 volts)

  — Maximum number of units per circuit = 16.0/0.75 = 21.3 ≈ 21.
  — Minimum number of circuits = 70/21 = 3.3 ≈ 4.

Therefore, it is possible to wire the lighting layout as in Example 5.11 using only four circuits, as compared to ten required using 120 volt circuits.

12.3 Branch Circuits for Receptacles

- Reference: Rule 14-600, Protection of receptacles

  Comment: Two or more 15 ampere receptacles *cannot* be connected to a 20 ampere circuit.
- Reference: Diagram 1, CSA configurations for nonlocking receptacles

  Comment: The 20 ampere receptacle does not have a T-slot and therefore *cannot* accept 15 ampere attachment plugs.
- Reference: Rule 12-3000, Maximum number of outlets per circuit

  Comment: There shall not be more than 12 general-purpose receptacle outlets on any two-wire branch circuit. Each outlet shall be rated at not less than 1 ampere.
- Reference: Rule 26-700, Installation of receptacles

12.4 Lighting Panels

- Reference: CSA Standard C22.2 No. 29-M1983, Panelboard and panelboard enclosures

  Comments: Standard panels are available for 347/600Y, three-phase, four-wire systems.
- Reference: Rule 14-606, Panelboard overcurrent protection

  Comments: Individual overcurrent protection is required for panelboards supplied by conductors having overcurrent protection *greater than 100 amperes*.
- Reference: Rule 14-100(b), Requirements for feeder taps, same as shown in Figure 12.4(c)

12.7 Example Floor Layout of Lighting and Receptacles

- In Figures 12.8 and 12.9, the following modifications are required:

  — Circuit A2, since it supplies medium-base incandescent fixtures, must be protected by a 15 A breaker.
  — Circuit A4 must similarly be protected by a 15 A breaker. Only *four* type C, 300 W, medium-base incandescent fixtures can be connected to this circuit, giving a load of 10 A (maximum permitted is 80% of 15 = 12 A). The two other type C fixtures shown in the corridor have to be combined with two or more units and connected to an additional 15 A circuit.

- References: The following are applicable to branch circuits:

  — 12-100 series; Conductors in general
  — 12-3000 series; Installation of boxes, cabinets, outlets, and terminal fittings
  — Rule 12-3040; Maximum number of conductors in a box
  — Rule 30-312; Luminaire as a raceway
  — Section 46; Emergency Systems, Unit Equipment, and Exit Signs

12.8 Switching of Lighting Systems

Comments: Local switches rated for 347 volts, 15 and 20 amperes, and low-voltage remote-control switching relays with contacts rated for 347 volts are available.

12.9 Underfloor Raceway Systems

- References: 12-1700 series, Underfloor raceways; 12-1800 series, Cellular floors

12.10 Ground-Fault Circuit Interrupters

- References: Rule 26-702, Receptacles in residential occupancies; Section 68, Swimming pools (includes therapeutic pools and hydromassage bath tubs)

12.11 Computed Loads for Lighting and Receptacles

- References: Section 8, Circuit loading and demand factors; Table 14, Watts per square meter and demand factors for various types of occupancies
- *Example 12.3*

$$10{,}000 \text{ ft}^2 = 10{,}000 \times 0.093 = 930 \text{ m}^2$$

Unit loading from CEC Table 14 is 50 watts per square meter (this includes allowance for general-use receptacles).

$$\text{Total computed load} = 930 \times 50 = 46{,}500 \text{ W}$$

$$\text{Load current} = \frac{46{,}500}{1.732 \times 208 \times 1.0^{a}} = 129.2 \text{ A}$$

[a] Assume 100% power factor.

This continuous load cannot exceed 80% of feeder ampacity.

$$\text{Minimum ampacity} = \frac{129.2}{0.80} = 161.5 \text{ A}$$

- *Example 12.4*

$$12{,}000 \text{ ft}^2 = 12{,}000 \times 0.093 = 1116 \text{ m}^2$$

(a) For feeder taps to each panel:

— From Rule 8-206, basic load is 20 W/m²
— Demand for first 900 m² is 80% of (20 × 900) = 14,400 W
— Demand for remaining area:

$$(1116 - 900) = 216 \text{ m}^2 = 65\% \text{ of } (20 \times 216) = \underline{2{,}808 \text{ W}}$$

$$\text{Total computed load} = 17{,}208 \text{ W}$$

$$\text{Load current} = \frac{17{,}208}{1.732 \times 208 \times 1.0} = 47.8 \text{ A}$$

Since the load as calculated by Rule 8-206 is not specifically excluded from being considered as a continuous load:

$$\text{Minimum ampacity} = \frac{47.8}{0.80} = 59.75 \approx 60 \text{ A}$$

(b) For the main feeder:

— Total area is $3 \times 1116 = 3348 \text{ m}^2$
— Demand for first 900 m^2 is 80% of $(20 \times 900) = 14{,}400$ W
— Demand for remaining area:

$$(3348 - 900) = 2448 \text{ m}^2 = 65\% \text{ of } (20 \times 2448) = \underline{31{,}824 \text{ W}}$$

$$\text{Total computed load} = 46{,}224 \text{ W}$$

$$\text{Load current} = \frac{46{,}224}{1.732 \times 208 \times 1.0} = 128.4 \text{ A}$$

$$\text{Minimum ampacity} = \frac{128.4}{0.80} = 160.5 \quad (160 \text{ A})$$

Chapter 13

- References: Section 28, Motors and generators; Table 26

Comment: Table 26 lists specific values for the minimum ampacity of the motor circuit conductors and the maximum rating permitted for overload and overcurrent protection for motor full-load currents up to 500 amperes.

13.1 Branch Circuit for a Single Motor

- References: Tables 44 and 45

Comments: The values listed in Table 13.1 of this text for single-phase motors are consistent with the values listed in CEC Table 45. The values listed in Table 13.2 of this text for three-phase induction type motors are consistent with the values listed in CEC Table 44.

13.1.1 Short-Circuit and Ground-Fault Protection

- References: Rules 28-200 and 28-210; Table 26 or 29 (whichever is applicable)

Comments: The CEC uses the term overcurrent protection. However, for the reasons stated in this text, the motor branch circuit protective device cannot adequately protect the circuit from overloads and in reality provides only short-circuit and ground-fault protection.

The values listed in CEC Table 29 are consistent with the values shown in Table 13.3 of this text except that for reduced-voltage autotransformer starting of more than 30 amperes the maximum value permitted for non-time-delay fuses is 200%.

13.1.2 Overload Protection

- References: 28-300 series

Comments: The values of the setting of overload devices as listed in CEC Table 26 are also based on being a maximum of 125% of the full-load current of motor with a service factor of 1.15.

Separate overheating protection is required under the conditions as specified in Rule 28-302.

13.1.3 Branch-Circuit Conductors

- References: Rules 28-104 and 28-106

Comment: Rule 28-104 requires that, even if the temperature rating of the insulation is 90°C, the ampacity of the conductors connected to the motor shall be based on the 75°C rating.

13.2 Disconnecting Means

- Reference: 28-600 series

13.2.1 Location

Comments: The disconnecting means must be located within sight of and within *9 meters* (approximately 30 ft) of the motor or controller.

A disconnecting means, capable of being locked in the open position, may be installed out of sight or more than 9 meters from a motor or controller only if *a trained and qualified electrical maintenance staff is available*.

13.2.2 Ratings and Types

Comments: A manually operated, general-purpose ac switch can only be used as a disconnecting means for a *single-phase* motor. The ac switch shall have a rating *not less than 125%* of the rated motor current.

13.3 Examples of Motor Branch Circuits

- *Example 13.1* Conductor type will be TW75. Using CEC Tables 2, 6, and 26, all ratings and conductor and conduit sizes as selected remain the same.
- *Example 13.2* CEC Table 26 permits a maximum of *100 ampere* time-delay fuses to be used for a full-load motor current of 52 amperes.
- *Example 13.3* CEC Table 26 permits a maximum of only *125 ampere* trip rating for the breaker. See Figure 16.6 of this text, which shows that a trip rating as low as 100 amperes would still be satisfactory.

13.4 Feeders for Two or More Motors

- References: Rules 28-108, 28-110, and 28-204
- *Example 13.4* Conductor type will be TW75. Calculations for feeder protection: from CEC Table 26, the maximum time-delay fuse permitted for a 40 horsepower motor with full-load current of 120 amperes is *225 amperes*.

The maximum rating of feeder protection is 225 + 142 = 367 amperes. A 350 ampere fuse will still be selected. Otherwise, all calculations, ratings, and sizes of conductors and conduit as selected remain the same.

- *Example 13.5* CEC Table 26 permits a 300 ampere circuit breaker for the 40 horsepower motor, full-load current of 120 amperes. Therefore, all calculations and ratings selected remain the same.

13.5 Single Motor Taps

- Reference: Rule 28-106(4)

  Comment: Maximum distance for tap is 7.5 meters (approximately 25 feet).
- *Example 13.6* Conductor type will be TW75. From CEC Table 2, 1/0 copper is also rated for 150 amperes but No. 8 copper is rated for *only 45 amperes*. Therefore, tap conductors will have to be No. 6 TW75.
- *Example 13.7* From CEC Table 2, the ampacity of No. 6 TW75 copper is also 65 amperes; therefore, no change to selection.

Chapter 14

- Reference: 28-500 series, Control

14.2.1 Control for Magnetic Starters

- Reference: Rule 14-100(d), Protection of control circuits

  Comment: This rule covers only control circuits that extend beyond the starter enclosure. The maximum rating of the overcurrent device cannot be more than 300% of the ampacity of control circuit conductors. This agrees with the values shown in Table 14.2 of this text. For example, No. 14 copper conductors (60°, 75°, and 90°C) are rated for 15 amperes (CEC Table 2). The maximum rating of overcurrent protective devices is (3 × 45) = 45 amperes.

14.5.3 Layout of Motor-Control Centers

- Reference: Rule 2-308, Working space about electrical equipment

  Comment: Minimum working space of *1 meter* is required.

Chapter 15

15.2.2 Lightning Protection

- Reference: 26-500 series

  Comment: The term *lightning* arrester is used rather than surge arrester.

15.3 Transformer Section

- Reference: Rule 26-248, Installation of dry-core, open-ventilated type transformers

15.6 Location of Unit Substations

- References: Rule 2-308, Working space about electrical equipment; Rule 2-310, Entrance to and exit from working space

Comment: A minimum working space of 1 meter is required about a switchboard. This space is in addition to the space required for the drawout circuit breakers (see Figure 15.7, this text).

- *Figure 15.10* Clearance required by the CEC is a minimum of 1 meter at the rear and ends of the unit substation. The minimum clearance in front of the unit is 1 meter plus the space required to withdraw the largest circuit breaker.

Chapter 16

16.5 Design of an Electrical System

- The feeder conductors are to be type TW75. The 480Y/277 volt system is not a preferred voltage in Canada. A 347/600Y volt system would normally be used. However, the presentation serves as an example of the methods used to design a system.
- *Step 2* The ampacities of type TW75 copper conductors as per CEC Table 2 and the conduit size as per CEC Table 6 agree with the values as shown.
- *Step 5* The maximum rating for the trip unit of the motor branch breaker from CEC Table 26 (FLMA = 180 amperes) is 400 amperes (a 350 ampere trip rating is eventually selected in Step 11).
- *Step 6* The maximum setting of the trip unit for the feeder breaker is 400 + 425 = 825 amperes. The final setting selected in Step 12 is 840 amperes, which is satisfactory.
- *Steps 7 and 8*

  Reference: Rule 26-252 and Table 50, Overcurrent protection for power and distribution transformers rated over 600 V

  Comment: The values as selected for the primary fuse and the secondary breaker comply with the CEC requirements with regard to the overcurrent protection of the transformer.

Appendix B

ASSOCIATIONS THAT ISSUE ELECTRICAL STANDARDS

Standards are extensively used throughout the design and installation of the electrical system for a building. Standards establish specific requirements, such as the ratings and dimensions of equipment, performance requirements, methods of measurement and test procedures, and definition of electrical terms. The following associations issue standards documents that relate to electrical equipment and recommended practices for the installation of electrical systems.

United States

1. *American National Standards Institute* (ANSI): This association does not write standards. It promotes and coordinates the development of standards and approves as American National Standards those documents that are prepared in accordance with ANSI regulations.
2. *Institute of Electrical and Electronic Engineers* (IEEE): This association issues several hundred standards documents covering most fields of electrical engineering. Those that specifically relate to building electrical systems are listed in the Bibliography.
3. *National Electrical Manufacturers Association* (NEMA): This association prepares standards that establish dimensions, ratings, and performance requirements for electrical equipment among manufacturers.
4. *National Fire Protection Association* (NFPA): This association publishes standards documents specifying requirements for fire protection and safety. One of its publications is NFPA 70, *National Electrical Code (NEC)*.
5. *Occupational Safety and Health Administration* (OSHA): This administration of the U.S. Department of Labor is responsible for the Occupational Safety and Health Act. OSHA's electrical safety standards cover all electrical equipment and installations used to provide electric power and light for employee workplaces.
6. *Underwriters Laboratories, Inc.* (UL): Underwriters Laboratories, Inc., prepares safety standards for electrical equipment, including appliances, and tests equipment for compliance with these standards. Manufacturers whose products are approved by UL are authorized to use the UL label on the equipment.

Canada

1. *Canadian Standards Association* (CSA): This association prepares and publishes the *Canadian Electrical Code* (CEC). It also tests equipment for compliance with CSA standards. Manufacturers whose products are approved by CSA are authorized to use the CSA label on the equipment.
2. *Electrical and Electronic Manufacturers of Canada* (EEMAC): This association develops product standards for the electrical and electronic industry to encourage uniformity in equipment nomenclature, performance, rating, dimensions, and test methods and to assure users that the equipment complies with established performance, safety, rating, and capacity requirements. These standards are developed in cooperation with inspection authorities, utilities, user groups, consultants, CSA, and Canadian Government agencies.

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Chapter 8: Circuit Breakers

Breaker Basics. Beaver, Pa.: Westinghouse Electric Corporation, Low-Voltage Breaker Division.

Chapter 10: Grounding

Recommended Practice for Grounding of Industrial and Commercial Power Systems, ANSI/IEEE Std 142-1982. New York: The Institute of Electrical and Electronics Engineers, Inc.

Chapter 14: Motor Starters and Motor-Control Centers

Humphries, J. T., and L. P. Sheets. *Industrial Electronics*, 2nd ed. Boston: PWS–KENT Publishers.

Kosow, I. L. *Control of Electric Machines*. Englewood Cliffs, N.J.: Prentice-Hall, Inc.

Siskind, C. S. *Electrical Control Systems in Industry*. New York: McGraw-Hill, Inc.

Chapter 15: Secondary Unit Substations

Guide for the Application of Valve-Type Surge Arresters for Alternating-Current Systems, ANSI C62.2-1981. New York: American National Standards Institute.

Answers to Selected Problems

Chapter 1

1. 15 Ω
3. 6 A
5. 8 Ω
7. 200 V
9. 480 V
11. (a) 11.18 Ω (b) 0.894 [89.4%] (c) 4606 W
13. 5 A
15. 27.8 A
17. 20

Chapter 2

1. 91.3 lb. ft
3. (a) 900 rpm (b) 94.2 rad/s
5. 1164 rpm
7. 0.83 yr

Chapter 3

1. 750 lx
3. 125 fc
5. (a) 78.3 fc (b) 842 lx
7. 100 lm/ft^2
9. 1398 cd

Chapter 5

1. 500 lx (50 fc)
3. ρ_{CC} = 75%; ρ_{FC} = 25%
5. 0.80
7. 0.56
9. (a) 10.4 ft (b) 14.4 ft
11. 3 rows of 5; S_W = 14.0 ft, S_L = 12.0 ft
13. 27.0 luminaires
15. 2.13 W/ft^2
17. 0.82 yr

Chapter 6

1. (a) 75 A (b) 1200 A (c) Z_S = 0.0625 pu: I_{SC} = 16.0 pu
3. 0.015 pu
5. 32,800 A symmetrical

Chapter 7

1. (a) 0.12 s (b) 0.7 s (c) 70 s
3. 1.5 and 2.0 s
5. 125 A

Chapter 8

1. 65 and 24 s
3. 95 and 20 s
5. 2000 A
7. 360 A

Chapter 9

1. 1200 A
3. 8000 A

Chapter 10

1. No. 2 copper
3. No. 3/0 copper
5. 690,000 kW-cycles; extensive damage

Chapter 11

1. 69 A
3. 140 A
5. 118,000 A
7. 2″ C
9. 3½″C, 4-500 MCM, TWH (CU)
11. 2½″C, 4-250 MCM, TWH (CU)
13. 225 A frame, 225 A trip
15. 225 A, high interrupting capacity
17. two parallel runs, each 2″ C, 4-#3/0, XHHW (cu)

Chapter 12

1. Ampacity is 13.2 A; not satisfactory
3. (a) 4 circuits (b) 5 circuits
5. 9 circuits
7. 169 A

Chapter 13

1. No. 8 THW
3. 200 A
5. 100 A, 600 V
7. 60 A, 600 V
9. 250 A fuse; 250 V, 400 A switch
11. No. 4 THW
13. 80 A fuse; 600 V, 100 A switch

Chapter 14

1. (a) Size 3 (b) Size 2 (c) Size 5 (d) Size 4
3. Yes. Maximum protection allowed is 45 A
5. (a) Three vertical sections; 31 space factors used leaving 5 spare
   (b) Standard 600 A bus

Chapter 15

1. I_S = 1203 A; frame size is 1600 A
3. I_S = 2080 A; frame size is 3000 A
5. (b) I_P = 139 A; load-interrupter switch is 5 kV, 600 A
   (c) Transformer cubicle is 90″ wide
   (d) I_S = 2780 A; main bus is 4000 A and main breaker is 4000 A frame; use Unit 5, 34″ wide
   (e) Branch breakers, minimum 1600 A frame with interrupting capacity of 65,000 A sym at 208 V. Four vertical sections, similar to Unit 3, 26″ wide, for 10 branch breakers leaving 2 spaces.
   (f) Overall length of unit substation is 22′0″. Assume 66″ depth.
7. Branch breakers are 600 A frame (combination fused type). Three vertical sections, similar to Unit 2, 18″ wide, for 10 branch breakers leaving 2 spaces. Overall length of unit substation is 17′10″. Minimum room size is 27′10″ by 16′2″.

Chapter 16

1. Z_U = 0.0075 pu
3. I_{SC} = 13,700 A symmetrical
5. I_{SC} = 8130 A symmetrical
7. I_{SC} = 10.700 A symmetrical
9. (a) 35.6 A (b) 16.1 A (c) 38.5 A (d) 88.5 A
11. (a) 14.5 s (b) 15.5 s (c) 15 s (d) 15.5 s
13. 1600 A frame, 400 A sensor with LDPU set at 0.9
15. 200 A fuse assembly with 200 A fuse unit. Maximum permitted by code is 250 A.

Modifications to answers to suit Canadian Electrical Code

Chapter 10

1. No. 1/0 copper (service entrance feeders, CSA type TW75)

Chapter 11

1. 61 A (CSA type RW90 conductors)
3. 120 A (CSA type RW75 conductors and CEC Table 2)
7. 2½″ C [CSA type RW90(XLPE) conductors]
9. 3½″ C, 4-300 kcmil, TW75 (Cu)
11. 2½″ C, 4-250 kcmil, TW75 (Cu)
17. Two parallel runs, each 2½″ C, 4-#4/0 RW90(XLPE) Cu

Chapter 12

1. Ampacity is 9.24 A (CSA type TW75 conductors); not satisfactory
5. 10–15 A circuits
7. 190 A

Chapter 13

1. No. 8 TW75
3. 175 A
9. 300 A fuse; 250 V, 400 A switch
11. No. 4 TW75

Chapter 15

7. Minimum room size is 7.44 m by 4.68 m (use 0.80 m allowance for space required for the drawout circuit breakers).

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