DC POWER SYSTEM DESIGN FOR TELECOMMUNICATIONS

Whitham D. Reeve

IEEE Press Telecommunications Handbook Series
Whitham D. Reeve, *Series Editor*

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PREFACE

This is a book on the design of dc power systems that operate at nominal voltages of 24 and 48 V direct current (dc) and use lead–acid batteries and are used in public network telecommunications systems and other exclusive-use environments. Other voltages have been used over the years, but modern telecommunications systems in the United States use only these two voltages.

This is not a book on the theory of electrical power production, transmission, and distribution. Further, this book does not cover power-limited dc systems or components used with line-powered digital transmission technologies, such as the high bit-rate digital subscriber line (HDSL), T1-Carrier, and some proprietary line-powered access network equipment, nor does it cover older dc power technologies, such as counter emf (electromotive force) cells and end-cells (although these are briefly discussed in Appendix A). Further, this book does not cover audio tone and ringing systems (a traditional component in older telecommunications power systems), 130-Vdc systems, uninterruptible power systems (UPS), battery technologies other than lead–acid, or alternating current generating systems.

This volume was written for practicing telecommunications engineers and technicians because of their stated need for a book that concisely and systematically describes how to design telecommunications dc power systems. No work of this type exists in any language, so far as I am aware.

I started writing this book in the fall of 1973 when I first started working in the telecommunications industry; it took more than 30 years to write. The company I worked for at the time had neglected all of its dc power systems, and they all were badly overloaded, some to a frightening extent (busbars too hot to touch and warped so badly that wooden blocks had been strapped between opposite polarities to prevent a short). As a central office engineering manager, I suggested that "we need to do something," and I was told to "take care of it." And so I started my education, which continues to this day. Most of it has been the hard way.

It is important for the reader to know that dc power system design, as with all types of design, does not so much involve right ways or wrong ways but involves systematic analyses to make the most correct choices based on a number of economical, operational, electrical, and physical constraints. Just about all statements of practice and rules of thumb in this book have exceptions, and the reader is strongly cautioned to use common sense and good engineering judgment.

In preparing this book, I have kept two points in mind: first, to make statements as clear as possible, considering the technical nature of the subject; and, second, to present the facts accurately and as fully as necessary. I have sought to use plain language so that readers can obtain a clear understanding, but it is impossible to discuss any technical matter without using terms peculiar to it. Definitions of terms used in this book are traceable to industry standards and dictionaries and industry practice.

I have made some assumptions as to the reader's previous knowledge and experience. First, although I have tried to minimize the amount of mathematics, readers must be comfortable using algebra, which is the use of symbols and letters to state a generalized solution and then the substitution of specific numbers in place of the letters and symbols to solve a particular problem. Second, I have avoided the development of most concepts from so-called first principles. I do not believe such development is necessary to the understanding and design of low-voltage dc power systems. However, after introducing and briefly describing the basic components of dc power systems in Chapter 1, I have laid down the basic principles of electricity in Chapter 2. More experienced readers may find Chapter 2 unnecessary, although those same readers may find the information interesting and worth reviewing. The remaining chapters describe the power system components (Chapter 3), battery systems (Chapter 4), system design (Chapter 5), and system installation and maintenance (Chapter 6).

Several reviewers have provided very helpful suggestions and criticism. I am especially grateful to Marco Migliaro, Percy Pool, and Roy Thompson, who carefully went over the manuscript and made many important suggestions that greatly improved the general presentation.

This book, as it is presented in this first edition, is far from being perfect. However, it is a good start, and I believe that the demand is sufficient to warrant its immediate publication. But it is my purpose to work and ask others to work at its improvement and elaboration.

I ask for private communications from readers stating where they have found the writing unclear, or suggesting information not contained in it (I already have a list for a future edition). Such suggestions will be a valuable aid to future enlargement and revision. You can contact me at w.reeve@ieee.org.

Finally, although the focus of this book is telecommunications systems, much of the material also applies to low-voltage dc power systems used in other industries.

WHITHAM D. REEVE

Anchorage, Alaska
September 2006

CHAPTER 1

INTRODUCTION

This chapter provides a brief description of requirements and the basic elements and components that make up telecommunications direct current (dc) power systems, including their associated alternating current (ac) power sources. Also included in this chapter are brief descriptions of system design considerations. Design considerations are described in greater detail in subsequent chapters.

1.1 BASIC REQUIREMENTS FOR TELECOMMUNICATIONS POWER SYSTEMS

The basic requirements for a telecommunications power system are listed in Table 1.1. Designing to achieve these requirements entails the analysis of many details and considerations (Table 1.2).

1.2 APPLICATIONS REVIEW

Telecommunications dc power systems and modern network equipment in the United States most often operate at nominal voltages of 24 or 48 volts dc (Vdc). Other voltages

Table 1.1 Basic Requirements for Telecommunications Power Systems

Requirement	Achieved by
• Provide uninterruptible power to critical loads	• Using batteries to bridge interruptions
• Be safe to workers and the public	• Using relatively low voltages, current limiting and grounding
• Have long life (20–30 years, or more)	• Using conservative design and planned preventive maintenance

Table 1.2 Detailed Requirements and Considerations

Detailed Requirement	Design Consideration
Voltage tolerance range of the load equipment	• Requirements for minimum and maximum equipment operating voltages • Circuit conductor voltage drops • Battery float, equalize, and final discharge voltages
Control of noise on the supplied voltage	• Voltage and current ripple limits on rectifier output circuits • Conducted emissions to and from load equipment[a] • Proper grounding and bonding • Power filters near load equipment
Monitoring and signaling	• Alarm thresholds • Signal alarms when performance thresholds have been exceeded • System control and metering
Protecting and limiting of electrical circuits	• Equipment malfunctions and circuit faults • Overcurrent protective device ratings • Conductor current rating (ampacity)
System operation and maintenance	• Skill and training levels for daily operation and routine repair • Ease of repair and routine maintenance
Expansion and extension	• Growth and changes during the life of the system • Minimizing or eliminating service outages
Capital investment and operating and maintenance costs	• Engineering economy • Budget constraints and requirements
Floor space and structural requirements	• Building modifications and strengthening before and after initial system installation • Floor and wall penetrations for cabling
Specifications and regulations	• Compliance with industry standards, codes, and company practices • Listing with independent testing laboratories
Prime and standby power sources	• Long-term requirements • Reliability and availability • Operating costs • Electrical distribution • Voltage and current ratings • Standby system fuel type and prime mover technology

[a] Conducted emissions are noise currents that follow a conductive path into or out of the equipment, for example, via power or signal leads.

have been used over the years to meet specific system requirements, but they are not used in modern systems and are beyond the scope of this book. Also beyond the scope of this book are power-limited and current-limited higher voltage systems used to power access network equipment and subscriber terminals such as optical network nodes, high bit-rate digital subscriber line (HDSL) technologies and other line-powered transmission technologies. Telecommunications power systems are used in many types of facilities and locations,

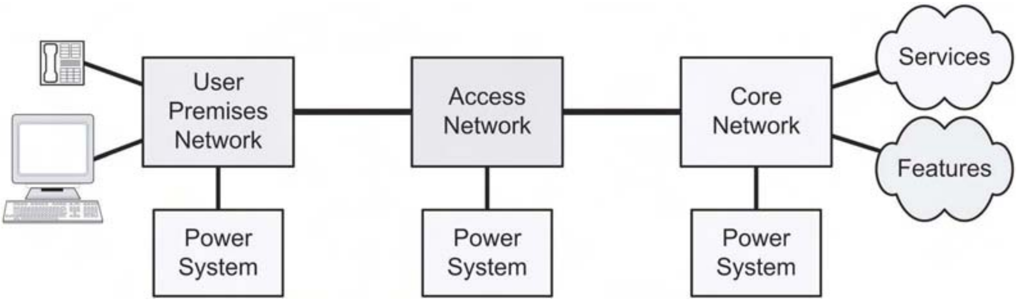

Fig. 1.1 Power systems applications in the telecommunications network.

including core network central offices, access nodes, user premises, and where network operators are collocated (Fig. 1.1).

Central offices, also called *wire centers,* contain core telecommunication facilities including end office, access tandem, and transit switching systems, mobile switching centers, packet switches and routers, fiber-optic and other digital landline transmission system terminals, terrestrial microwave radio terminals, and satellite earth stations (Fig. 1.2). Core network facilities provide user (subscriber) features and services.

Access networks deliver the services and features from the core to the user and include landline facilities, such as metallic twisted pairs and optical fibers, fixed and mobile wireless base stations, and, in some cases, satellite earth terminals dedicated to individual users. Access nodes are important in any modern access network. They include transmission and multiplexing facilities, such as digital loop carrier (DLC) systems, optical network units (ONU), optical network terminations (ONT), and other electronic systems deployed close to the user.

All but the simplest telecommunications terminals require on-site power systems for the facilities that are located on user premises. These power systems can be low-current systems (fractions or a few amperes at 24 or 48 Vdc) or complex systems equivalent to those used in the core network. The so-called lifeline POTS (*plain old telephone service*) lines generally are line powered over the metallic twisted pair plant from the central office or serving access node. In some modern technologies, such as voice-over-packet [e.g., voice-over-asynchronous transfer mode (VoATM) and voice-over-Internet protocol (VoIP)], the network equipment located on the user premises requires more power than can be delivered over the access network. In those cases, a local power supply including battery is required to ensure that regular telephone service is available during commercial power outages at the premises.

Collocation of telecommunications core and access network equipment owned by different network operators is another application for dc power systems. In some cases, such as a "carrier hotel,"[1] space may be provided for a number of different network operators, each with its own power system. In other cases, a single large centralized power system provides power to numerous network operators.

---

[1] A "carrier hotel" is a euphemism used to describe a building that is occupied by a number of different and sometimes competing network operators. These network operators, including competitive local exchange carriers (CLEC) generally differ from the incumbent local exchange carrier (ILEC) serving the area in that the CLECs do not have extensive access network infrastructure.

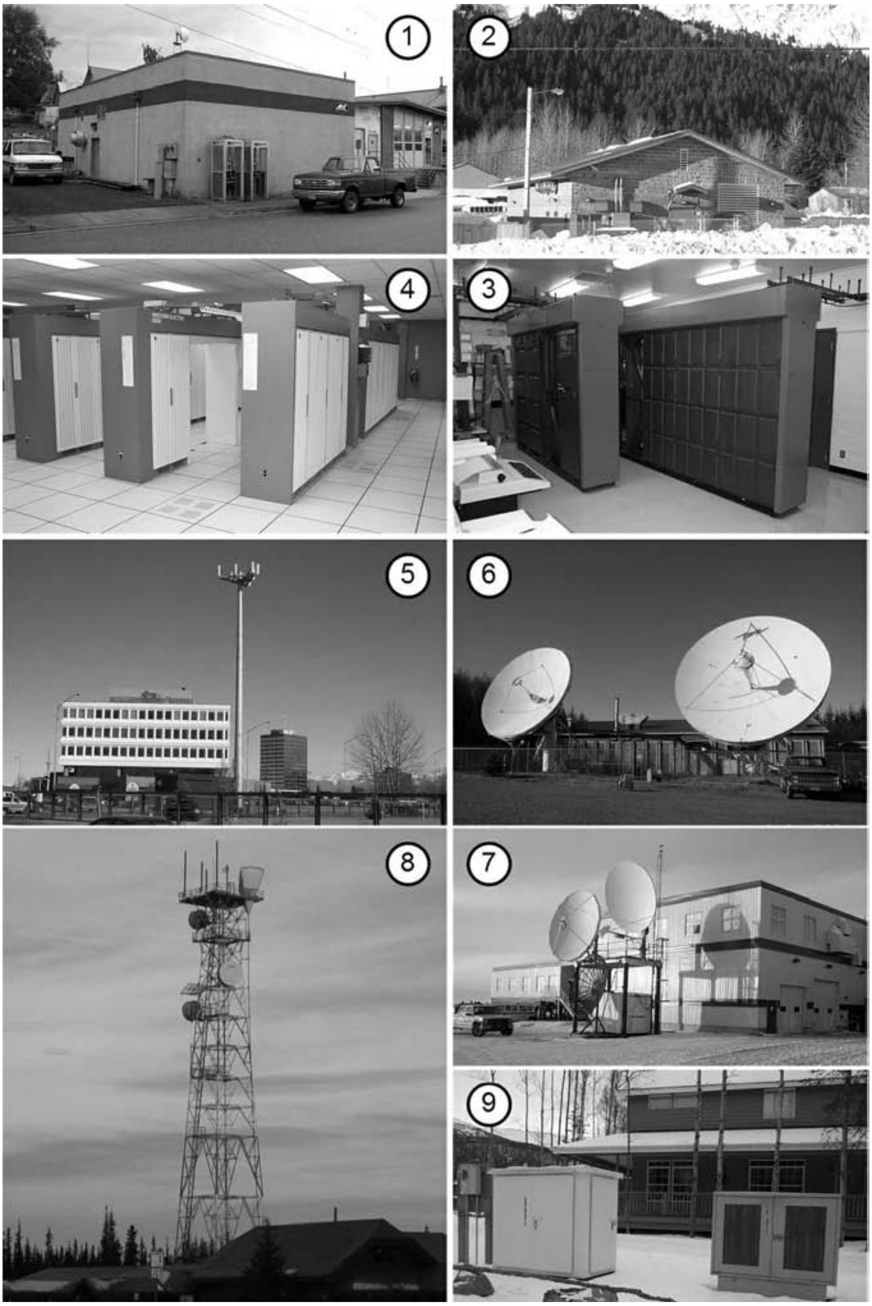

Fig. 1.2 Applications—central office buildings (wire centers) (1 and 2), switching systems (3 and 4), mobile wireless (5), satellite earth stations (6 and 7), terrestrial microwave radio (8), access mode (9).

1.3 DIRECT CURRENT POWER SYSTEM ELEMENTS

A telecommunications dc power system consists of seven basic elements, shown schematically in Figure 1.3:

- Rectifier (charger) system
- Battery system
- Charge bus
- Discharge bus
- Primary distribution system
- Secondary distribution system
- Voltage conversion

The following brief descriptions are keyed to the more detailed block diagram in Figure 1.4. All components are described in greater detail in Chapter 3 (dc Power System Components). The design and selection of the various system components are described in Chapter 5 (System Design).

① *Rectifiers* (also called chargers) convert the prime power source ac voltage to direct current (dc). Rectifiers serve three main purposes:

a. Power the loads when commercial ac power is available.
b. Supply float charge to the battery to overcome battery internal losses.
c. Recharge the battery upon restoration of commercial power after failure while simultaneously supplying the normal equipment load.

② *Battery,* which is an energy storage device, powers the loads during prime power ac outages (Fig. 1.5). The battery always is connected directly to the discharge bus (de-

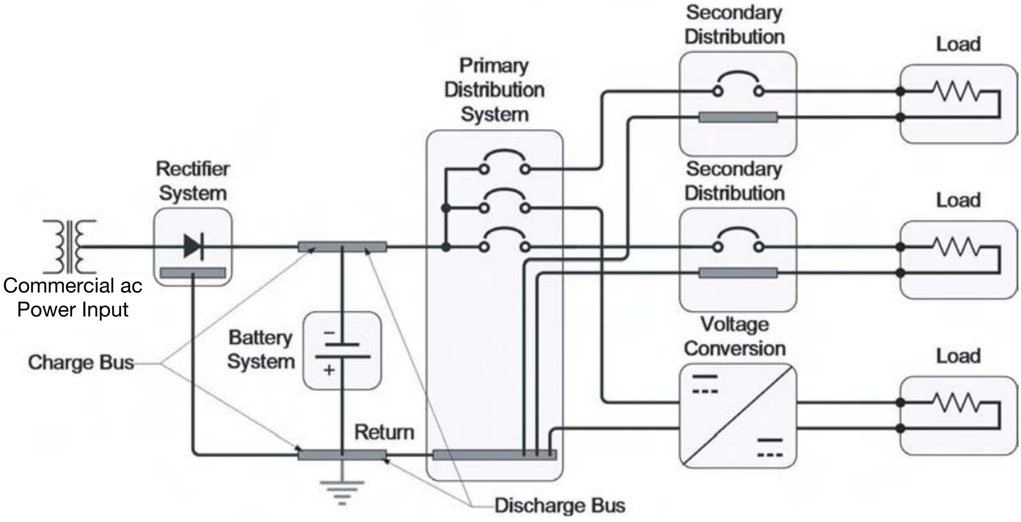

Fig. 1.3 Simplified schematic of a telecommunications dc power system.

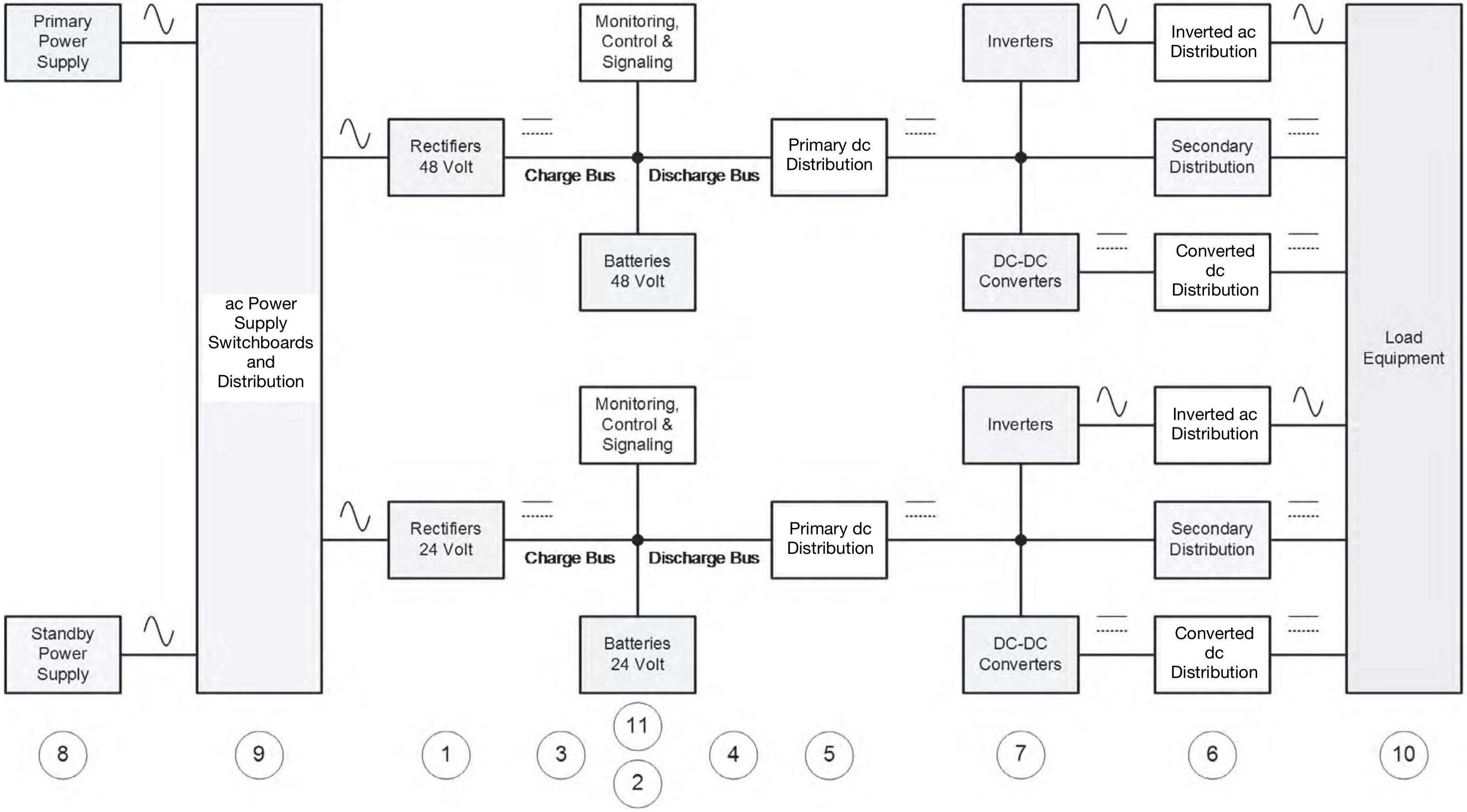

Fig. 1.4 Basic elements of a telecommunications dc power system.

Fig. 1.5 Battery system (battery and battery disconnect switches are in the left half and the rectifiers and powerboards are in the right half of the picture). (Photo courtesy of Power-One Inc.)

fined below) so there is no switchover time or interruption when the prime power source (and standby source, if equipped) fails or if the rectifier system fails.

③ *Charge bus* provides a centralized location for connecting rectifiers to the battery. The charge bus carries equipment load current and float charge current for the batteries during normal operation. When the ac power source fails, the charge bus carries battery discharge current to the discharge bus. Upon restoration of the ac power source, the charge bus carries equipment load current and battery recharge current. A separate busbar is provided for the positive (+) and negative (–) outputs of the charge bus.

④ *Discharge bus* provides a centralized location for connecting the battery and rectifiers to the primary dc power distribution system. In most power systems, the charge and discharge buses are rigid copper busbars separated by a current shunt and, in some installations, a low-voltage disconnect device (Fig. 1.6). A current shunt is a low-resistance, high-power resistor for measuring load current. The load current causes a small voltage drop across the accurate resistance, which is measured by a voltmeter in the *monitoring and control system.* The low-voltage disconnect device disconnects the loads from the battery to prevent battery overdischarge or to prevent undervoltage damage to equipment. As with the charge bus, a separate discharge busbar is provided for the positive (+) and negative (–) outputs. In most installations the charge and discharge return buses are one continuous busbar.

⑤⑥ *Distribution systems* provide central locations for feeding loads and for protecting circuit wiring. The distribution systems also provide a convenient way to isolate indi-

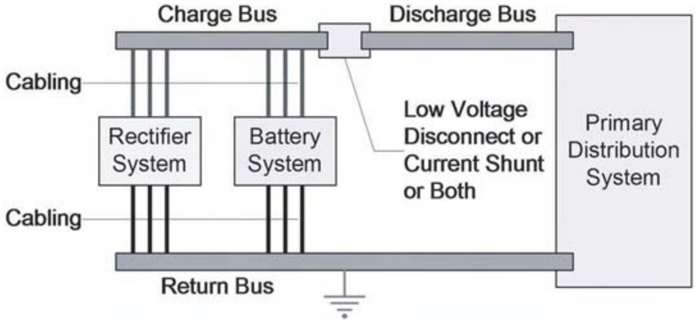

Fig. 1.6 Typical charge and discharge bus arrangements.

vidual loads from each other during fault conditions. The *primary distribution system* (⑤) has the first overcurrent protective device (either fuse or circuit breaker) between the discharge bus and the load. Sometimes the primary distribution system is given the unwieldy name battery distribution fuse bay (BDFB) or battery distribution circuit breaker bay (BDCBB), depending on the type of overcurrent device. Although the primary distribution system can directly feed loads if desired, a *secondary distribution system* (⑥) may be used. The secondary distribution system is an intermediate protected distribution network between the primary distribution network and the load equipment. There can be one or more secondary distribution systems, which serve individual loads or groups of loads downstream from the primary distribution system.

⑦ *Voltage converters* consist of two basic types: DC–DC converters and inverters. DC–DC converters change the battery–rectifier system voltage and polarity to other utilization voltages and polarities. Inverters change the dc back into ac, typically 120 Vac, 60 Hz, for ac-powered load equipment that requires an uninterruptible, or *protected,* ac supply. Each such voltage conversion system usually has its own distribution system for connecting and protecting load circuits.

In addition to the main components just described, all dc power systems include *ancillary systems* such as

⑧ *Prime and standby ac power systems.* Commercial electric utility ac power systems almost always are the first choice for providing power to telecommunications facilities so, when available, they are called prime power sources. At many sites, but not all of them, standby power is provided by an engine–generator set fueled by diesel, propane (liquefied petroleum gas, or LPG) or liquefied natural gas (LNG)[2] (Fig. 1.7).

Many remote sites are not served by commercial power supply systems. In this case, on-site generation is required in which case the local generation system is the prime power source. A number of technologies may be used including internal combustion engine–generator sets, wind generator sets, thermoelectric generators, solar (photovoltaic) generators, fuel cells, and, occasionally, hydroelectric stations. Hybrid power systems, consisting of two or more technologies, are used at many sites (Fig. 1.8). The battery re-

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[2] LPG is either propane or a mixture of propane and butane, but domestic bottled gas normally is plain propane. LPG is produced in the extraction of heavier liquids from natural gas and as a by-product in petroleum refining. LNG is created by refrigerating subterranean natural gas. This reduces the volume by approximately 600 times for transport. LNG is then converted back to a gas by warming it.

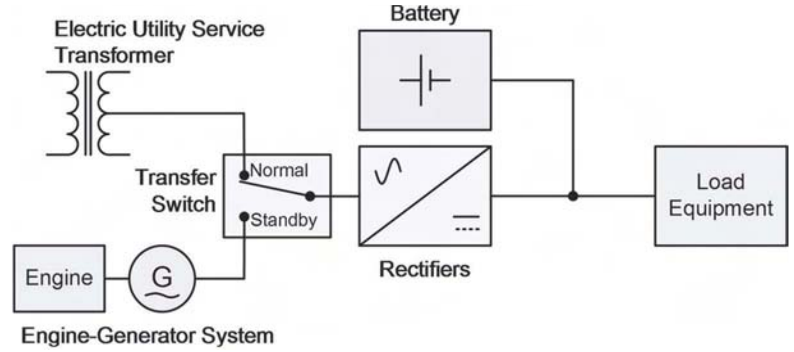

Fig. 1.7 Electric utility (prime) and engine–generator (standby) ac power systems.

serve time requirements generally are relaxed at sites with multiple primary sources or standby generation.

⑨ *Alternating current power distribution system.* Commercial ac systems consist of an electric service entrance and metering and distribution switchboards or panelboards (Fig. 1.9). Panelboards include circuit breaker panels for overcurrent protection of ac circuits and a transfer switch for transferring from the prime ac supply source to the standby source upon failure of the prime source. Not all sites have a standby source, in which case the transfer switch and standby generator system components are not equipped and the service entrance is connected directly to the distribution panelboard. Alternating current distribution systems are used not only for the rectifiers but also for lighting, heating, ventilating, and air conditioning (HVAC), convenience receptacles, and other ac-powered equipment at the site. Depending on the prime service voltage, the ac distribution system may include step-up or step-down transformers to match supply voltages to load equipment utilization voltages.

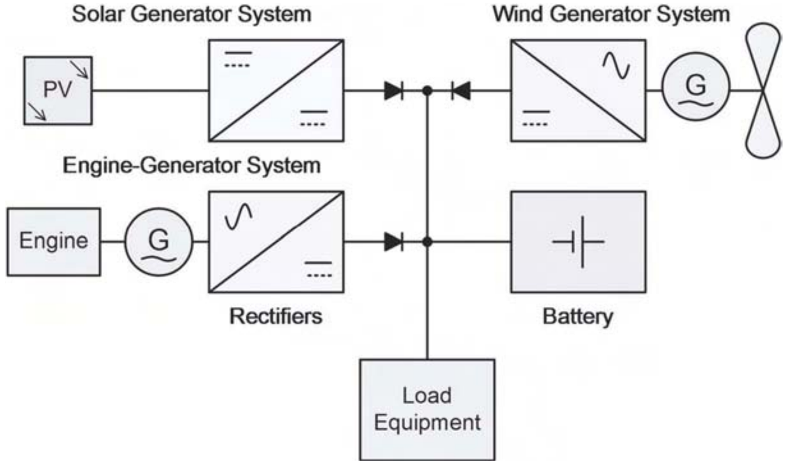

Fig. 1.8 Block diagram of a hybrid power supply system.

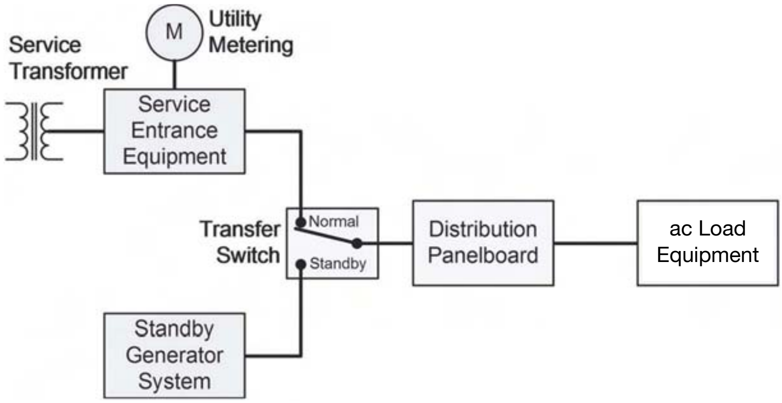

Fig. 1.9 Simplified on-site ac power distribution system with standby generator.

⑩ *Load equipment* includes all the network equipment and associated operational support systems at the site that are required to be powered by the dc system. Depending on the site purpose, this can include core switching, multiplexing and transmission equipment, wireless base stations, and related dc and ac-powered equipment.

⑪ *Monitoring and control system* includes alarm collection, processing and sending systems, and metering. Control systems include rectifier float/equalize control and timing, parametric recorders, and local area network (LAN), serial port, and modem interfaces.

Other important infrastructures required for power system operation are:

- *Cable and rigid bus supporting structures* are cable and ladder racks and raceway systems used to physically protect and support wire and cable.
- *Equipment frames* are assemblies of equipment or components mounted on a common support structure. Other names are *relay rack, bay,* and *cabinet;* however, relay racks are open on all sides while bays and cabinets usually are enclosed frames with doors for access to the front and rear.
- *Powerboard* is an equipment frame or frames containing dc power equipment such as the charge and discharge busbars, rectifiers, primary distribution system, and power system controllers, meters, and alarm panels (Fig. 1.10). Power system frames usually are dead-front, which means no live parts are exposed to persons on the operating side of the equipment. Live-front, on the other hand, means live (conductive) parts with potential difference with respect to ground are exposed to persons on the operating side of the equipment. All modern power system frames are dead-front.
- Special *floor structural components* or physical support systems may be required for batteries due to their high weight and small footprint.
- *HVAC* and *lighting* are required in all installations.
- *Grounding system* is a system consisting of earth grounding electrodes and interior grounding busbars and components. All dc power systems used in telecommunications are referenced to earth ground. Telecommunications facilities grounding electrode systems may consist of buried copper grids or plates, ground rods, water

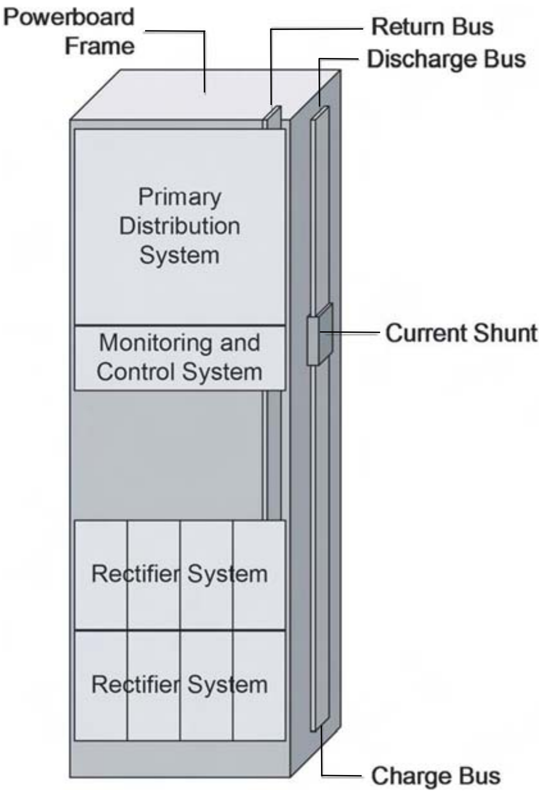

Fig. 1.10 Powerboard frame assembly.

wells, concrete encased electrodes (footings and slabs), buried copper radials at an antenna supporting structure and other buried metallic components, and building structural steel. Grounding systems also include lightning and surge suppression systems.

- Older end office switching systems required central ringing voltage and precision audible tone supplies (e.g., ringback tone and dial tone), which were provided as part of the dc power system. However, almost all modern switching systems have integrated power supplies for these purposes and their design is beyond the scope of this book.

A common method of improving the reliability and performance of dc power systems is through redundancy of components, such as rectifiers, circuits, and batteries. Typically, component groups, such as rectifiers, are sized and equipped such that the failure of any one of them does not result in any service degradation and the remaining components in that group carry the load. Circuit redundancy is provided by running two independent circuits (A and B) from the primary distribution system to all secondary distribution systems and to all load equipment. It also is possible to provide two independent power systems that are interconnected only by common reference to the earth grounding electrode system.

1.4 POWER SOURCES AND LOADS

A system may include a number of different power sources, including prime and standby power sources and energy storage systems, such as batteries.

1.4.1 Prime Power Sources

Prime power sources by their nature are very reliable. The most common prime power source is the commercial electric utility that serves the telecommunications facility. Commercial electric service normally is less expensive than alternate prime power systems.

Commercial electric utility systems have quite high reliability, but they are nevertheless subject to interruption or outage, and the reliability is not 100% when measured over months, a year, or several years. Any interpretation of what is termed an interruption includes the magnitude and duration of the voltage dip. For purposes of telecommunications dc power system design, interruption is defined in terms of a minimum duration and assumes the voltage is zero during that period. Interruptions may last from fractions of a millisecond (microinterruptions) to weeks. Interruption statistics vary widely by region and area of the country and only gross generalizations can be made about them.

It is important that commercial electrical service interruptions do not affect network equipment. All modern network equipment is based on processor-controlled digital technology, and these systems cannot withstand even a short loss of voltage. Some equipment or systems that support network equipment can withstand varying degrees of interruption. For example, the dry air pressurization systems for waveguide and coaxial cable transmission lines can loose power for significant time periods—hours or even days—depending on how leakproof they are. Other equipment may operate correctly if the interruption does not exceed a few seconds but may fail or need to be restarted on longer interruptions.

Short-time interruptions in the millisecond range may be bridged by the capacitors in rectifier and chassis power supply output filtering circuits. Longer duration interruptions are bridged first by batteries, which are online all the time, and ultimately by standby power systems such as engine–generator sets if the site is so equipped. If not equipped, the network equipment stops working or falls out of specification when the batteries discharge to the *minimum equipment operating voltage* or when the battery voltage reaches the threshold of the low-voltage disconnect (LVD) and the LVD disconnects the load.

Electric utility circuit switching and automatic circuit reclosing during faults (e.g., line slap during wind storms, lightning, or trees falling into lines) typically cause interruptions lasting less than 0.5 s. Most utility interruptions last less than 30 min, but some may last much longer; the interruption frequency and duration can be higher in some rural areas. Longer interruptions usually are due to

- Electrical equipment failures (e.g., damage to service transformers, distribution lines, or substations)
- Natural disasters (earthquakes, floods)
- Weather (hurricanes, tornados, freezing rain, and severe storms)
- Cascading faults in large interconnected electric power grids (when large power systems collapse, the resulting outages may last for several days or even weeks in some areas)
- Human error

Where commercial electric service is not available, an alternate prime power source must be used to power the telecommunications power system. A variety of prime movers (means to mechanically power an electrical generator) and other energy sources are available, both nonrenewable and renewable (Table 1.3). The most common prime mover falls in the broad category of reciprocating internal combustion (RIC) engine. A number of different RIC engine technologies are available including air and liquid-cooled spark ignition (e.g., gasoline) and air- and liquid-cooled compression ignition (e.g., diesel). Both spark and compression ignition engines can be set up with multifuel capability. Gas-turbine (GT) engines also have been used successfully as prime movers, particularly in larger installations. So-called microturbines are seeing greater use as power sources in small systems. Many full-size GT and microturbines have been adapted from aircraft engines or aircraft auxiliary power units (APU) and can have multifuel capability.

1.4.2 Standby Power Sources

On a unit power or energy basis, standby power sources usually are considerably more expensive than a comparably rated prime power source and are run only when the prime power source fails. Although they may use the same basic technologies as prime power sources, standby power sources are designed to run for much shorter time periods such as hours, days, or a few weeks at a time. Standby sources run, on average, a few hours a month or year, although there are many sites that vary considerably from the average. At locations where the prime power source is reasonably reliable, standby sources may run only a few hundred hours over their lifetime, and most of that time is during regularly scheduled exercising tests.

The most common standby power sources are diesel, natural gas, or propane-fueled RIC engine–generator sets. Gasoline seldom is used because it is too difficult to safely handle and store. Where engine–generator sets are used in standby service, they usually have higher power ratings than comparable sets used in prime power service (this can be done without compromising the engine because of the relatively low duty cycle in standby service).

Table 1.3 Prime Movers and Other Energy Sources

Nonrenewable Energy Source	Prime Mover or Generator
Biomass[a]	Reciprocating internal combustion (RIC) engine
Diesel	RIC or gas-turbine (GT) engine
Gasoline	RIC engine
Heavy oil	RIC engine
Jet fuel	RIC or GT engine
Kerosene	RIC or GT engine
LPG and LNG	RIC or GT engine
Wood gas	RIC engine
Renewable Energy Source	**Prime Mover or Generator**
Hydrogen	Fuel cell (no prime mover)
Sunlight (solar)	Photovoltaic (no primer mover)
Water	Water turbine
Wind	Wind turbine

[a] Timber and agricultural residues, nonhazardous solid waste, wastewater, and animal manures.

For convenience, the standby system generation voltage and frequency generally is the same as the prime power source. In remote unattended sites there may be advantages to directly generating direct current at the telecommunications system operating voltage.

Standby systems can be designed to automatically start and stop and to switch to and from online operation, or they may be manually started and switched. In some installations, there is no permanent standby system installation except for a generator electrical receptacle and transfer switch. In this case, a portable generator set is hauled to the site, plugged in and run for the duration of the outage. The battery must be large enough to bridge the interruption until the generator arrives and is placed online, while accounting for inevitable problems in dispatching and setting up portable equipment.

1.4.3 Alternating Current Power System Loads

The ac power system at a telecommunications facility serves a variety of ac loads. The loads can be categorized according to their importance as nonessential, essential, and protected (Fig. 1.11).

Nonessential Load An ac load that does not need to operate during prime ac power outages of any length.

Essential Load An ac load that must operate during extended prime ac power outages but can tolerate power interruptions lasting a few or several seconds, or possibly longer. During longer prime power source outages, essential ac loads are powered by a standby engine–generator set if the site is so equipped.

Protected Load An ac load that cannot tolerate any interruption of its input power. Protected ac loads (other than the dc power system rectifiers) are powered by an *inverter* that, in turn, is powered by the dc power system battery during outages. Some protected loads only need to operate long enough for an orderly shutdown. In these cases, an Uninterruptible Power System (UPS) is used to power the load.[3]

1.4.4 Energy Storage

A battery is an electrochemical storage device that takes energy from the prime power source through the rectifier system and stores it as chemical energy. Upon failure or interruption of the prime power source or rectifier system, the battery reconverts the chemical energy to electrical energy and powers the network equipment loads. Both lead–acid and nickel–cadmium (NiCd) batteries are used in telecommunications with lead–acid types being the most common and the only type considered in this book.

Two basic lead–acid technologies are used—*vented lead–acid* (VLA) and *valve-regulated lead–acid* (VRLA). A VLA battery consists of cells that allow gases evolved during operation to escape from the cell containers. A VRLA battery consists of cells with a pressure relief valve that prevents the relatively low amounts of evolved gas from escaping during normal operation, allowing the gases to recombine and eliminating the need to periodically add water to the cells.[4] However, during abnormal operation the gases are allowed to escape through the pressure relief valve.

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[3] In general, most stand-alone uninterruptible power systems have a relatively short battery reserve time—typically 15 min to 1 h—compared to the telecommunications dc power system.

[4] The recombination process is not 100% efficient so a small amount of gases will eventually escape.

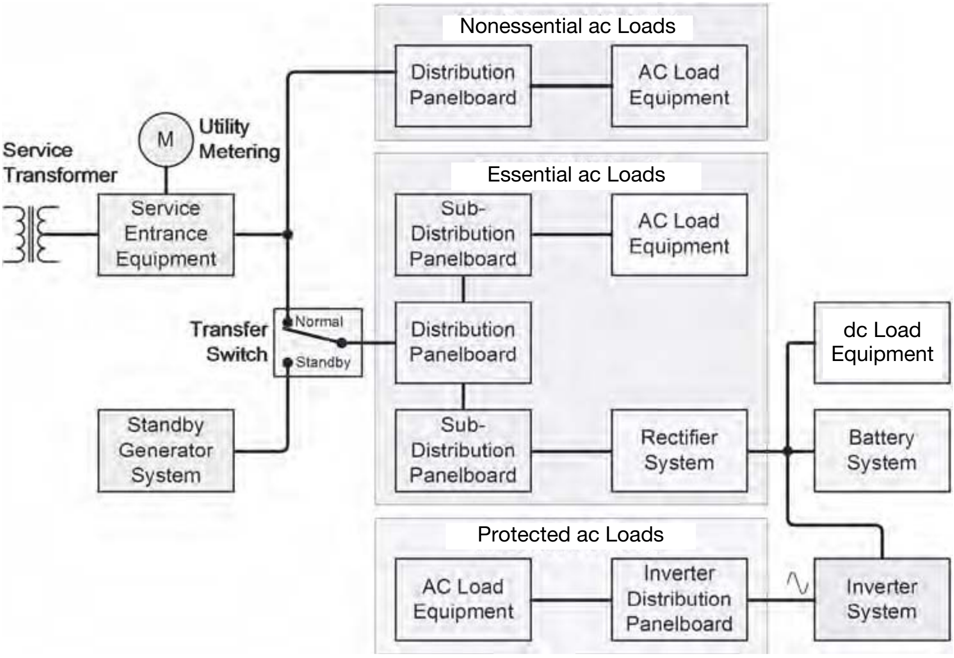

Fig. 1.11 Alternating current (ac) load categories—nonessential, essential, and protected.

Batteries used in telecommunications are classified as secondary (rechargeable) and for stationary (fixed) service.[5] Because of their different electrical characteristics, individual battery designs can be categorized according to their reserve times:

- Batteries for short-term loading (< 1 h)
- Batteries for long-term loading (> 1 h)

Telecommunications applications fall into the long-term loading category, and that category is the focus of this book. All telecommunications batteries of concern here use lead-active materials in the plates and a dilute electrolyte of sulfuric acid in water. In VRLA batteries the electrolyte is immobilized as a gel or absorbed in a glass fiber mat separator between the lead plates. In VLA batteries the electrolyte is a free liquid.

A battery, or battery string, consists of a number of cells connected in series. Each cell has a nominal voltage of 2 V. Modern telecommunications dc power systems in the United States use 24 or 48 V (or both) and the battery strings consist of 12 cells and 24 cells, respectively. Other cell counts are sometimes seen in older systems. Battery plant capacity can be increased by connecting individual strings in parallel (Figs. 1.12 and 1.13). Batteries and battery systems are described in detail in Chapter 4 (Telecommunications Batteries).

There are numerous other energy storage devices that are promising for telecommunications power system applications, particularly fuel cells (fuel cells convert the chem-

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[5] Primary batteries are not rechargeable and are disposable. A familiar example is a simple flashlight battery.

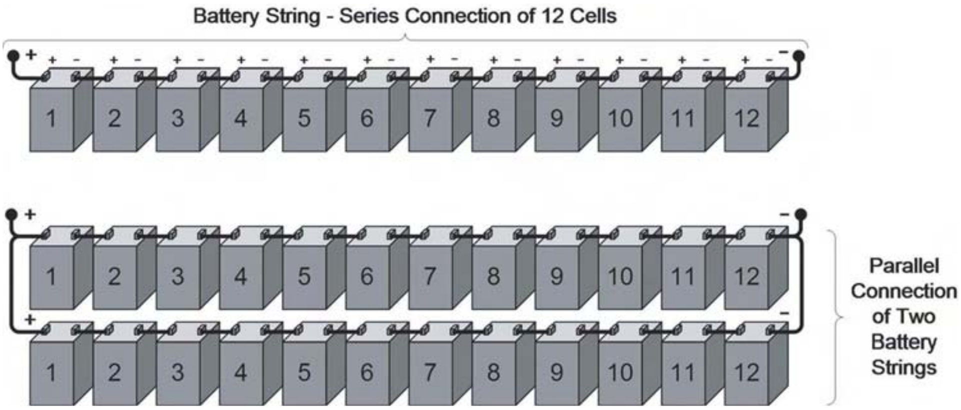

Fig. 1.12 Twelve-cell (24-V) battery strings (*upper,* series arrangement; *lower,* series–parallel arrangement).

ical energy of hydrogen to electricity without combustion and with little pollution). Also, there are battery active materials other than lead that are becoming more important. However, at the time of this writing (2005), none of these alternate technologies adequately meet the cost requirements of the typical installation supplying several tens to thousands of amperes of load current over 3-h or longer reserve times. These alternate technologies presently are suitable in small applications where at most only a few amperes are required, and their size and cost do not present undue economic penalties.

1.4.5 Voltage Magnitudes

1.4.5.1 Alternating Current The ac power systems in the United States operate at a frequency of 60 Hz, and the service voltages at buildings and facilities are standardized. For many facilities, the service voltages are nominally 120 V line-neutral and 240 or 208 V line-line, depending on whether the service is one-phase or three-phase, respectively.

Fig. 1.13 Battery systems (24-cell VRLA on the left and 24-cell VLA on the right).

Another common three-phase service voltage is 277 V line-neutral and 480 V line-line. Larger facilities may be served at primary voltages in the range of 7 kV line-neutral and 13 kV line-line, or higher.

1.4.5.2 Direct Current

The *nominal* dc system voltages used by modern telecommunications facilities in the United States are either +24 or –48 V. A +24 Vdc system has its negative terminal bonded to the facility earth grounding system. A –48 Vdc system has its positive terminal bonded to the earth grounding system. The positive terminal on 48-Vdc power systems originally was connected to earth to reduce galvanic corrosion due to leakage currents on buried lead-sheathed outside plant cables and other metallic pipes (water, gas) and components buried in the ground. Although lead is no longer used to sheath outside plant cables, the practice continues to minimize corrosion on existing lead-sheath cables and other buried metallic components. Systems that use 24 Vdc normally do not have any buried components and thus are not subject to corrosion. For example, 24-V private branch exchanges (PBX) normally do not have outside plant twisted-pair cables, and 24-V radio frequency (RF) base stations do not have buried outside plant coaxial cables.

Both 24- and 48-V systems fall in the 60-Vdc class and are considered central supply systems that directly feed the loads. Other voltages have been used in the past including ±130 Vdc for powering T1-carrier span lines[6] and coin telephone collect and return circuits. These higher voltage systems fall in the 160-Vdc class and are not covered in this book because they are not used in modern telecommunications systems.

1.4.6 Direct Current Power System Loads

Most load equipment uses distributed, or decentralized, power supplies to convert the 24- or 48-V direct fed voltages to component or electronic voltages, such as 5 and 12 V (Fig. 1.14). These voltages are provided by on-board or chassis-mounted DC–DC converters (e.g., 48 to 5 Vdc).

All load equipment has a voltage tolerance specified by a minimum and maximum operating voltage. The minimum voltage determines when the equipment stops operating or no longer meets operating specifications as batteries discharge during a prime power source or rectifier system failure. The maximum voltage determines the upper limit at which the equipment can safely operate without damage either from electrical stress or heat damage. The type of battery technology and the voltage at which it is charged affects the maximum operating voltage.

Load equipment spends most of its time at a voltage somewhat higher than the nominal system voltage, typically 9 to 14% higher. For example, –48-Vdc systems with 24-cell VRLA batteries typically operate at 54.0 to 54.5 V. The actual magnitude of the operating voltage varies with the type of battery technology and other factors, but the overall change from the minimum to maximum is around 25 to 30% (e.g., 44 to 56 Vdc). Some modern load equipment has a much wider range, on the order of 100% (e.g., 36 to 72 Vdc). However, in a given central office or telecommunications facility, the equipment

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[6] T1-carrier is a type of twisted-pair transmission system originally deployed in the early 1960s that uses line-powered repeaters to extend its operating distance to as far as 200 miles (320 km). Although T1-carrier still is used today, line powering is by individual line interface units called central office repeaters and not by a centralized system.

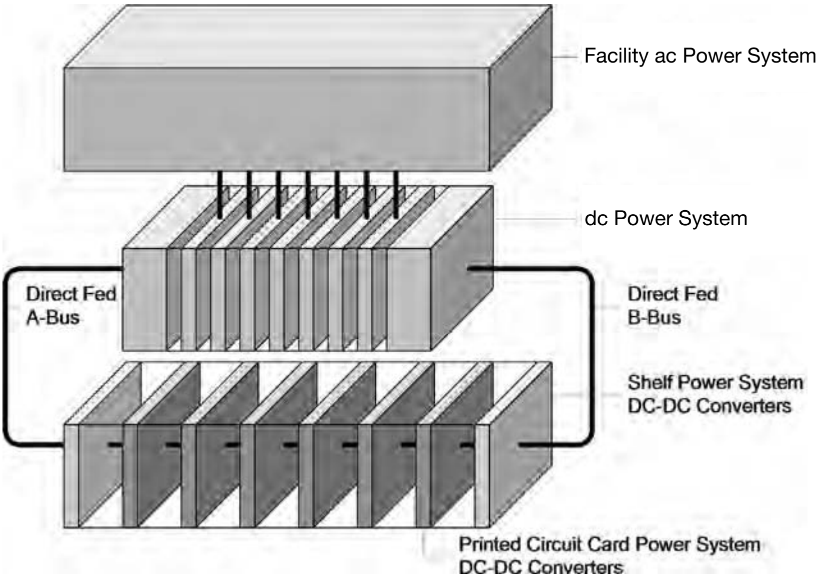

Fig. 1.14 Decentralized power for network equipment shelves.

with the *highest* minimum operating voltage and the *lowest* maximum operating voltage determines the actual design voltages for the power system.

Network equipment loads fall into two basic categories, resistive and constant power, with most modern loads in the constant power category. Resistive loads draw current in proportion to the applied voltage. Therefore, when a discharging battery powers a resistive load, the load current decreases as the battery voltage decreases. On the other hand, the current to constant power loads is inversely proportional to the voltage, and the load current increases as the discharging battery voltage decreases.

1.5 GENERAL DESIGN CONSIDERATIONS

A telecommunications dc power system is required to provide the specified voltage range at the load equipment under all operating conditions. When the commercial ac power system fails, the dc power system must operate the load equipment for a specified battery reserve time. Power system design involves many variables including *battery reserve time, circuit current ratings,* and *voltage drop* in the battery circuits and dc distribution circuits. Other design considerations include the choice between rigid bus and cable bus in feeder and distribution circuits, rectifier sizing, and voltage conversion device sizing.

1.5.1 Design Loads

For convenience, dc load currents are separated into two basic categories called *normal* and *peak.* Normal current specifies the average load current during normal operation. Normal load current is used to size rectifiers. Rectifiers are relatively easy to add to an operating system and their ratings and quantities are based on the initial and ultimate normal equipment loads. In some telecommunications switching systems and wireless base stations, the load current depends on traffic levels, so the normal load current takes into account peak traffic conditions associated with these equipment types.

Peak current specifies load current during worst-case conditions of low battery discharge voltage. Peak currents include inverter loads if the inverter is offline during normal conditions (if the inverter in online during normal conditions, its load is included in the normal category). Peak load currents are used to size equipment that cannot be expanded without incurring considerable operational risk, including primary distribution circuits, primary overcurrent protective devices, and system charge and discharge buses. Peak load currents also are used to determine initial and ultimate battery capacities; however, unlike charge/discharge buses and the primary distribution system, batteries may be added relatively easily in an operating system.

1.5.2 Voltage Drop

A telecommunications dc power system consists of four basic types of circuits—battery circuit, rectifier circuit, primary distribution circuit, and secondary distribution circuit (Fig. 1.15). A system may have cascaded secondary distribution circuits (Fig. 1.16). A circuit always consists of two conductors, *feed* and *return,* so the circuit forms a loop, and voltage drop calculations must include the drop in both conductors.

During normal operation, the rectifiers power the load equipment and the dc electrical circuit consists of the rectifier, primary distribution and secondary distribution circuits. Since the rectifier output voltage is well regulated and considerably higher than the minimum equipment operating voltage, the voltage drop from the rectifiers to the load equipment is not an important design issue. When the ac input, ac source, or the rectifiers fail, the battery powers the load. In this case, the electrical circuit consists of the battery, primary distribution, and secondary distribution circuits. The voltage drop from the battery to the load when the rectifiers are not operating plays an important role in keeping the equipment in operation for the longest possible time as the battery discharges and its voltage decreases.

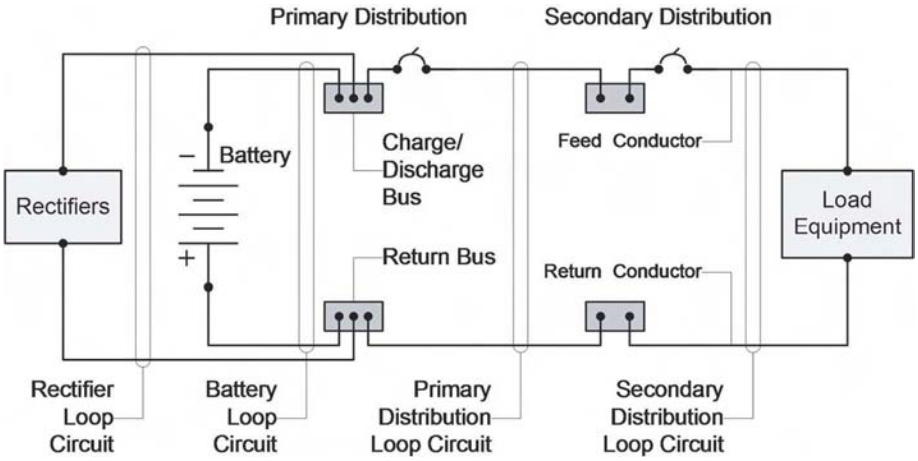

Fig. 1.15 dc power system circuits.

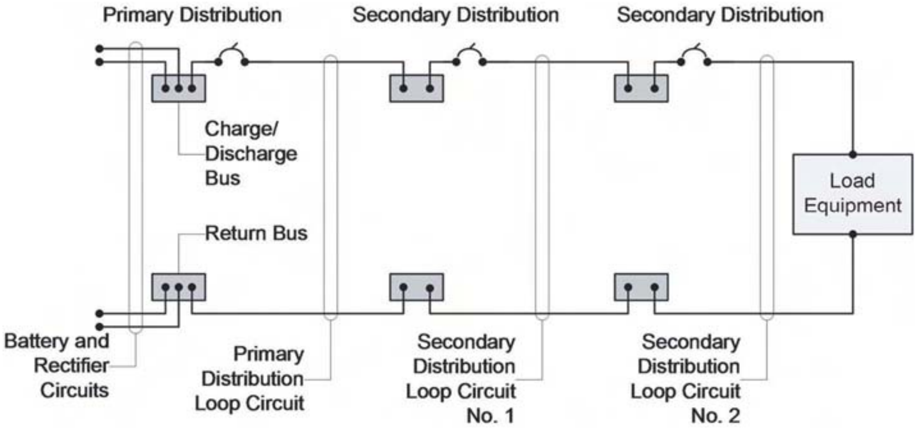

Fig. 1.16 Cascaded secondary distribution circuits.

The maximum allowed total voltage drop from the battery to the load equipment during battery discharge is around 4%. Since the important factor is the total voltage drop, the voltage drop in each segment (battery circuit, primary distribution circuit, and secondary distribution circuits) can be designed for any value as long as the sum of the voltage drops does not exceed the specified maximum. More specific requirements are discussed in Chapter 5, System Design.

1.5.3 Conductors

Copper conductors consisting of rigid bus or cable bus (Fig. 1.17) are used in telecommunications dc power systems, although rigid aluminum busbar has been used occasionally.[7] Current-carrying capacity (ampacity) and voltage drop are the two criteria used to select the conductor size in any given circuit. Voltage drop is determined from the conductor resistance at the desired design temperature and load current. Since conductor resistance depends on length, the circuit path distance must be known. Each circuit consists of two conductors, feed and return, so the total conductor length is always twice the path distance. Feed and return conductors always are paired and never shared with other circuits. The feed conductor is the circuit conductor operating at the system voltage and the return conductor is the circuit conductor operating nearest ground potential.

Ampacity is the term used to describe the current the conductor may safely carry without overheating.[8] In low-voltage dc systems, currents are relatively high. On short conductor runs, ampacity usually determines conductor size, while on long runs voltage drop most often determines conductor size. On any given circuit, the conductors must be large enough to meet both criteria (ampacity and voltage drop) simultaneously.

In the United States, conductor sizes are stated in American Wire Gauge (AWG, or just gauge) or circular mils (CM). Conductor sizes 4/0 (0000) and smaller are described in

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[7] Aluminum cable conductors are not used in telecommunications dc power systems because of the relative difficulty making aluminum wire connections due to aluminum's tendency to cold-flow and corrode.

[8] The term *ampacity* is peculiar to the National Electrical Code (NEC). Engineering books about electrical power cables use the terms *current rating* and *current-carrying capacity.*

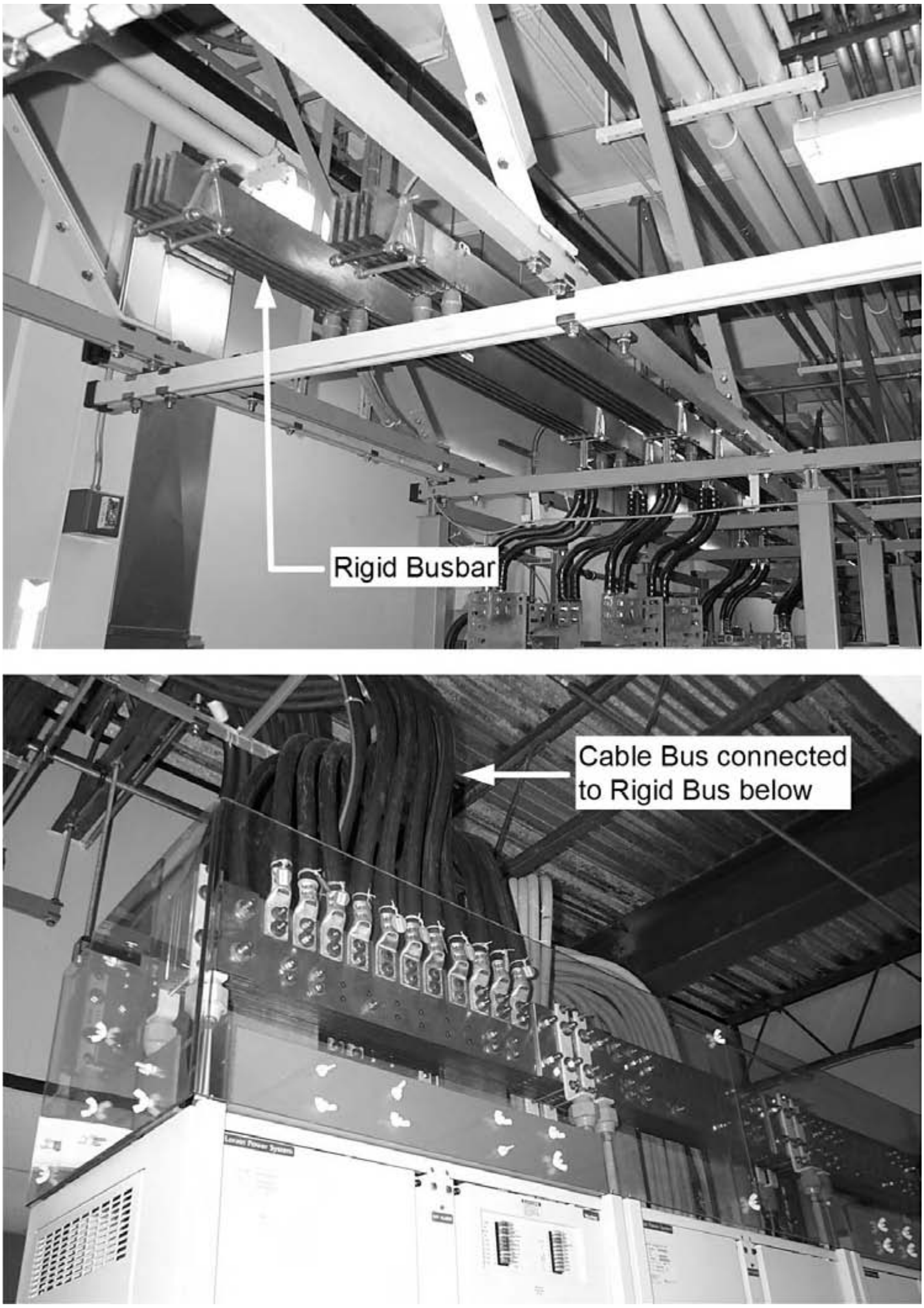

Fig. 1.17 Rigid bus (*upper*) and cable bus connected to rigid bus (*lower*).

AWG (e.g., 1/0 AWG) while conductors larger than 4/0 are described in circular mils (e.g., 250,000 CM). The circular mil is a measure of the cross-sectional area of a conductor and is equal to the square of its diameter, where the diameter is measured in mils (1 mil = 0.001 inch). A common variation of CM is kilocircular mil (kcmil), which is 1000 CM (kcmil sometimes is seen in older documents as MCM). Conductor properties are described in greater detail in Chapter 2, Electricity Review.

1.5.4 Overcurrent Protection

Basic electrical circuit design requires conductors to be protected at their power source from overloads and short circuits by an overcurrent protection device, such as a fuse or circuit breaker. The source for all circuits except battery circuits is the primary and secondary distribution panels (Figs. 1.18 and 1.19). In many instances it is impossible to provide reliable battery circuit operation at the same time as reliable overcurrent protection. Therefore, other means are used to reduce the probability that a fault occurs on battery circuit conductors.

A short circuit is an unintentional contact of an ungrounded conductor to a live, grounded, or dead metal part, whereas an overload is a higher-than-normal current due to an equipment fault or operational problem.

An overcurrent protection device must protect each load branch circuit. During fault conditions, if the overcurrent protection devices are properly coordinated, only the overcurrent device closest to the fault trips open and upstream devices are unaffected. The choice between a fuse and circuit breaker is dictated by a number of factors, including cost (the initial cost of fuses usually is less), convenience (resetting a circuit breaker is easier, safer, and faster than replacing a fuse) and fault current-carrying capabilities (some fuses can carry very high fault currents and may be used to protect a circuit breaker under high fault conditions).

1.5.5 Rectifiers

Rectifiers must be able to serve load currents and simultaneously recharge a discharged battery. Once the battery is recharged, the rectifiers closely regulate the float voltage to ensure a long battery life. Battery recharge times typically range between 12 and 24 h. The rectifier system is based on $N + 1$ redundancy, where N is the number of rectifiers required to meet load and recharge requirements and one additional rectifier is added for re-

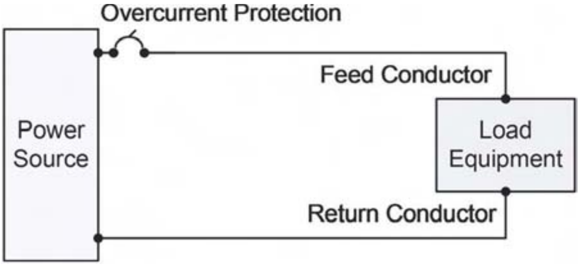

Fig. 1.18 Overcurrent protection.

Fig. 1.19 Primary distribution (*left*) and secondary distribution (*right*).

dundancy. This means there always are at least two rectifiers in a system. Rectifiers always are configured in the hot-standby mode so they can pick up the load immediately upon failure of one of the other rectifiers. Rectifiers may be modular plug-in types or fixed mounted (Fig. 1.20).

1.5.6 Battery Capacity

Battery capacity is determined from the peak load current, the required reserve time, anticipated growth, and the need to provide for expansion as the power system grows. The reserve time depends on whether a standby engine–generator set is installed at the site and can vary from as little as 3 h to upwards of 12 h or more. Remote sites may require a reserve time measured in days or weeks. Other considerations, such as cost, weight, floor space requirements, and system reliability, affect the battery system design. The growth in battery capacity is related to the growth in rectifier capacity because both increase with load current.

Where service reliability is critical, two battery strings may be installed, each with at least 50% of the total required capacity. If full $N + 1$ redundancy is required, each of the two strings must have 100% of the required capacity (Fig. 1.21). In either case, multiple strings allow easier battery maintenance without jeopardizing service to the load equipment. The number of battery strings in any given installation is the minimum required to achieve reserve time and maintenance requirements.[9]

[9] The author has been told of systems consisting of 64, 72, and 100 battery strings in parallel.

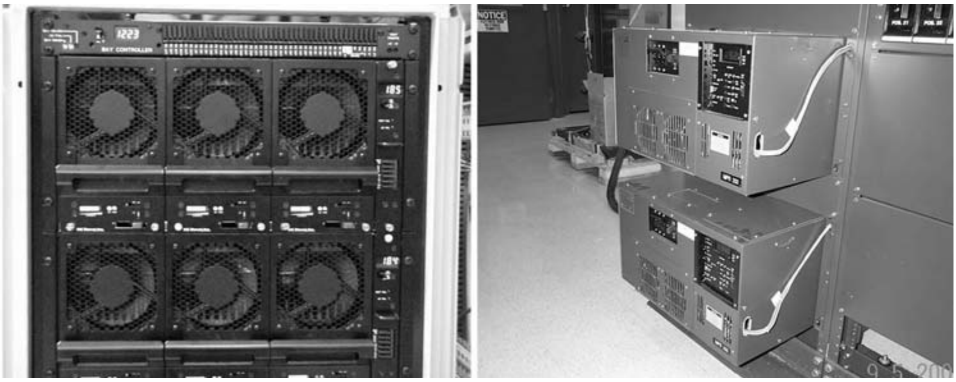

Fig. 1.20 Modular switch-mode rectifiers (*left*) and fixed mounted ferroresonant rectifiers (*right*). (Left photo courtesy of Power-One, Inc.)

1.6 STANDARDS, PRACTICES, AND CODES

Standards, practices, and codes are written documents that provide interoperability, efficiency, and uniformity in components and systems and uniformity in design, construction, operation, and maintenance methods. This section briefly describes such documents related to dc power systems.

Standards in the United States are voluntary consensus standards. The American National Standards Institute (ANSI), headquartered in Washington, D.C., administers, coordinates, and safeguards the integrity of the U.S. voluntary standardization and conformity assessment system. While many standards specify detailed requirements, some specify only general requirements and details are provided through company or industry practices.

Two important organizations that develop national standards related to telecommunications dc power systems are the Institute of Electrical and Electronics Engineers (IEEE) and the Alliance for Telecommunications Industry Solutions (ATIS) Network Interface, Power and Protection (NIPP) Committee (formerly T1E1).

Standards may be obtained from ANSI at http://webstore.ansi.org or Global Engineering Documents at http://global.ihs.com. IEEE and NIPP Committee standards also may be obtained as described in the following paragraphs. All standards are updated or reaffirmed at least every 5 years (the dates are not shown in the following listing because the most current should be used in design work; where standards are cited in later chapters, the date in effect at the time this book was written is given).

Practices reflect common design, installation, and operation methods, but a given practice may not be universally accepted throughout the industry. There may be numerous acceptable practices for accomplishing the same task or meeting the same end. Practices can be formal and written or informal and verbal and in many cases technically unjustified (“We’ve always done it that way”). Standards and practices are not legally binding unless adopted by reference by federal, state, county, or municipal jurisdictions.

Codes generally specify safety requirements and are adopted by governmental jurisdictions and, as such, are legally binding. Examples of codes that may apply to dc power systems are the National Electrical Code® and International Fire Code.[10]

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[10] The NEC® does not apply in spaces used exclusively for telecommunications equipment. Additional detail on the application of various codes is covered in Chapter 5 (System Design).

Fig. 1.21 Redundant VRLA battery installation (*upper,* B-Blue; *lower,* A-Red). (Photos courtesy of Nick Nichols.)

1.6.1 ATIS Network, Interface, Power and Protection Committee

NIPP Committee (NIPP— http://www.atis.org) develops standards for interfaces, power, and network protection. Important NIPP Committee standards are:

- ANSI/T1.304, Ambient Temperature and Humidity Requirements for Network Equipment in Controlled Environments
- ANSI/T1.307, Fire Resistance Criteria—Ignitability Requirements for Equipment Assemblies, and Fire Spread Requirements for Wire and Cable
- ANSI/T1.311 DC Power Systems—Telecommunications Environment Protection
- ANSI/T1.313, Electrical Protection of Telecommunications Central Offices and Similar Type Facilities
- ANSI/T1.315, Voltage Levels for DC Powered Equipment Used in the Telecommunications Environment
- ANSI/T1.319, Equipment Assemblies—Fire Propagation Risk Assessment Criteria
- ANSI/T1.328, Protection of Telecommunications Links from Physical Stress and Radiation Effects and Associated Requirements for DC Power Systems (a baseline standard)
- ANSI/T1.329, Network Equipment Earthquake Resistance Standard
- ANSI/T1.330, Valve Regulated Lead-Acid Batteries Used in the Telecommunications Environment
- ANSI/T1.333, Grounding and Bonding of Telecommunications Equipment

1.6.2 Institute of Electrical and Electronics Engineers (IEEE—http://standards.ieee.org)

- ANSI/IEEE Std 446, IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications (*IEEE Orange Book*)
- ANSI/IEEE Std 450, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications
- ANSI/IEEE Std 484, IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications
- ANSI/IEEE Std 485, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications
- ANSI/IEEE Std 946, IEEE Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Stations
- ANSI/IEEE Std 1187, IEEE Recommended Practice for Installation Design and Installation of Valve-Regulated Lead-Acid Storage Batteries for Stationary Applications
- ANSI/IEEE Std 1188, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead Acid (VRLA) Batteries for Stationary Applications
- ANSI/IEEE Std 1189, IEEE Guide for Selection of Valve-Regulated Lead Acid (VRLA) Batteries for Stationary Applications
- ANSI/IEEE Std 1375, IEEE Guide for the Protection of Stationary Battery Systems

1.6.3 Telecommunications Industry Association

The Telecommunications Industry Association (TIA—http://www.tiaonline.org/) is a trade association of telecommunications equipment manufacturers.

- ANSI/J-STD-607-A, Commercial Building Grounding (Earthing) and Bonding Requirements for Telecommunications

1.6.4 Telcordia

Telcordia (http://www.telcordia.com) develops numerous technical requirements for its clients, the Regional Bell Operating Companies (RBOC) and others. Because of the RBOC's purchasing power, most telecommunications equipment manufacturers build equipment to Telcordia requirements; however, these are *not* national standards although some have become ad hoc or de facto standards. Of particular interest are the widely quoted NEBS, or Network Equipment Building Systems, documents:

- GR-1089-CORE, Electromagnetic Compatibility and Electrical Safety Generic Criteria for Network Telecommunications Equipment
- GR-63-CORE Network Equipment Building Systems Requirements: Physical Protection

1.6.5 Rural Utilities Service

The Rural Utilities Service (RUS—www.usda.gov/rus/telecom/publications/bulletins) is an arm of the U.S. Department of Agriculture—Rural Development Agency that loans money to rural telecommunications service providers and has developed technical requirements and approved equipment lists for use by its borrowers. Three documents particularly relevant to this book are

- Bulletin 1751E-302—Power requirements for digital central office equipment
- Bulletin 1751E-320—Emergency generating and charging equipment
- Bulletin 1751F-810—Electrical protection of digital and lightwave telecommunications equipment

1.6.6 Electrical Generating Systems Association

The Electrical Generating Systems Association (EGSA—http://www.egsa.org) only recently became a nationally approved standards developer but not all of its requirements are national standards as of this writing; however, EGSA has been developing performance requirements for electrical generating systems since 1965 and its requirements are widely recognized. Unlike NIPP and IEEE standards previously listed, EGSA standards are free.

- EGSA 100B: Performance Standard for Engine Cranking Batteries Used with Engine Generator Sets—Requirements for rating, classifying, applying, installing, and maintaining engine cranking batteries
- EGSA 100C: Performance Standard for Battery Chargers for Engine Starting Batteries and Control Batteries (Constant Potential Static Type)—Requirements for

voltage and temperature limits, application, and accessories for charging engine cranking batteries

- EGSA 100D: Performance Standard for Generator Overcurrent Protection, 600 Volts and Below—Performance specifications for circuit breakers, field breakers, thermostats, thermistors, and other temperature detectors
- EGSA 100E: Performance Standard for Governors on Engine Generator Sets—Classifications, performance requirements, and optional accessories for generator set engine governors
- EGSA 100F: Performance Standard for Engine Protection Systems—Performance specifications for engine control systems including temperature, level, pressure, and speed sensing
- EGSA 100G: Performance Standard for Generator Set Instrumentation, Control and Auxiliary Equipment—Requirements for generator set engine starting controls, instrumentation, and auxiliary equipment
- EGSA 100M: Performance Standard for Multiple Engine Generator Set Control Systems—Performance requirements for manual, automatic fixed sequence, and random access generator set paralleling systems
- EGSA 100P: Performance Standard for Peak Shaving Controls—Requirements for parallel operation and load transfer peak load reduction controls
- EGSA 100R: Performance Standard for Voltage Regulators Used on Electric Generators—Application and performance requirements for generator voltage regulators
- EGSA 100S: Performance Standard for Transfer Switches for Use with Engine Generator Sets—Classifications, applications, and performance requirements for transfer switches for emergency and standby transfer switches
- EGSA 100T: Performance Standard for Diesel Fuel Systems for Engine Generator Sets with Above Ground Steel Tanks—Application and performance requirements for diesel fuel supply systems with above-ground steel tanks for diesel engine driven generator sets
- EGSA 101G: Glossary of Electrical and Mechanical Terminology and Definitions—Definitions of terms specific to the on-site power industry
- EGSA 101P-1995: Performance Standard for Engine Driven Generator Sets—Classifications of use, prime mover configuration and ratings, and performance requirements for complete generator sets
- EGSA 101S: Guideline Specification for Engine Driven Generator Sets, Emergency or Standby
- EGSA 107T: Performance Standard for Generator Test Methods
- EGSA 109C: Code Listing: Safety Codes Required by States and Major Cities—Listing of national and international codes and standards adopted by U.S. states and selected major cities

1.6.7 Practices

Many large network operators have developed their own power system practices. Perhaps the most well known, but now obsolete, practices are the old AT&T Bell System Practices (BSP) and the General Telephone & Electronics Practices (GTEP). The development of these types of practices changed course when AT&T was divested of the Regional Bell Operating Companies in 1984 and when Bell Atlantic and GTE merged into Verizon in 2000.

Smaller companies to some extent use the practices of larger companies. However, in many cases the larger company's practices are out of date or simply do not specify the best methods for smaller companies.

1.6.8 Codes

- National Electrical Code (NEC), NFPA 70-2005 (http://www.nfpa.com)—Applies to electrical installations in public and private buildings and industrial electrical substations. It does not apply to "Installations of communications equipment under the exclusive control of communications utilities located outdoors or in building spaces used exclusively for such installations" [NEC par. 90.2(B)].
- National Electrical Safety Code (NESC), ANSI C2-2002 (http://standards.ieee.org)—Although the NESC has little to do with telecommunications power systems, its grounding requirements apply to outside plant enclosures such as access nodes.
- International Fire Code (IFC)—International Code Council (http://www.iccsafe.org).
- International Building Code (IBC)—International Code Council (ICC, http://www.iccsafe.org).
- U.S. Dept. of Labor, Occupational Safety & Health Administration (OSHA, http://www.osha.gov)—Title 29 Code of Federal Regulations.

1.6.9 Other Applicable Standards and Recommendations

National Fire Protection Association (NFPA—http://www.nfpa.com)

- NFPA 75-2003, Standard for Protection of Information Technology Equipment
- NFPA 76-2003, Recommended Practice for Fire Protection of Telecommunications Facilities
- NFPA 110-2002, Standard for Emergency and Standby Power Systems
- NFPA 111-2001, Standard on Stored Electrical Energy Emergency and Standby Power Systems

International Telecommunications Union—Telecommunications Standardization Sector, ITU-T) (http://www.itu.int)

- K.27 Protection Against Interference—Bonding Configurations and Earthing Inside a Telecommunications Building
- K.31 Bonding Configurations and Earthing of Telecommunication Installations Inside a Subscriber's Building
- K.35 Bonding Configurations and Earthing at Remote Electronic Sites

European Telecommunications Standards Institute (ETSI—http://www.etsi.org)

- EG 201 147—Equipment Engineering (EE); Interworking Between Direct Current/Isolated (DC/I) and Direct Current/Common (DC/C) Electrical Power Systems
- ETS 300 253—Equipment Engineering (EE); Earthing and Bonding of Telecommunication Equipment in Telecommunication Centers
- ETSI EN 302 099—Environmental Engineering (EE); Powering of Equipment in Access Network

CHAPTER 2

ELECTRICITY REVIEW

This chapter emphasizes telecommunications direct current (dc) power systems but also introduces relevant alternating current (ac) topics. The concept of current flow is introduced followed by a discussion of voltage sources and resistances. DC voltages, currents, and power and a number of dc circuits are solved using Ohm's law and Kirchhoff's current and voltage laws. Finally, certain topics associated with ac voltage, current, and power as they apply to rectifier input and inverter output circuits are discussed.

2.1 ELECTROMOTIVE FORCE

All matter is made from atoms. An atom consists of a positively charged central nucleus, composed of protons and neutrons, around which one or more negatively charged *electrons* rotate. In conductors, some of the electrons can freely move or drift from atom to atom when a difference in potential is applied to the two ends of the conductor. The potential difference can be due to an excess of electrons at the negative terminal of a battery and a deficiency of electrons at the positive terminal due to chemical action in the battery, or it can be from other sources such as an electrical generator, thermocouple, photoelectric cell, or piezoelectric generator.

The potential difference is commonly called electromotive force, or *emf,* and is expressed in volts. In this book, emf is called by its most familiar name, *voltage*. It is the algebraic difference between the voltages at two points in a circuit that determines the force with which charges move. Generally, the Earth ("ground") is taken as the zero reference point or zero reference plane (Fig. 2.1).

2.2 CURRENT FLOW

The movement of the free electrons, or charges, constitutes electric current (or current flow). The direction of current flow through a load in electrical engineering is taken to be from a region of higher potential (such as the positive terminal of a battery) to a region of lower potential (such as the battery negative terminal) as shown in Figure 2.2. Within a

dc Power System Design for Telecommunications. By Whitham D. Reeve

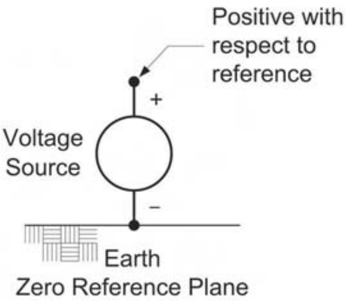

Fig. 2.1 Voltage source and reference plane. In this illustration, the negative terminal of the voltage source is connected to the reference plane, or ground, and the other terminal is positive with respect to ground. A voltage source may be connected the other way, that is, with a positive ground.

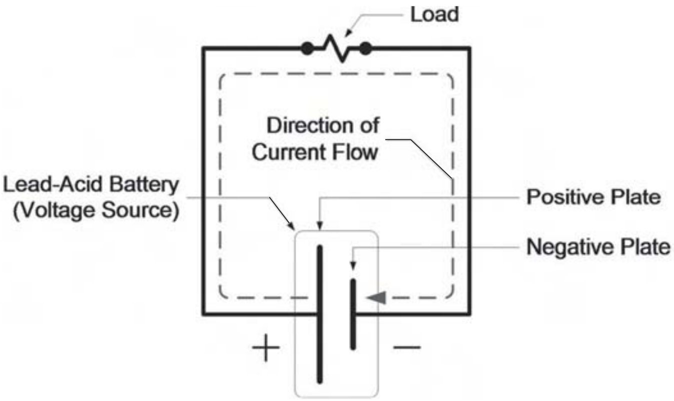

Fig. 2.2 Current flow.

voltage source, current flows from the negative terminal to the positive terminal. A battery is a voltage source, and current flows within the battery cells via ions.[1] The opposite direction of current flow in a circuit is sometimes seen in textbooks (the so-called electron theory of current flow). It makes no difference which direction is used as long as it is used consistently throughout the circuit.

2.3 VOLTAGE SOURCES

There are four types of voltage sources used in telecommunications dc power systems:

- Alternating current power sources including commercial electric utility (or prime power source) and standby power system
- Batteries

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[1] Ions are atoms or groups of atoms in which the number of electrons is different from the number of protons, giving a net positive or negative charge.

- Rectifiers
- Voltage conversion devices (dc–dc converters and inverters)

Rectifiers convert ac currents and voltages from the commercial electric utility or prime power source to dc currents and voltages for use by network load equipment and for charging the batteries. As power storage devices, batteries allow network equipment to operate during commercial electricity outages. DC–DC converters and inverters provide voltages for loads that do not operate at the nominal system dc voltage. DC–DC converters convert the nominal system dc voltage to another dc voltage (e.g., from –48 Vdc to +24 Vdc or from +24 Vdc to –48 Vdc) while inverters convert the nominal system dc voltage to ac voltage. Since inverters are powered by the dc system, including the batteries, inverters allow ac powered equipment to operate during commercial electricity outages. Batteries, rectifiers, voltage conversion devices, and other dc power system components are covered in Chapter 3.

Direct current voltage sources always have some internal resistance, which causes the output voltage to decrease under load. Rectifiers and voltage conversion devices have internal regulating mechanisms that maintain a fairly constant output voltage regardless of load.

2.4 RESISTANCE

2.4.1 Conductors

The current in an electrical circuit depends not only on the applied voltage but on the circuit properties as well. For example, if a copper conductor is connected across the terminals of a battery or other voltage source, current will flow. If the conductor makes a poor contact at one of the terminals or at some other point in the circuit, the current will decrease even though the voltage remains unchanged. Also, heat will be dissipated at the point of poor contact. If the conductor is cut in the middle and some type of load equipment is connected in the circuit, the current will further decrease and more heat will be dissipated. In each case, a current decrease accompanies the insertion or addition of the poorer conducting medium or of the load.

The property of an electric circuit that prevents or decreases current flow and at the same time causes electric energy to be converted to heat energy is called *resistance*. A *resistor* is a component that has intentional resistance. Resistance is measured in ohms.[2] Load equipment has equivalent resistance, which in some cases may depend on the voltage across it or the current through it. *Conductance* is the inverse of resistance ($1/R$, where R is the resistance), and its unit of measure is the siemens[3] (formerly mho). The higher the conductance, the lower the resistance. The term conductance is useful in some contexts, for example, when the ability to conduct is more relevant than the ability to resist current flow.

Resistance may be accounted for by considering that electrons moving through a conductor must pass through the molecules or the atoms. In doing so, they collide with other

[2] The resistance unit, ohm (Ω), was named after Georg Simon Ohm, a Bavarian mathematician and physicist, who developed Ohm's law.

[3] The conductance unit, siemens (S), was named after Werner von Siemens, a German inventor and industrialist. In 1866 he discovered the dynamo-electric principles that helped establish electricity as a power source.

electrons and with the atoms and in the process dissipate heat. The number of collisions, and the heat dissipated, in a given time varies with the square of the current. The velocity of the electrons (and their electric energy) decreases and thus the current is reduced. When this happens, the voltage must be increased to maintain a given current.

Electrons move relatively easily from atom to atom in a conductor, but they do not move easily in an insulator. Oils, glass, dry paper, cotton, rubber, porcelain, and plastics are nonconductors or insulators. Wood, either dry or impregnated with oil, is a good insulator, while wet wood and wood treated with some preservatives is a partial conductor.

Conductors may be categorized as metallic, electrolytic, or gaseous. With metallic conductors, such as copper wire, conduction is due to interatomic movement of the electrons within the conductor. This movement is not accompanied by any movement of material through the conductor or by any chemical action. With electrolytic conductors, conduction is accompanied by movement of material (ions) through the conductor and usually by chemical action. The diluted sulfuric acid used in lead–acid batteries is an example of an electrolytic conductor. With gaseous conductors, conduction is due to movement of free positive ions and free negative ions, or electrons, into which the gas atoms become divided when the gas is ionized. The ionized gas in a neon sign is an example of a gaseous conductor.

The best metallic conductors are silver and copper and alloys of these elements. Table 2.1 shows the conductance of some metallic conductors of the same cross-sectional area relative to silver. Copper is the only metal used in telecommunications dc power systems wiring, but aluminum is common in commercial and industrial ac wiring.

A 1-Ω resistor will allow 1 A of current flow if 1 V is applied across it.[4] Also, if 1 A flows for 1 s through a 1-Ω resistor, the heat energy dissipated by it is 1 W-s (1 W = 1 J/s).[5] The resistivity of a material is the ohmic resistance of a unit cross section of the material per unit length. The resistivity, or resistance between opposite faces of a centimeter cube (face dimension of 1 cm), of soft or annealed copper[6] at 20°C (68°F) is 1.724×10^{-6} Ω (1.7241 μΩ-cm or 0.67879 μΩ-in.), or approximately 98% of pure copper, while the resistance between opposite faces of a centimeter cube of hard rubber is about 1×10^{16} Ω. The ratio of the two resistances is about 6×10^{21}, or 6 followed by 21 zeros. Resistivity can be specified in other units, such as ohms-circular mil/ft (Ω-CM/ft).

Since the resistances of insulators are ordinarily very large numbers and the resistances of other electrical components may be very small numbers, it is convenient to use prefixes to scale resistance values. Table 2.2 shows the common values encountered in dc design work. For example, if an insulator has 10,000,000 Ω resistance, the equivalent resistance is 10 MΩ, and if a conductor has 0.001 Ω resistance, the equivalent resistance is 1 mΩ.

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[4] The current unit, ampere (A), was named after André Marie Ampère, a French research mathematician, who published a theory of electrodynamics phenomena in 1826. Ampere frequently is shortened to amp. The voltage unit, volt, was named after Alessandro Giuseppe Antonio Anastasio Volta, who invented the voltaic pile, or battery, in 1800.

[5] The power unit, watt (W), was named after James Watt, a Scottish instrument maker, who produced the first rotary-motion steam engine in 1781. The energy unit, joule (J), was named after James Joule, an English physicist, who in the mid-1800s conducted experiments to demonstrate the unity of heat and motion forces.

[6] Annealed copper has been heated and held at a certain temperature to allow full recrystalization and then cooled to make it less brittle.

Table 2.1 Relative Conductance

Conductor	Relative Conductance (%)
Silver	100
Copper	94
Gold	66
Aluminum	62
Tin	14

If a conductor has a constant cross section, its resistance will vary directly with the conductor length. If a conductor has a constant length, its resistance will vary inversely with its cross-sectional area. These two properties are summarized in

$$R = \rho \frac{L}{A} \tag{2.1}$$

where R = resistance (Ω)
ρ = resistivity of a cube of material with a face dimension of 1 cm or 1 m (Ω-cm or Ω-m, respectively)
L = length of the conductor in the direction of current flow (cm or m)
A = cross-sectional area at right angles to the direction of current flow (cm^2 or m^2).

In the above expression, the same dimensional units must be used throughout (such as all centimeters or all meters).

Example 2.1 Determine the resistance of a 100-cm length of copper wire with a cross-sectional area of 0.133 cm^2 and a temperature of 20°C (68°F).

$$R = \rho \cdot \frac{L}{A} = (1.7241 \times 10^{-6})\frac{100}{0.133} = 0.00130\ \Omega\text{, or } 1.3\ \text{m}\Omega$$

2.4.2 Temperature Coefficient of Resistance

The resistance of copper (and other nonalloyed metals) increases appreciably with temperature. The temperature at which electrical conductors operate varies with the current and depends on the ambient temperature and installation conditions. For example, for a

Table 2.2 Common Resistance Units

Name	Multiplication Factor
microhm (μΩ)	1 Ω/1,000,000
milliohm (mΩ)	1 Ω/1,000
ohm (Ω)	1 Ω
kilohm (kΩ)	1,000 Ω
Megohm (MΩ)	1,000,000 Ω

given current, a wire in conduit will operate at a higher temperature than the same wire in free air because the wire in free air is better able to dissipate the heat developed during operation.

Over a limited temperature range, the resistance of copper wire is a linear function of the temperature. If the resistance at a temperature is known, the resistance at any other temperature can be determined from

$$R_T = R_0[1 + \alpha_0(T_T - T_0)] \tag{2.2}$$

where R_T = resistance at temperature T_T (Ω)
R_0 = resistance of copper of 100% conductivity at the initial or standard temperature (Ω)
T_T = temperature at which resistance is desired (°C)
T_0 = initial or standard temperature (°C)
α_0 = temperature coefficient of resistance corresponding to T_0 (Ω/°C)

At 20°C, the temperature coefficient for copper is 0.00393/°C.[7] The coefficient at other temperatures over the temperature range of 0 to 75°C may be determined from Figure 2.3. The curve is extrapolated using a trend function above 50°C.

Example 2.2 Determine the resistance of No. 14 AWG copper wire in ohms/foot at 75°C. The resistance at 20°C is 0.00252 Ω/ft.

$$\begin{aligned} R_T = R_0[1 + \alpha(T_T - T_0)] &= 0.00252[1 + 0.00393(75 - 20)] \\ &= 0.00306\ \Omega/\text{ft} \quad \text{(over 20\% increase)} \end{aligned}$$

Table 2.3 gives copper conductor resistivity at various temperatures in ohm-circular mil/ft.

Copper melts at around 1100°C (2000°F) but wire is never operated even close to this temperature. Wire operating temperatures are limited by insulation and the terminal temperature ratings. High heat thermoplastic and cross-linked polyethylene are the most common insulations and their maximum operating temperatures are usually 60, 75, or 90°C (140, 167, or 194°F, respectively) depending on the insulation material and working environment (dry or wet). Operating insulated wire above their maximum operating temperatures can damage the insulation.

2.4.3 Resistance in Series

A series circuit is one in which the resistor (or other electrical component) terminals are connected end-to-end (Fig. 2.4). In such a circuit, the same current flows through each component but the applied voltage divides among the components. If a number of resistors having resistances $R_1, R_2, R_3, \ldots, R_N$ are connected in series, the total (or equivalent) resistance of the combination is

$$R_T = R_1 + R_2 + R_3 + \cdots + R_N \tag{2.3}$$

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[7] The temperature coefficient of resistance for most nonalloyed metals is around 0.004 Ω/°C.

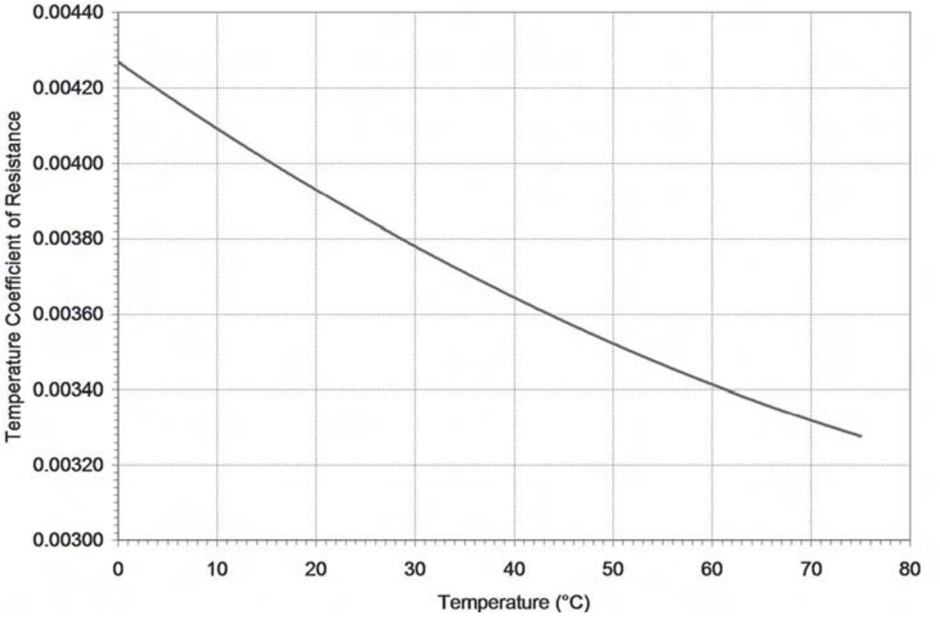

Fig. 2.3 Temperature coefficient of resistance for copper.

Example 2.3 Determine the equivalent resistance of three resistors, with values $R_1 = 1.0$ Ω, $R_2 = 1.5$ Ω, and $R_3 = 2.0$ Ω, connected in series. From Eq. (2.3), the resistance is

$$R_T = R_1 + R_2 + R_3 = 1.0 + 1.5 + 2.0 = 4.5\ \Omega$$

2.4.4 Resistance in Parallel

A parallel circuit is one in which one terminal of each resistor (or other electrical component) is connected to a common point and the other terminal is connected to a second common point (Fig. 2.5). Under these conditions, each component of the parallel system

Table 2.3 Resistivity of Copper Building Wire

Resistivity (Ω-CM/ft)	Temperature (°C)	Temperature (°F)
10.7	20	68
11.1	30	86
11.6	40	104
11.8	50	122
2.3	60	140
12.7	70	158
12.9	75	167

Fig. 2.4 Resistors in series.

is across the same applied voltage, but the total current divides among them. If a number of resistors are connected in parallel, the equivalent resistance of the combination is

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_N}} \tag{2.4}$$

For the case of two resistors in parallel

$$R_T = \frac{R_1 R_2}{R_1 + R_2} \tag{2.5}$$

For three resistors in parallel

$$R_T = \frac{R_1 R_2 R_3}{R_1 R_2 + R_2 R_3 + R_1 R_3} \tag{2.6}$$

Example 2.4 Determine the equivalent resistance of three resistors, with values $R_1 = 1.0$ Ω, $R_2 = 1.5$ Ω, and $R_3 = 2.0$ Ω, connected in parallel. From Eq. (2.6), the resistance is

$$R_T = \frac{R_1 R_2 R_3}{R_1 R_2 + R_2 R_3 + R_1 R_3} = \frac{(1.0)(1.5)(2.0)}{(1.0 \times 1.5) + (1.5 \times 2.0) + (1.0 \times 2.0)} = 0.462\ \Omega$$

In a parallel resistance circuit, the equivalent resistance always is less than the smallest resistance in the circuit. Remembering this helps to quickly gauge whether a calculation was done correctly. In the above example, the equivalent resistance is about 0.5 Ω (rounded), which is less than the smallest resistance (1.0 Ω) in the circuit.

The concept of series and parallel resistors tracks perfectly with the connection of wires in series and parallel circuits. Wires have resistance, and an example of a series circuit has feed and return conductors from a battery to the primary distribution bus, from the primary distribution bus to the secondary distribution bus, and from the secondary distribution bus to the load (Fig. 2.6).

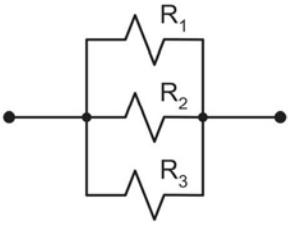

Fig. 2.5 Resistors in parallel.

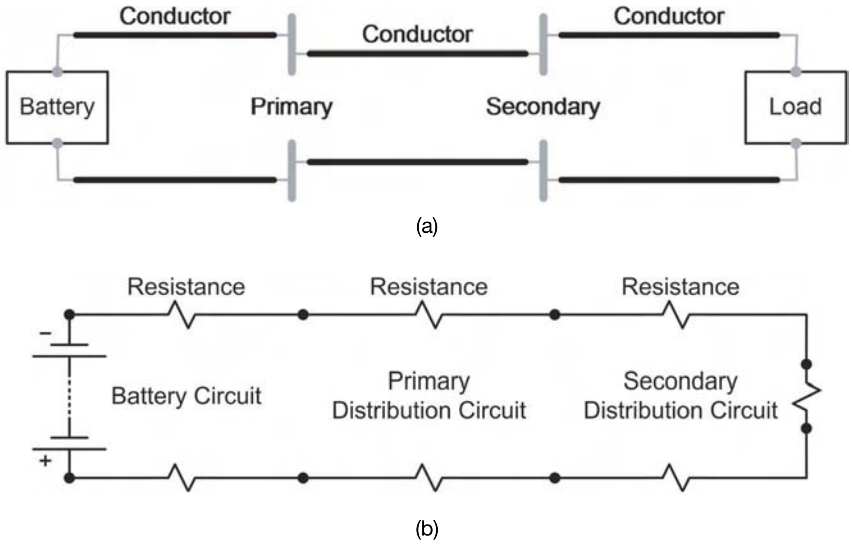

Fig. 2.6 Series circuit using conductors: (a) physical circuit and (b) equivalent electrical circuit.

Similarly, an example of a parallel circuit has feed and return conductors connected in parallel to reduce the overall resistance and voltage drop in the circuit (Fig. 2.7).

2.5 WIRE AND RIGID BUSBAR CONDUCTORS

In the United States, the American Wire Gauge (*AWG*) and *circular mil* are used to describe wire size.[8] AWG is based on a constant ratio between diameters of successive gauge numbers; that is, the diameters taken in order form a geometrical progression. The diameter of No. 4/0 is defined as 0.4600 in. (11.68 mm) and the diameter of No. 36 as 0.0050 in. (0.127 mm). There is a span of 39 gauge numbers between No. 4/0 and No. 36. Hence, the ratio of any diameter to the diameter of the next greater gauge number is

$$\sqrt[39]{\frac{0.4600}{0.0050}} = \sqrt[39]{92} = 1.1229$$

Since the cross section of a circular conductor varies as the square of its diameter, the ratio of any cross section to the cross section of the next greater gauge number is $(1.1229)^2 = 1.2610$. The sixth power of 1.1229 is 2.0050, which for practical purposes is 2. Therefore, the ratio of any diameter to the diameter of a gauge number that is 6 gauges greater is 2. It follows that the cross section either doubles or halves for every three gauge numbers.

The smallest wire size normally used in dc power wiring is 16 or 18 AWG. Wires larger than 4/0 AWG are measured in circular mils or kilocircular mils.

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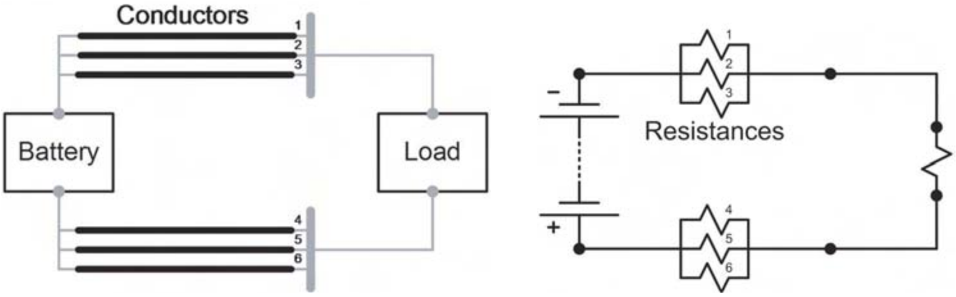
[8] In most places outside of the United States, metric sizes in square millimeters (cross-sectional area) or millimeters (diameter) are used.



(a) (b)

Fig. 2.7 Parallel circuit using conductors: (a) physical circuit and (b) equivalent electrical circuit.

The circular mil is a measure of wire cross section. A mil is one-thousandth of an inch, or 0.001 in. A circular mil is the area of a circle whose diameter is 1 mil (Fig. 2.8). The area in square inches of 1 circular mil is $(\pi/4) \cdot (0.001)^2 = 0.7854 \times 10^{-6}$ in.^{2}. The advantage of the circular mil is that circular areas measured in terms of this unit have a very simple relation to their diameters. Also, with the circular mil as the unit, the factor π does not enter computations of cross sections. The general relation may be written

$$\mathrm{CM} = \frac{D_{\mathrm{in.}}^2}{(0.001)^2} = 1{,}000{,}000(D_{\mathrm{in.}})^2 = D^2 \tag{2.7}$$

where CM = circular mils (upper case is used to avoid confusion with the abbreviation for centimeters)
$D_{\mathrm{in.}}$ = diameter of wire (in.)
D = diameter of wire (mils)

The concept of circular mils may be summed up in two rules:

- *To obtain the number of circular mils in a circular conductor of given diameter, express the diameter in mils, then square it.*
- *To obtain the diameter of a conductor having a given number of circular mils, take the square root of the circular mils, and the result will be the diameter in mils. Divide the diameter in mils by 1000 to obtain the diameter in inches.*

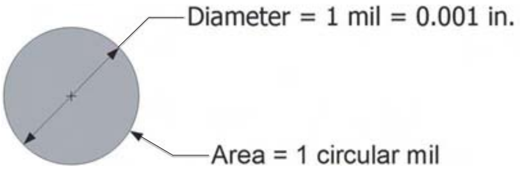


Fig. 2.8 Circular mil.

Example 2.5 A 6-AWG wire has a diameter of 0.162 in. Determine its cross-sectional area in circular mils:

0.162 in. = 162 mils
$(162)^2 = 26{,}244$ CM

Example 2.6 Determine the diameter of a wire with a cross-sectional area of 250,000 CM:

$$\text{Diameter} = \sqrt{250{,}000} = 500.0 \text{ mils} = 0.500 \text{ in.}$$

The next standard wire size larger than 4/0 AWG is 250,000 CM. Wire sizes generally increase in 50,000-CM increments above 250,000 CM in building wire applications. Common sizes are 350,000, 400,000, 500,000, and 750,000 CM. It is more convenient to state these wire sizes in terms of the kilocircular mil, or kcmil, so that 250,000 CM is 250 kcmil and 750,000 CM is 750 kcmil.[9]

The unit circular mil–foot can be used to make quick approximations of wire resistance. The resistance of a circular mil–foot of standard copper at 20°C is 10.371 Ω. For approximations, this is rounded to 10 Ω with an error of about –3.6%. Knowing this resistivity value, the resistance of any length and size of conductor may be determined from Eq. (2.1), where ρ is the resistance of a circular mil–foot of copper (10 Ω, approximately), L is in feet and A is in circular mils.

Example 2.7 Determine the resistance of a 750,000-CM copper wire that is 250 ft long. This example can be solved by direct application of Eq. (2.1):

$$R = 10\left(\frac{250}{750{,}000}\right) = 0.00333\ \Omega$$

or by thought: A 250-ft wire that has a cross section of 1 CM has a resistance of about 10 × 250 = 2500 Ω. However, the cross section of the wire in question actually is 750,000 CM; therefore

$$R = \frac{2500}{750{,}000} = 0.00333\ \Omega$$

A wire can consist of one or more strands. If it consists of one strand, it is called a solid wire, and if more than one strand, it is called a stranded wire. Solid wires typically are not used in telecommunications dc power systems because of their stiffness. Stranded wires, which are more flexible, are used exclusively. Two types of stranding generally are used—coarse strand (also called concentric strand) and fine strand. Coarse strand is built in concentric layers (or lays) according to the simple geometric properties of circular wires. Six strands will just fit around a center strand of the same diameter. Each additional strand layer has 6 more wires than the previous layer. Thus, the first layer has 6 wires, the second has 12 wires, the third layer has 18 wires, and so on. Following this basic construction rule, concentric strand wires will contain 1, 7, 19, 37, 61, 91, 127, . . . strands.

Figure 2.9 shows the cross section of a 19-strand wire and Table 2.4 shows the number of strands used in common concentric strand building wire. Concentric strand conductors

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[9] Some older conductor data shows the unit MCM, which is the same as kcmil.

Fig. 2.9 Cross section of 19-strand building wire.

Table 2.4 Typical Coarse-Strand (Class B) Building Wire Strand Counts

Wire Size	Number of Strands	Strand Diameter (mils)
14–2 AWG	7	24.2–97.4
1–4/0 AWG	19	66.4–105.5
250–500 kcmil	37	82.2–116.2
600–1000 kcmil	61	95.0–128.0
1250–1500 kcmil	91	109.9–128.4
1,750–2,000 kcmil	127	112.2–125.5

used in telecommunications dc power systems typically (but not always) are built according to American Society for Testing and Materials (ASTM) B8 Class B requirements [1].[10]

The diameter of a concentric strand conductor is greater than a solid conductor of the same gauge due to the stacking of the strands. For example, a 4/0 AWG solid wire is 0.460 in. in diameter while a 4/0 AWG 19-strand wire is 0.528 in. in diameter. However, the effective cross-sectional area (the total area of the individual strands) of solid and stranded wires is the same.

Fine-strand wire is used to obtain greater flexibility. With fine-strand wire the unit strands themselves are also stranded with very fine wire. Fine-strand wire is built much like a rope (and is called a rope-lay construction). Fine-strand wire typically is used in sizes larger than 4/0 AWG where installation may be difficult or damage to the insulation is possible due to many bends. Because large fine-strand wire is easier to handle and support, there is less chance of insulation or conductor damage during installation. Fine-strand wire also is used for equipment connections in seismic areas where the stiffness of coarse strand wire may damage terminations during a seismic event.

Fine-strand wire used in telecommunications dc power systems typically (but not always) is built according to ASTM B172 Class I requirements [2]. Class I stranded conductors consist of individual 24 AWG wires. Other B172 classifications use 30 or 34 AWG wires. Figure. 2.10 shows the cross section of a 105-strand wire made up of 7 members of 15 bunch-stranded wires (the strands are bunched into a circular cross section). Table 2.5 shows typical strand counts for fine-strand wire used in telecommunications dc power applications (ASTM B172 allows other constructions and strand counts).

It is important to understand how the different stranding configurations affect the conductor diameter and the selection of a connector lug for terminating the conductor. The

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[10] Numbers in brackets indicate reference numbers at end of chapter.

Fig. 2.10 Cross section of 105 (7 × 15) strand, rope-lay, bunch-stranded wire.

following chart shows the number of strands and diameter of a 4/0 AWG conductor in different ASTM classifications:

ASTM Class	**B**	**C**	**D**	**G**	**H**	**I**	**K**	**M**
No. Strands	19	37	61	133	259	532	2,107	5,320
Diameter (in.)	0.528	0.529	0.530	0.599	0.601	0.613	0.627	0.645

The diameter change for the 4/0 AWG class B, C, and D concentric strand conductors is small and the same connector lug will fit them all. However, the class G through M rope-lay, bunch stranded conductors have significantly larger diameters and most likely will require different lugs. Some connector lug manufacturers flare the barrel to make it easier to insert the fine-strand wire.

In many applications, wire strands are coated with a thin layer of tin or lead to reduce tarnishing from insulation materials or the air (tarnish is a form of surface oxidation or corrosion and acts as an insulator). The physical and electrical characteristics of tinned wire are slightly different than uncoated wire. Some network operators use only tinned wire in telecommunications dc power systems.

Table 2.5 Typical Fine-Strand (ASTM B172, Class I) Wire Strand Counts[a]

Wire Size	Number of Strands	Strand Layout	Strand Diameter (mils)
6 AWG	63	1 × 7 × 9	20.1
4 AWG	105	1 × 7 × 15	20.1
2 AWG	161	1 × 7 × 23	20.1
1/0 AWG	266	1 × 19 × 14	20.1
2/0 AWG	342	1 × 19 × 18	20.1
4/0 AWG	532	1 × 19 × 28	20.1
250 kcmil	637	7 × 7 × 13	20.1
350 kcmil	882	7 × 7 × 18	20.1
500 kcmil	1225	7 × 7 × 25	20.1
750 kcmil	1862	19 × 7 × 14	20.1
1000 kcmil	2527	19 × 7 × 19	20.1
1250 kcmil	3059	19 × 7 × 23	20.1
1500 kcmil	3724	19 × 7 × 28	20.1
2000 kcmil	4921	19 × 7 × 37	20.1

[a] The stand layout uses a simple nomenclature, $A \times B \times C$, where A = number of rope-stranded conductors, B = number of bunch-stranded members that make up each rope-stranded member, and C = number of wire strands in each bunch-stranded member.

Rigid, rectangular copper busbars are used in many installations in place of round wire conductors. The busbars may be bare or tinned, as with stranded wire. Typical dimensions are 2, 4, 6, and 8 in. wide by $\frac{1}{4}$, $\frac{3}{8}$, and $\frac{1}{2}$ in. thick. Busbars normally are mounted with the long dimension vertical for convection cooling (Fig. 2.11).

The cross-sectional area of rigid busbars is given in circular mils, but the calculation of the circular mil area from bar dimensions is not as simple as for round wire:

$$\mathrm{CM}_{\mathrm{Busbar}} = \frac{T_{\mathrm{in.}} W_{\mathrm{in.}}}{(0.001)^2}\left(\frac{4}{\pi}\right) = 1{,}000{,}000(T_{\mathrm{in.}} W_{\mathrm{in.}})\left(\frac{4}{\pi}\right) \tag{2.8}$$

where $T_{\mathrm{in.}}$ = bar thickness (in.)
$W_{\mathrm{in.}}$ = bar width (in.)

Example 2.8 Determine the cross-sectional area in circular mils of a 4-in. × $\frac{1}{4}$-in. busbar and determine the diameter of a round conductor with equivalent area. From Eq. (2.8)

$$\mathrm{CM}_{\mathrm{Busbar}} = \frac{0.25\ \text{in.} \times 4.0\ \text{in.}}{(0.001)^2}\left(\frac{4}{\pi}\right) = 1{,}273{,}239.5\ \text{CM} = 1273\ \text{kcmil}$$

and solving Eq. (2.7) for the diameter

$$D = \sqrt{\mathrm{CM}} = \sqrt{1{,}273{,}239.5} = 1{,}128.4\ \text{mils} = 1.128\ \text{in.}$$

2.6 OHM'S LAW AND ELECTRICAL CIRCUITS

Ohm's law states that, for a steady current, the current in a circuit is *directly* proportional to the total voltage in the circuit and *inversely* proportional to the total resistance in the circuit. This is summarized mathematically in

$$I = \frac{V}{R} \tag{2.9}$$

where I = current (A)
V = voltage (V)
R = resistance (Ω)

Ohm's law may be rewritten as

$$V = IR \tag{2.10}$$

Example 2.9 Figure 2.12 shows a simple electrical circuit containing a resistor and a battery. Determine the current.

The values from the illustration are plugged into Eq. (2.9) as follows:

$$I = \frac{V}{R} = \frac{50}{1.5} = 33.3\ \text{A}$$

Example 2.10 Figure 2.13 shows an electrical circuit containing two conductors, an indicating lamp, and a battery. The two conductors have equal resistances and their value is

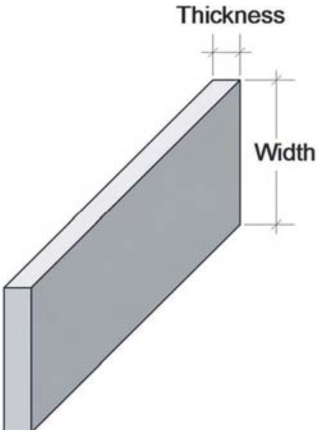

Fig. 2.11 Normal busbar orientation.

shown along with the resistance of the indicating lamp. Determine the current and the voltage across each of the conductors and the lamp.

The components are essentially three resistors connected in series, so using Eq. (2.3), the total resistance is the sum of the individual resistance values, $R_1 + R_2 + R_3$, or 1.5 + 1.5 + 0.8 = 3.8 Ω. Using Eq. (2.9) the current is

$$I = \frac{V}{R} = \frac{50}{3.8} = 13.2 \text{ A}$$

The same current flows through each resistance. Equation (2.10) is used to find the voltage across the components. The subscripts in the following three expressions indicate the voltage across each component due to the current though it:

$$V_1 = IR_1$$
$$V_2 = IR_2$$
$$V_3 = IR_3$$

The current was found previously as 13.2 A. Therefore, the voltages are

$$V_1 = IR_1 = 13.2 \times 1.5 = 19.7 \text{ V}$$

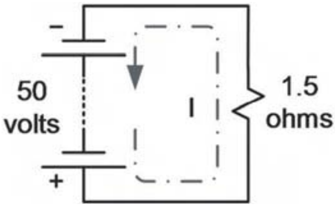

Fig. 2.12 Simple electrical circuit.

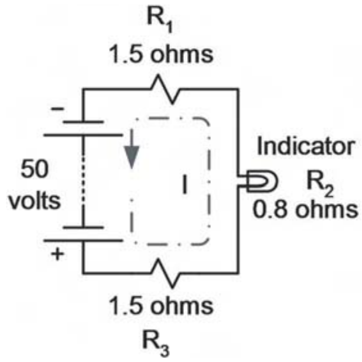

Fig. 2.13 Electrical circuit consisting of two resistors and a lamp.

$$V_2 = IR_2 = 13.2 \times 0.8 = 10.6 \text{ V}$$

$$V_3 = IR_3 = 13.2 \times 1.5 = 19.7 \text{ V}$$

A quick cross-check can be made by adding the individual voltage drops to give (19.7 + 10.6 + 19.7), or 50 V, which is the voltage of the battery.

Example 2.11 Three conductors with equal resistances are connected in parallel and to a battery as shown in Figure 2.14. Determine the resistance of each conductor and the current through it.

Equation (2.9) can be rearranged to solve for the resistance. Note that the voltage across each conductor is the same. The resistances are equal, so the total current will divide equally through each conductor. Since the total current is 15 A, the current through each conductor is 5 A, and the resistance of each conductor is

$$R_1 = \frac{V}{I_1} = \frac{50}{5} = 10\ \Omega$$

A quick cross-check can be made by determining the equivalent resistance of the three conductors in parallel and then solving for the current. From Eq. (2.4), the equivalent parallel resistance R_P is

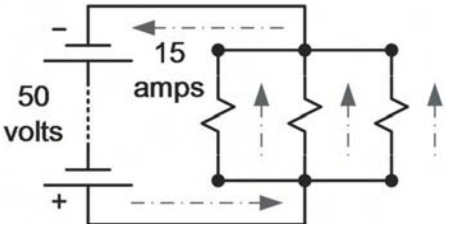

Fig. 2.14 Three equal resistances in parallel.

$$R_P = \frac{1}{\frac{1}{10}+\frac{1}{10}+\frac{1}{10}} = \frac{1}{0.1+0.1+0.1} = \frac{1}{0.3} = 3.33\ \Omega$$

The total current through the equivalent resistance is

$$I_T = \frac{V}{R_P} = \frac{50}{3.33} = 15\ \text{A}$$

which is the original current that was given.

The above example illustrates the division of current in a parallel circuit, but it is simplified by using equal resistances. If the resistances are different, the current will not divide equally but, instead, will divide inversely as to the resistances.

Example 2.12 Two unequal resistances are connected in parallel as shown in Figure 2.15. Determine the current through each resistance.

The voltage across each resistance is the same, and the current through each resistance is given by

$$I_1 = \frac{V}{R_1} = \frac{50}{15} = 3.33\ \text{A}$$

$$I_2 = \frac{V}{R_2} = \frac{50}{20} = 2.50\ \text{A}$$

The total current in the circuit is the sum of the two branch currents, or 5.83 A. This can be checked by first finding the equivalent parallel resistance and then using Ohm's law as follows:

$$R_P = \frac{1}{\dfrac{1}{R_1}+\dfrac{1}{R_1}} = \frac{1}{\dfrac{1}{15}+\dfrac{1}{20}} = \frac{1}{0.0667+0.0500} = \frac{1}{0.1167} = 8.57\ \Omega$$

Using Ohm's law

$$I_T = \frac{V}{R_P} = \frac{50}{8.57} = 5.83\ \text{A} \quad \text{as expected}$$

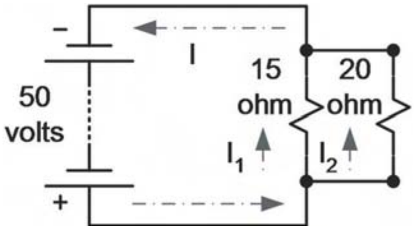

Fig. 2.15 Two unequal resistances in parallel.

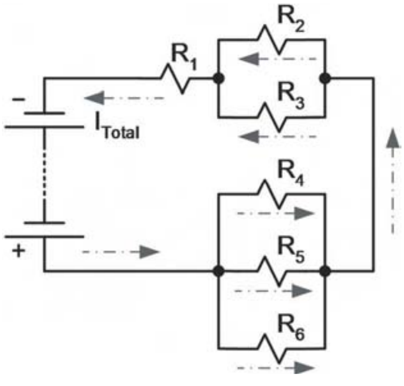

Fig. 2.16 Series–parallel circuit.

A circuit may consist of groups of parallel resistances in series with other resistances as shown in Figure 2.16. In this case, each group of parallel resistances is replaced by its equivalent parallel resistance and the entire circuit is then treated as a series circuit.

Example 2.13 In the circuit of Figure 2.16, determine: (a) equivalent resistance of each parallel group of resistances; (b) total equivalent series resistance; (c) total current; (d) voltage across each series component; and (e) current in each resistance. Use the following values: $R_1 = 5\ \Omega$; $R_2 = 10\ \Omega$; $R_3 = 12\ \Omega$; $R_4 = 15\ \Omega$; $R_5 = 20\ \Omega$; $R_6 = 25\ \Omega$; and $V_T = 50$ V. The circuit is redrawn in Figure 2.17 with all values shown.

(a) The equivalent parallel resistances of the 10- and 12-Ω resistors and of the 15-, 20-, and 25-Ω resistors are

$$R_{10\|12} = \frac{1}{\frac{1}{10} + \frac{1}{12}} = \frac{1}{0.100 + 0.083} = 5.45\ \Omega$$

$$R_{15\|20\|25} = \frac{1}{\frac{1}{15} + \frac{1}{20} + \frac{1}{25}} = \frac{1}{0.0667 + 0.0500 + 0.0400} = 6.38\ \Omega$$

(b) The total series resistance is (5 + 5.45 + 6.38), or 16.83 Ω.

(c) The total current is found from Ohm's law using the total series resistance

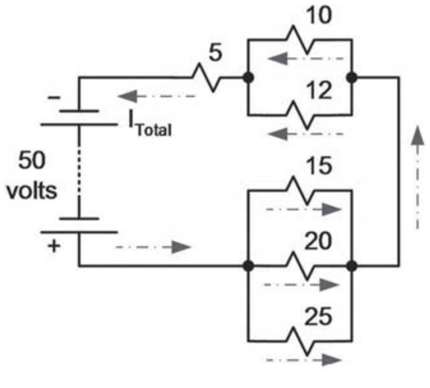

Fig. 2.17 Example series–parallel circuit. Resistances are in ohms.

$$I_T = \frac{V}{R_S} = \frac{50}{16.83} = 2.97 \text{ A}$$

(d) The voltage across each series component is found by solving Ohm's law for voltage and using the equivalent resistance of each series component:

$$V_1 = I_T R_1 = 2.97 \times 5 = 14.85 \text{ V}$$

$$V_{R_{10\|12}} = I_T R_{10\|12} = 2.97 \times 5.45 = 16.19 \text{ V}$$

$$V_{R_{15\|20\|25}} = I_T R_{15\|20\|25} = 2.97 \times 6.38 = 18.95 \text{ V}$$

A quick check shows the total voltage to be (14.85 + 16.19 + 18.95), or 50 V, as expected.

(e) Since the voltages across the resistances are now known, it is a simple matter to calculate the current through them using Ohm's law. The current through the 5 Ω resistance is the same as the total current:

$$I_5 = 2.97 \text{ A}$$

The currents through the other resistances are

$$I_{10} = \frac{16.19}{10} = 1.62 \text{ A}$$

$$I_{12} = \frac{16.19}{12} = 1.35 \text{ A}$$

$$I_{15} = \frac{18.95}{15} = 1.26 \text{ A}$$

$$I_{20} = \frac{18.95}{20} = 0.95 \text{ A}$$

$$I_{25} = \frac{18.95}{25} = 0.76 \text{ A}$$

Note that $I_{10} + I_{12}$ is 2.97 A and $I_{15} + I_{20} + I_{25}$ is 2.97 A, as expected.

Voltage drop is an important consideration in low-voltage dc power systems, and wire sizes frequently have to be larger than the sizes required for current-carrying capacity to compensate for it. Some older telecommunications equipment has a fairly narrow operating range and landline end-office switching systems cannot meet line supervision and signaling requirements unless the voltage is above a certain value, so proper wire sizing is one of the most important jobs in dc power system design.

2.7 ELECTRICAL POWER

In dc circuits, the power dissipated, P, is

$$P = VI \tag{2.11}$$

A simple substitution from Eq. (2.10) gives

$$P = I^2R \tag{2.12}$$

and substituting Eq. (2.9) in Eq. (2.11) gives

$$P = \frac{V^2}{R} \tag{2.13}$$

If any two of the three quantities (voltage, current, and resistance) are known, the preceding three equations can be used to solve for the third quantity. It is important to remember that the above equations apply only to dc circuits and need to be modified slightly, as explained later, for ac circuits.

When 1 A flows between two points with a potential difference of 1 V, the power dissipated is 1 W. The watt frequently is too small a unit, particularly when large amounts of power are being considered. The kilowatt (kW), which is 1000 W, is frequently used. For example, the modular rectifiers used in telecommunications commonly are rated 1500 or 3000 W, which are equivalent to 1.5 and 3.0 kW, respectively.

Power is the rate of doing work, or the rate of energy use. Therefore, electrical energy is the product of electrical power and time:

$$E = Pt \tag{2.14}$$

where E = electrical energy (Wh)
P = power (W)
t = time (h)

If power P in Eq. (2.14) is stated in kilowatts, the energy will be in kilowatt-hours (kWh).

Example 2.14 Determine the amount of energy consumed in 30 days by a steady load of 3000 W. There are a total of 720 h in a 30-day period, so the electrical energy consumed is

$$E = Pt = 3000 \times 720 = 2{,}160{,}000 \text{ Wh, or } 2160 \text{ kWh}$$

The amount of energy consumption is relevant when calculating the electric bill or amount of fuel used by a standby engine–generator set. The rate of energy consumption, or power, is relevant when calculating the size of the standby engine–generator set or calculating circuit conductor sizes or the size of a transformer serving ac loads in a building.

The components used in dc power systems are not perfect. Their efficiency is not 100%, and some of the energy used by the components is dissipated as heat. For example, the efficiency of rectifiers at full load is around 90% (i.e., 10% of the power input is converted in the rectifier to heat), some heat is dissipated in wiring between the rectifiers and battery and the loads, and inverters and DC–DC converters may have low efficiency when lightly loaded. Therefore, the power required by a dc system is always greater than the power delivered by it to the loads.

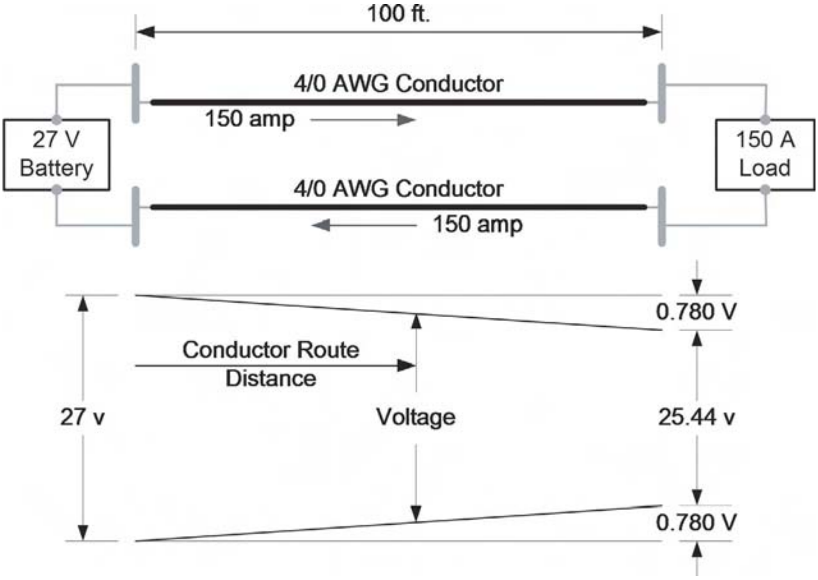

Fig. 2.18 Example feeder circuit for power and voltage calculations.

Example 2.15 Figure 2.18 shows a feeder circuit consisting of positive and negative conductors supplying a load. The feeder is connected to busbars operating at a constant voltage of 27 V. The feeder is 100 ft long and consists of 4/0 AWG conductors operating at 30°C. The maximum load is 150 A. Determine: (a) Voltage drop from the busbars to the load and the voltage at the load; (b) power dissipated in the feeder wires; (c) power dissipated in the load; and (d) total power supplied and efficiency of power transmission.

(a) From Chapter 5, the resistance of 4/0 AWG wire at 30°C is 0.05197 Ω/1000 ft or 0.00005197 Ω/ft. Since the current flows through both wires, there is a voltage drop in both wires as determined by their resistance. Each wire is 100 ft long, so its resistance is 100 × 0.00005197, or 0.005197 Ω. The total resistance of both wires is 2 × 0.005197, or 0.010394 Ω. Using the wire resistance and the 150 A load in Eq. (2.10), the voltage drop in each wire is 150 × 0.005197, or 0.780 V, and the total voltage drop in both wires is 150 × 0.010394, or 1.559 V. Therefore, the voltage at the load is the busbar feeder voltage less the voltage drop in the feeder wires, or 25.44 V.

(b) From Eq. (2.12), the power dissipated in each feeder wire is

$$P_W = I^2 R_W = (150)^2 \times 0.005197 = 116.9\text{ W (233.8 W for both wires)}$$

(c) The power dissipated in the load is determined from Eq. (2.11) using the load voltage [calculated in (a) above] and the load current

$$P_L = V_L I = 25.44 \times 150 = 3816\text{ W (or 3.816 kW)}$$

(d) The total power supplied to the circuit has to equal the power consumed by it; that is, 233.8 + 3816, or 4049.8 W. The power supplied can be calculated using Eq. (2.11):

$$P_T = VI = 27 \times 150 = 4050.0 \text{ W}$$

which is only slightly different because of rounding. The efficiency can be found by taking the ratio of the power delivered to the load to the power supplied by the source, or

$$\text{Eff} = \frac{P_L}{P_S} = \frac{3816}{4050} = 0.942 = 94.2\%$$

2.8 CURRENT DENSITY

As mentioned previously in Section 2.5, a circular mil–foot of copper at 20°C has a resistance of 10.371 Ω (or, approximately, 10 Ω). A typical (or "normal") current density for wiring is 1 A per 1000 CM, or 0.001 A/CM. The approximate voltage drop through a circular mil–foot carrying 0.001 A is

$$V = IR = 0.001 \times 10 = 0.01 \text{ V}$$

Another circular mil–foot conductor, carrying 0.001 A, also will have a voltage drop of 0.01 V between its ends. If these conductors are placed side by side, the voltage drop across the two still will be 0.01 V. With any number of conductors, each having 1 CM cross section, a length of 1 ft, and a current of 0.001 A, the drop between the ends of each conductor will be 0.01 V. The wires may be separated or they may be made into a cable.

Four separate conductors are shown on the upper part of Figure 2.19, each with a dimension of 1 CM-ft and each carrying 0.001 A. The voltage drop across each must be 0.01 V. On the lower part of Figure 2.19, the same four conductors are bundled together, and since each is carrying 0.001 A, the total current is 0.004 A. The voltage drop across the wire bundle is still 0.01 V. If any number of circular mil–foot conductors, each carry-

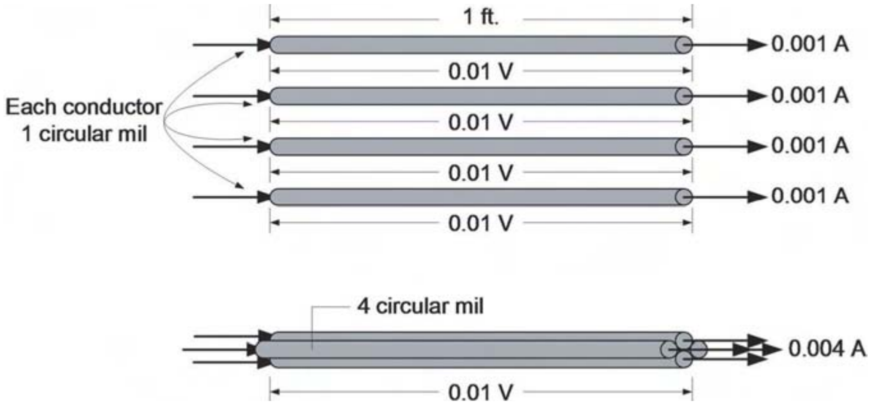

Fig. 2.19 1 Circular mil conductors carrying 0.001 A.

ing 0.001 A, are added in parallel to this bundle the drop remains 0.01 V. The following rule may be deduced from this discussion:

> *The voltage drop per foot of copper conductor whose resistivity is 10 Ω (circular mil–foot) is 0.01 V if the current density is 0.001 A per circular mil (1 A per 1000 CM). Further, if the current density is other than 0.001 A per circular mil, the voltage drop will be in direct proportion to the current density.*

Example 2.16 An equipment load of 110 A is located 75 ft (conductor path distance) from the power bus. The bus is operating at 54 V. Determine the wire size required so the voltage drop does not exceed 2.0 V.

For the wire to operate at the normal current density (1 A per 1000 CM), it must have 110 × 1000, or 110,000 CM. The total voltage drop is 0.01 × 75 × 2 = 1.5 V (note the total conductor length is twice the conductor path distance). The allowable voltage drop is 2.0 V, and so a proportionally smaller wire may be used:

$$110{,}000\left(\frac{1.5}{2.0}\right) = 82{,}500 \text{ CM}$$

The actual current density in the smaller wire is

$$\frac{110{,}000}{82{,}500} = 1.33 \text{ A/1000 CM}$$

which is one-third higher than the normal current density.

Another way of looking at this problem is as follows: The voltage drop per unit length of conductor is known as the voltage gradient in the conductor and is the slope of the voltage graph similar to Figure 2.18. The relation between the voltage gradient and current density is shown by combining Eq. (2.10) with Eq. (2.1), that is,

$$V = IR = \frac{I\rho L}{A}$$

from which

$$\frac{V}{L} = \rho\left(\frac{I}{A}\right) \tag{2.15}$$

Therefore, the voltage gradient (voltage drop/unit length) equals the product of the current density (amperes per unit area) and the resistivity (ohms–unit length). As has been shown for copper conductors, the resistivity is approximately 10 Ω (circular mil–foot), and the voltage drop per foot is 10 times the current density in amperes per circular mil.

The previous example may be solved from the voltage gradient point of view. By substitution in Eq. (2.15), the voltage gradient in the wire is

$$\frac{2.0}{2 \times 75} = 10\left(\frac{110}{A}\right)$$

Solving for area *A* gives

$$A = 10 \times 110 \times 2\left(\frac{75}{2.0}\right) = 82{,}500 \text{ Cm}$$

and the actual current density is

$$\frac{110}{82{,}500} = 0.001333 \text{ A/CM } (1.333 \text{ A/1,000 CM})$$

As before, this density is one-third higher than the “normal” density of 0.001 A per circular mil. The implication of this higher current density is that conductor heating will be higher than normal and conduit or cable rack fill may have to be reduced to ensure the heat is dissipated.

The above methods may be used to determine the power loss in a copper wire. At the normal density, the approximate power loss is

$$P' = I^2R = (0.001)^2 \times 10 = 0.00001 = 1 \times 10^{-5} \text{ W per circular mil-foot}$$

where P' is the approximate power loss (it is approximate because the resistance is rounded to 10 Ω).

In general, the total power loss at the normal density is 0.00001 × CM-L where CM is the conductor circular mil cross section and L is its length in feet. The actual power loss is proportional to the square of the ratio of the actual to the normal current density; that is,

$$P = P_0 \frac{D^2}{(D_0)^2} \tag{2.16}$$

where P = actual power loss (W)
P_0 = power loss at normal current density (W)
D = actual current density in amperes per 1000 CM
D_0 = normal current density in amperes per 1000 CM

Example 2.17 Determine the power loss in the previous example.

$$P_0 = 0.00001 \times 82{,}500 \times 75 \times 2 = 123.75 \text{ W at the normal current density}$$

The actual power loss is

$$P = 123.75\left(\frac{1.333}{1.000}\right)^2 = 219.9 \text{ W}$$

As a check, the power loss is readily determined from the voltage drop and current. In this example, the voltage drop is 2.0 V and the current is 110 A. Hence, the power loss in the wire is

$$P = 2.0 \times 110 = 220 \text{ W (slightly different due to rounding)}$$

A current density of 1 A/1000 CM is equivalent to 1273 A/in.^{2} (a conductor with a cross section of 1000 CM has a diameter of 31.6 mils = 0.0316 in., and its cross-sectional area in square inches is

$$\pi \frac{d^2}{4} = \pi \frac{(0.0316)^2}{4} = \frac{1}{1273} \text{ in.}^2$$

One way to control the temperature rise in the wire is to limit the current density or, looked at another way, the lower the current density, the lower the temperature rise. For a single copper wire, safe current densities are 1200 to 2000 A/in.^{2} (~1060 to 640 CM/A). Where wire is cabled or bundled, it cannot dissipate heat as effectively, and the safe current densities decrease to 1000 to 1600 A/in.^{2} (~1270 to 800 CM/A) or less depending on the configuration. Temperature rise is related to how effectively the heat generated by resistive losses can be dissipated to ambient air, and a low current density does not always ensure a low temperature rise.

Where two conductors are joined, there is a certain amount of contact resistance and heat is developed at the point of contact. Generally, the greater the clamping pressure and the greater the contact area, the smaller the contact resistance will be. However, the nature of the contact surfaces affects the contact resistance; smooth surfaces have less contact resistance than rough surfaces. Contacts are designed such that for a given current, the contact area is large enough to keep the contact resistance from being too high and causing excess heating.

The current densities for conductor contacts are much less than for conductors themselves. For example, copper-to-copper spring contacts in switches are limited to 60 to 80 A/in.^{2} (21,200 to 15,900 CM/A), copper-to-copper clamped contacts are limited to 100 to 125 A/in.^{2} (12,730 to 10,180 CM/A), and fitted and screwed copper-to-copper contacts are limited to 200 to 250 A/in.^{2} (6370 to 5090 CM/A) [3].

2.9 KIRCHHOFF'S CURRENT AND VOLTAGE LAWS

Kirchhoff's laws provide a means for solving electrical networks that may not be easily solved by simple application of Ohm's law.[11]

1. Kirchhoff's current law (or first law): In any electrical network, the algebraic sum of the currents that meet at a point (or junction or node) is zero.
2. Kirchhoff's voltage law (or second law): In any closed electrical circuit, the sum of all the voltages and all the resistance drops, taken with their proper sign, is zero.

The first law may be expressed as follows:

$$\sum I = 0 \text{ at any junction} \tag{2.17}$$

The second law may be similarly expressed:

$$\sum V + \sum IR = 0 \text{ in any closed electrical circuit} \tag{2.18}$$

Equation (2.18) is frequently written

$$\sum V = -\sum IR \tag{2.19}$$

---

[11] Gustav Robert Kirchhoff, a Prussian, developed the laws named after him in 1845.

Both Eq. (2.18) and Eq. (2.19) have the same meaning—the sum of voltage drops around a closed loop is zero.

Kirchhoff's current law is obvious:

> *The total current leaving a junction must equal the total current entering the junction.*

In Figure 2.20, four currents, I_1, I_2, I_3, and I_4 meet at the junction. The directions of the first three currents are toward the junction, so the currents have plus signs as they add to the quantity of electricity at the junction. The direction of current I_4 is away from the junction, so it has a minus sign since it subtracts from the quantity at the junction. According to Kirchhoff's current law,

$$I_1 + I_2 + I_3 - I_4 = 0$$

Example 2.18 Assume $I_1 = 5$ A, $I_2 = 8$ A, and $I_4 = 17$ A. Determine I_3.

$$I_1 + I_2 + I_3 - I_4 = 5 + 8 + I_3 - 17 = 0$$

or

$$I_3 = +17 - 5 - 8 = +4 \text{ A}$$

where the plus sign indicates that the current direction is toward the junction as shown.

The second law is really another application of Ohm's law, Eq. (2.9), and its basis is straightforward:

> *Starting at a certain point in a circuit with a given voltage, and following the paths around the circuit until reaching the starting point, the voltage must be the same. Therefore, the voltage sources encountered in the path must equal the voltage drop in the resistances, with every voltage being given the proper sign.*

Example 2.19 Two voltage sources, $V_1 = 24$ V and $V_2 = 18$ V, are connected in series opposing (their positive terminals are connected together) as shown in Figure 2.21. The voltage sources have internal resistances $R_1 = 2$ and $R_2 = 1\ \Omega$, respectively, and the external resistance $R_{\text{External}} = 5\ \Omega$. Determine the current and voltage at each part of the circuit.

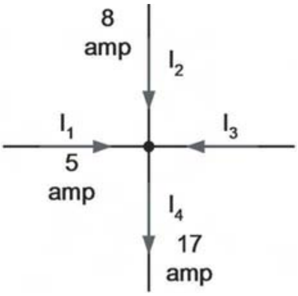

Fig. 2.20 Kirchhoff's current law at a junction.

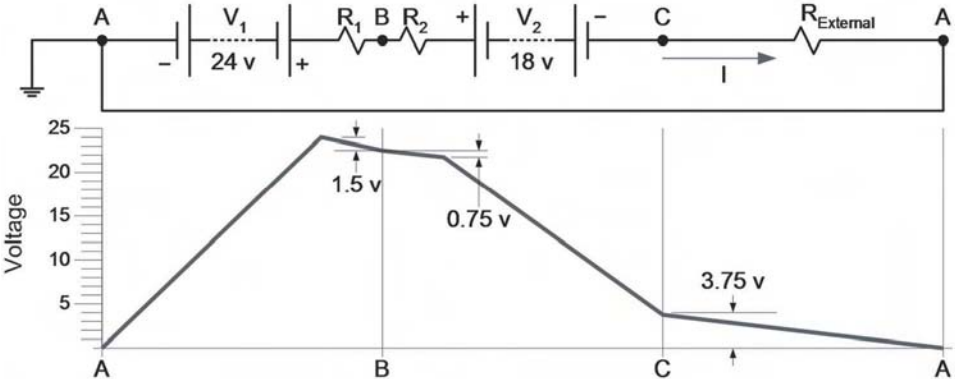

Fig. 2.21 Voltage variation in a circuit.

Since the two voltage sources act in opposition, the net voltage of the two is 24 – 18 = 6 V. The current is

$$I = \frac{V_1 - V_2}{R_1 + R_2 + R_{\text{External}}} = \frac{24 - 18}{2 + 1 + 5} = \frac{6}{8} = 0.75 \text{ A}$$

First, consider point A as the zero volt reference point. This is an arbitrary reference point for the purposes of this example, but in many real circuits, the point that is Earth grounded is the zero reference point. In moving from A to B there is a 24-V rise in voltage due to source V_1. However, there is a voltage drop of 0.75 × 2, or 1.5 V, due to the internal resistance of V_1. Therefore, the net voltage at B is 24 – 1.5, or 22.5 V as shown in Figure 2.21. From B to C there is a drop of 18 V due to going from the positive to the negative terminal of V_2 plus the 0.75-V drop due to the 1 Ω internal resistance of V_2. This makes the net voltage at $C = 22.5 - 18 - 0.75 = +3.75$ V. From C to A there is a voltage drop of 3.75 V due to the current of 0.75 A in the 5-Ω resistance. When A is reached, the voltage has dropped to zero. Therefore, as specified by Kirchhoff's second law, the sum of all voltages in the circuit, taken with their proper sign, is equal to the sum of the IR voltage drops as follows:

Voltages	***IR* Voltage Drops**
$V_1 = +24$ V	V_1 IR drop $= -0.75 \times 2 = -1.5$ V
$V_2 = -18$ V	V_2 IR drop $= -0.75 \times 1 = -0.75$ V
Total = +6 V	External resistance drop $= -0.75 \times 5 = -3.75$
	Total = –6 V

$$\sum \text{Voltages} = -\sum IR \text{ Voltage Drops} = +6 = -(-6)$$

The current also may be found by applying Kirchhoff's second law directly. Starting at point A, which is assumed to be zero (reference voltage),

$$+24 - I \times 2 - 18 - I \times 1 - I \times 5 = 0$$

$$I \times 8 = +6 \text{ V}$$

$$I = +0.75 \text{ A}$$

A problem frequently encountered and a source of error with Kirchhoff's second law is the assignment of algebraic signs. Following these rules can minimize problems:

- A voltage rise should be preceded by a + sign
- A voltage drop should be preceded by a – sign

For example, while moving through a battery from the negative terminal to the positive terminal, the voltage rises, and this voltage should be preceded by a + sign. On the other hand, in going from the positive terminal to the negative terminal, the voltage drops, and so a – sign should precede this voltage. These voltages are due to voltage sources. Therefore, the sign preceding them is *independent* of the direction of the current.

In going through a resistance in the same direction as the current, the voltage drops. Therefore, the voltage drop through a resistance in the direction of the current, whether the internal resistance of a voltage source (such as a battery internal resistance) or an external resistance, should be preceded by a – sign. In going through a resistance in the opposite direction of the current, the voltage rises (negative voltage drop) and the voltage should be preceded by a + sign. It should be noted that the algebraic signs preceding voltage drops or rises across resistances *depend only* on the direction of the current and are *independent* of the polarity of any voltage sources in the circuit.

In applying Kirchhoff's laws to any circuit, the following conditions are necessary for the solution:

- Kirchhoff's current law must be applied to a sufficient number of junctions to include every unknown current at least once.
- Kirchhoff's voltage law must be applied a sufficient number of times to include every element in the circuit at least once.

Example 2.20 Three voltage sources (batteries) are connected as shown in Figure 2.22. Assume the battery internal resistances are negligible compared to the external resistances. Use the following circuit values: V_1 = 22 V, V_2 = 20 V, V_3 = 24 V, R_1 = 0.5 Ω,

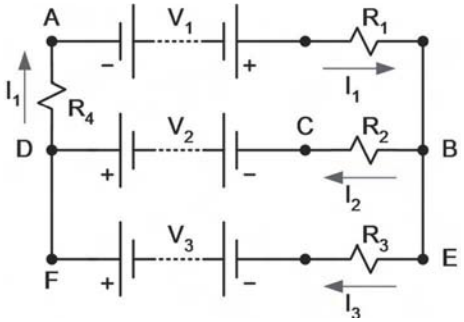

Fig. 2.22 Application of Kirchhoff's laws to solve for voltages and currents.

$R_2 = 3\ \Omega$, $R_3 = 1\ \Omega$, $R_4 = 1\ \Omega$. Determine the voltages and currents at all points in the circuit.

Starting at point A and applying Kirchhoff's voltage law to the path $ABCDA$, the following equation may be written:

$$+V_1 - I_1 \times R_1 - I_2 \times R_2 + V_2 - I_1 \times R_4 = 0 \tag{a}$$

Starting at point F and going along the path $FEBCDF$

$$-V_3 + I_3 \times R_3 - I_2 \times R_2 + V_2 = 0 \tag{b}$$

Equations (a) and (b) provide two equations for determining three unknown quantities (I_1, I_2, and I_3). Three independent equations are necessary to solve for three unknowns. A third equation may be obtained by applying Kirchhoff's voltage law but (a) and (b) already meet the requirement that every element be included at least once. For example, a third path $FEBADF$ may be followed; however, when the third equation is combined with either (a) or (b), the result is either (b) or (a), showing that another condition must be placed on the circuit if a solution is to be found. This third condition must be obtained by applying Kirchhoff's current law to one of the junctions, say B:

$$+I_1 - I_2 - I_3 = 0 \tag{c}$$

The signs in (c) are based on the assumed current directions: I_1 is toward the junction (+ sign) and I_2 and I_3 are away from the junction (– sign). This single equation meets the requirement that every unknown current is included at least once.

With the three equations, (a), (b), and (c), it is possible to solve for the three currents. The circuit is redrawn in Figure 2.23 with the numerical voltages and resistances shown.

Rewriting (a) with numerical values

$$+22 - 0.5I_1 - 3I_2 + 20 - 1I_1 = 0 \tag{d}$$

and simplifying

$$1.5I_1 + 3I_2 = 42 \tag{e}$$

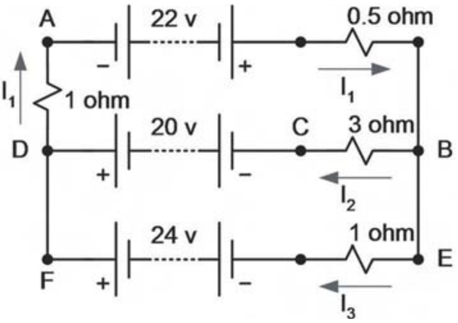

Fig. 2.23 Example circuit with numerical values.

Similarly, for (b)

$$-24 + 1I_3 - 3I_2 + 20 = 0 \tag{f}$$

or

$$1I_3 - 3I_2 = +4 \tag{g}$$

And for (c)

$$+I_1 - I_2 - I_3 = 0 \tag{h}$$

or

$$I_1 = I_2 + I_3 \tag{i}$$

Substituting (i) in (e) gives

$$1.5(I_2 + I_3) + 3I_2 = 4.5I_2 + 1.5I_3 = 42 \tag{j}$$

Multiplying (g) by 3 and (j) by 2 gives

$$3I_3 - 9I_2 = 12 \tag{g$'$}$$

$$3I_3 + 9I_2 = 84 \tag{j$'$}$$

and then adding (g′) and (j′) gives

$$6I_3 = 96 \tag{k}$$

or

$$I_3 = +16 \text{ A}$$

Substituting this value in (g) gives

$$16 \times 1 - 3I_2 = +4$$

Reducing and solving for I_2 gives

$$I_2 = 4 \text{ A}$$

From (i)

$$I_1 = I_2 + I_3 = 4 + 16 = +20 \text{ A}$$

Check by substituting the currents in (d) and (f)

$$+22 - 20 \times 0.5 - 4 \times 3 + 20 - 20 \times 1 = 0$$

$$-24 + 16 \times 1 - 4 \times 3 + 20 = 0$$

As a further check, Kirchhoff's second law may be applied to path *ABEFDA*, which was not originally used in the above solutions, and the appropriate substitutions made

$$+V_1 - (I_1R_1) - (I_3R_3) + V_3 - (I_1R_4) = 0$$

$$+22 - (20 \times 0.5) - (16 \times 1) + 24 - (20 \times 1) = 0$$

The application of Kirchhoff's laws to solving circuit problems is greatly simplified, and the chance of error is greatly reduced if systematic procedures are followed:

1. Make a clear diagram of the circuit. Letter the diagram and label every given quantity.
2. Indicate the assumed direction of current in each element of the circuit. Designate the currents in the different elements by $I_1, I_2, I_3, \ldots I_N$.
3. Use Kirchhoff's current law at each junction to write an equation involving the unknown current. If the direction of the current is toward the junction, its value enters the equation with a positive sign; if away from the junction, with a minus sign. Not all junctions will yield a new relation between the unknown currents. The number of unknown currents can be reduced by applying Kirchhoff's current law to certain junctions.
4. Use Kirchhoff's voltage law to write an equation for each closed portion of the circuit (loop). Proceed as follows: Begin at any convenient point in a circuit loop and pass completely around it in either direction. When a voltage source is passed over, write down its value preceded with a sign that is opposite of the sign attached to the polarity at the end of the source first encountered. When a resistance is passed over, write the value of its voltage drop (*IR* drop) preceded by a minus sign if the direction is the same as the current arrow through the resistance assigned in step 2 or a plus sign if the direction is opposite. Set the algebraic sum of the values written down to zero upon completing the loop. This process will yield more equations than are necessary to find the solution to the problem. Verify the sign of each quantity.
5. Select from the equations written down in steps 3 and 4 as many independent ones as there are unknown values.
6. Solve the equations algebraically for the unknowns by canceling terms or simplifying.

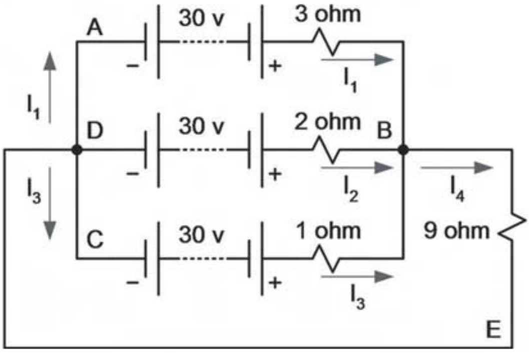

Fig. 2.24 Example parallel battery circuit.

7. Verify the solutions by substituting in the equation of a circuit branch or path not already used.

Example 2.21 Three batteries are connected in parallel as shown in Figure 2.24. The circuit includes battery internal resistances as well as external resistances. The arrows indicate the assumed current directions. Determine the currents.

Since there are four unknowns, four independent equations are necessary. Applying Kirchoff's voltage law in circuit path *ABDA*, starting at *A*,

$$+30 - 3I_1 + 2I_2 - 30 = 0 \tag{a}$$

In circuit *DBCD*, starting at *D*,

$$+30 - 2I_2 + 1I_3 - 30 = 0 \tag{b}$$

and in circuit *DBED*, starting at *D*

$$+30 - 2I_2 - 9I_4 = 0 \tag{c}$$

The equations given in (a), (b), and (c) each include a current that does not appear in any other equation. A fourth equation, (d), can be obtained by applying Kirchoff's current law to junction *B*, giving

$$I_1 + I_2 + I_3 = I_4 \tag{d}$$

or

$$I_1 + I_2 + I_3 - I_4 = 0 \tag{e}$$

A number of different steps may be used to simplify and eliminate terms. One such procedure follows:

1. Combine (a) and (b) to obtain (f). This expresses current I_1 in terms of I_3:

$$3I_1 = I_3 \tag{f}$$

2. Simplify (a) to obtain I_1 in terms of I_2:

$$3I_1 = 2I_2 \tag{g}$$

or

$$I_1 = \tfrac{2}{3} I_2 \tag{h}$$

3. Simplify (b) to obtain I_2 in terms of I_3:

$$2I_2 = I_3 \tag{i}$$

4. Substitute (f) in (e) and rearrange to obtain (j):

$$I_1 + I_2 + 3I_1 - I_4 = 4I_1 + I_2 - I_4 = 0 \tag{j}$$

5. Multiply (j) by +9 and combine with (c) to obtain (k):

$$-36I_1 - 9I_2 + 9I_4 = 0 \tag{j$'$}$$

$$-2I_2 - 9I_4 = -30 \tag{c}$$

$$-36I_1 - 11I_2 = -30 \tag{k}$$

6. Substitute (h) in (k) and solve for I_2:

$$-36(\tfrac{2}{3})\, I_2 - 11I_2 = -30$$

or

$$-24I_2 - 11I_2 = -30$$

and

$$-35I_2 = -30$$

or

$$I_2 = +\frac{30}{35} = +0.857 \text{ A} \tag{l}$$

7. Substitute (l) in (i) and solve for I_3:

$$I_3 = 2I_2 = 2 \times 0.857 = +1.714 \text{ A} \tag{m}$$

8. Substitute (l) in (h) to and solve for I_1:

$$I_1 = \tfrac{2}{3} \times I_2 = \tfrac{2}{3} \times 0.857 = +0.571 \text{ A} \tag{n}$$

9. Solve (d) for I_4:

$$I_4 = I_1 + I_2 + I_3 = 0.857 + 1.714 + 0.571 = 3.142 \text{ A}$$

Since the currents all have positive signs, the assumed directions are correct. As a quick check of the solutions, use circuit path *ABCDA*, starting at *A*,

$$+30 - 3I_1 + 1I_3 - 30 = 0 \tag{m}$$

Substituting I_1 and I_3 in (m) gives

$$+30 - 3 \times 0.571 + 1 \times 1.714 - 30 = 0$$

thus verifying the solutions.

When using Kirchhoff's laws, the direction of the currents must be assumed, but it does not matter which direction is used as long as the same direction is used throughout the analysis. If the assumed direction is not the actual direction, the current will have a minus sign when the equations are solved, thus indicating the current actually is in the other direction.

Example 2.22 The circuit of Figure 2.24 is redrawn in Figure 2.25 to show the assumed directions of I_1 and I_2 to be opposite of the previous example. Determine the currents I_1 through I_4.

The circuit is solved using the same procedures as the previous example. Applying Kirchoff's voltage law in circuit path *ABDA*, starting at *A*,

$$+30 + 3I_1 - 2I_2 - 30 = 0 \tag{a}$$

In circuit *DBCD*, starting at *D*,

$$+30 + 2I_2 + 1I_3 - 30 = 0 \tag{b}$$

and in circuit *DBED*, starting at *D*,

$$+30 + 2I_2 - 9I_4 = 0 \tag{c}$$

Applying Kirchoff's current law to junction *B* gives

$$I_1 + I_2 + I_4 = I_3 \tag{d}$$

or

$$+I_1 + I_2 - I_3 + I_4 = 0 \tag{e}$$

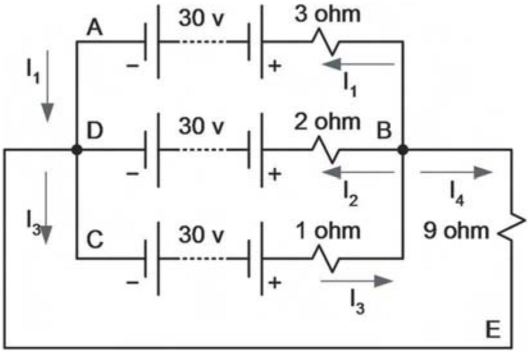

Fig. 2.25 Example battery circuit with I_1 and I_2 current directions reversed.

Using the same basic procedures as before:

1. Combine (a) and (b) to obtain (f):

$$3I_1 = -I_3 \tag{f}$$

2. Simplify (a) to obtain I_1 in terms of I_2:

$$3I_1 = 2I_2 \tag{g}$$

or

$$I_1 = \tfrac{2}{3} \times I_2 \tag{h}$$

3. Simplify (b) to obtain I_2 in terms of I_3:

$$2I_2 = -I_3 \tag{i}$$

4. Substitute (f) in (e) and rearrange to obtain (j):

$$+I_1 + I_2 + 3I_1 + I_4 = +4I_1 + I_2 + I_4 = 0 \tag{j}$$

5. Multiply (j) by +9 and combine with (c) to obtain (k):

$$+36I_1 + 9I_2 +9I_4 = 0 \tag{j$'$}$$

$$+2I_2 - 9I_4 = -30 \tag{c}$$

$$+36I_1 + 11I_2 = -30 \tag{k}$$

6. Substitute (h) in (k) and solve for I_2:

$$+36(\tfrac{2}{3})\, I_2 + 11I_2 = -30$$

or

$$+24I_2 + 11I_2 = -30$$

and

$$+35I_2 = -30$$

or

$$I_2 = -\tfrac{30}{35} = -0.857 \text{ A} \tag{l}$$

7. Substitute (l) in (i) and solve for I_3:

$$I_3 = -2I_2 = -2(-0.857) = +1.714 \text{ A} \tag{m}$$

8. Substitute (l) in (h) to and solve for I_1:

$$I_1 = \tfrac{2}{3}I_2 = \tfrac{2}{3}(-0.857) = -0.571\ \text{A} \qquad \text{(n)}$$

9. Solve (d) for I_4:

$$I_4 = -I_1 - I_2 + I_3 = -(-0.571) - (-0.857) + 1.714 = +3.142\ \text{A}$$

In this example, the currents I_1 and I_2 have minus signs indicating the assumed current directions are opposite to the actual directions, as is apparent from the original example. The signs of I_3 and I_4 are positive indicating their assumed directions are correct. As a quick check of the solutions, use circuit path ABCDA starting at A:

$$+30 - 3I_1 - 1I_3 - 30 = 0 \qquad \text{(c)}$$

Substituting I_1 and I_2 in (c) gives

$$+30 - 3(-0.571) - 1(+1.714) - 30 = 0$$

thus verifying the solutions.

Kirchhoff's laws provide a set of procedures for determining voltages and currents in a circuit. Other methods, such as Maxwell's mesh equations and network analysis techniques, are available to solve the same types of problems and, in many cases, are easier to use when the circuits are complex. References 4 and 5 provide additional detail. However, telecommunications dc power systems and the associated circuits usually are quite simple, and Kirchhoff's current and voltage laws and Ohm's law are sufficient for almost all purposes.

2.10 ALTERNATING CURRENT

2.10.1 Applications

The basic circuit analysis *methods* described in the previous sections apply to ac circuits but several additional considerations are necessary in order to use them properly. This section provides a brief review of ac electricity and how it is applied and used in telecommunications power systems.

Two basic applications of ac circuits are covered in this section—powering the rectifiers from the facility ac distribution system and powering inverter loads. The ac distribution system itself, including the ac service and metering equipment, ac load centers, and ac utilization equipment (such as air conditioners, lights, convenience outlets), are not covered. These ac systems are not unique to telecommunications dc power systems and are covered in References 6 and 7.

Except in remote sites where the prime power system generates direct current, telecommunications buildings and enclosures are powered by alternating current. Alternating current is most common because it can be generated economically and its voltage can be readily raised and lowered so that energy can be transmitted economically over considerable distances.

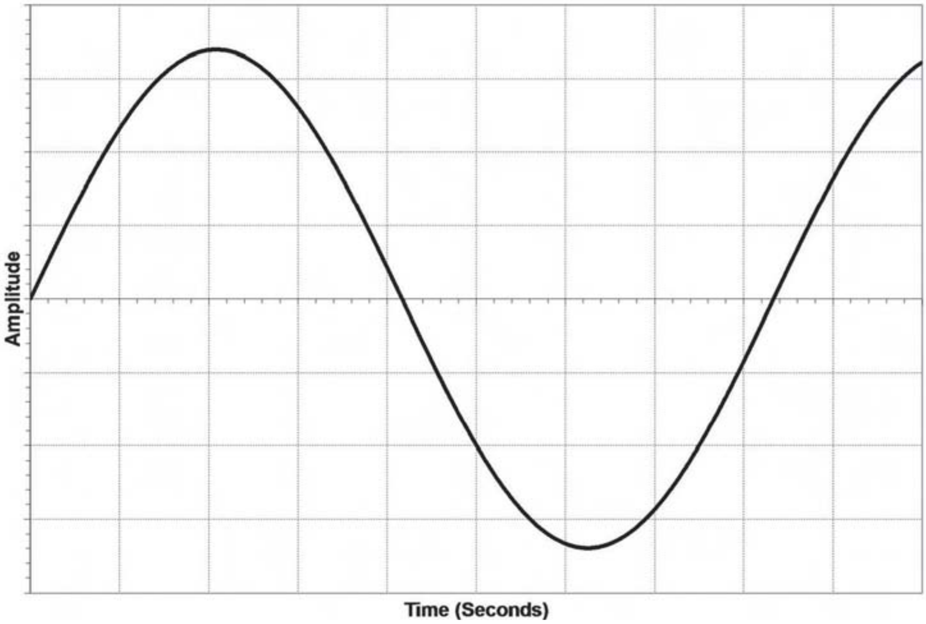

Fig. 2.26 Sine wave.

2.10.2 Sine Wave Voltage and Frequency

An ac generator converts mechanical energy into electrical energy by the principle of electromagnetic induction. Unlike dc, where the voltages and currents have constant or almost constant values at all times, the values of the alternating voltage or current vary with time and can be represented by a smooth curve called a sine wave (Fig. 2.26).

The voltage sine wave curve is a graph of the equation

$$v = V_m \sin(2\pi f t) \tag{2.20}$$

where v = instantaneous voltage
V_m = maximum voltage
π = pi (3.14159 . . .)
f = frequency (Hz)
t = time (s)
sin = trigonometric sine function

The current sine wave is identical in shape, but the values of i and I_m are substituted for v and V_m in Eq. (2.20). When the voltage or current wave goes through one complete set of positive and one complete set of negative values, it has completed one *cycle*. A wave of frequency f completes one cycle in $1/f$ seconds. The unit of frequency is the hertz (Hz), which indicates the number of complete cycles occurring in one second.[12]

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[12] The frequency unit, hertz, named after Heinrich Hertz, a German physicist in the late 1800s, replaced cycles per second (cps) in the 1960s.

In North America and some other parts of the world, the frequency of ac power systems is standardized at 60 Hz; that is, the voltage wave completes 60 cycles in one second. Other frequencies, such as 50 Hz, are used in other parts of the world.

Example 2.23 A 60-Hz voltage sine wave has a maximum value of 100 V. Determine the instantaneous voltage 2.083 ms after its zero crossing.

The quantity $2\pi ft$ in Eq. (2.20) is in radians so, if a calculator is used to solve this problem, it must be set to calculate trigonometric functions with angle inputs in radians. To convert radians to degrees, multiply by the quantity $360/(2\pi) \approx 57.3°$ per radian.

Assuming the voltage is rising after the zero crossing, its value after 2.083 ms will be

$$v = V_m \sin(2\pi ft) = 100 \sin(2 \times 3.14159 \times 60 \times 0.002083) = 70.7 \text{ V}$$

There are three important values associated with voltage or current sine waves:

- *Instantaneous value*—designated as v or i—may be any value between zero and maximum depending on the instant chosen.
- *Maximum value*—designated as V_m or I_m—the peak value of voltage or current reached twice in each cycle (one positive and one negative) when the instantaneous voltage or current is at its maximum.
- *Effective value*—designated as V_{rms} or I_{rms} (or just V or I)—the ac voltage or current value that produces as much power or heating effect as a dc voltage or current of the same value. The effective value also is known as the *root mean square,* or *rms,* value. A voltage of 1 V rms across a resistance will produce the same average power as 1 Vdc. When discussing ac voltages and currents, the subscript rms usually is dropped.

The effective value is the most common value used in ac circuit analysis. It is the value measured with common multimeters and the value used to indicate service and utilization voltages.

The relationship between the effective and peak voltage values for sine waves is (substitute I_m and I when the relationship between effective and peak currents is desired)

$$V_m = \sqrt{2}V = 1.414V \tag{2.21}$$

Similarly,

$$V = \frac{1}{\sqrt{2}} V_m = 0.707V_m \tag{2.22}$$

Example 2.24 Determine the peak voltage when $V = 120$ V and $V = 208$ V.

$$\begin{aligned} V_m &= 1.414V = 1.414 \times 120 = 169.7 \text{ V for rms voltage of 120 V} \\ &= 1.414V = 1.414 \times 208 = 294.1 \text{ V for rms voltage of 208 V} \end{aligned}$$

When the current or voltage waveform is distorted, it is not a pure sine wave but is composed of the fundamental frequency and harmonic frequency components. In this case, the rms value of the distorted wave includes the added effects of the harmonics and for current is calculated from (the rms value for a distorted voltage wave may be similarly expressed)

$$I = \sqrt{\sum_{h=1}^{n} (I_h)^2} \tag{2.23}$$

where I_h = rms current value of harmonic h
n = number of harmonics in calculation

Equation (2.23) may be expressed as:

$$I = \sqrt{(I_1)^2 + (I_2)^2 + \cdots + (I_n)^2} \tag{2.24}$$

The total rms current is calculated as follows:

- Square each current component including the fundamental and harmonics.
- Add the squared values together.
- Take square root of the result.

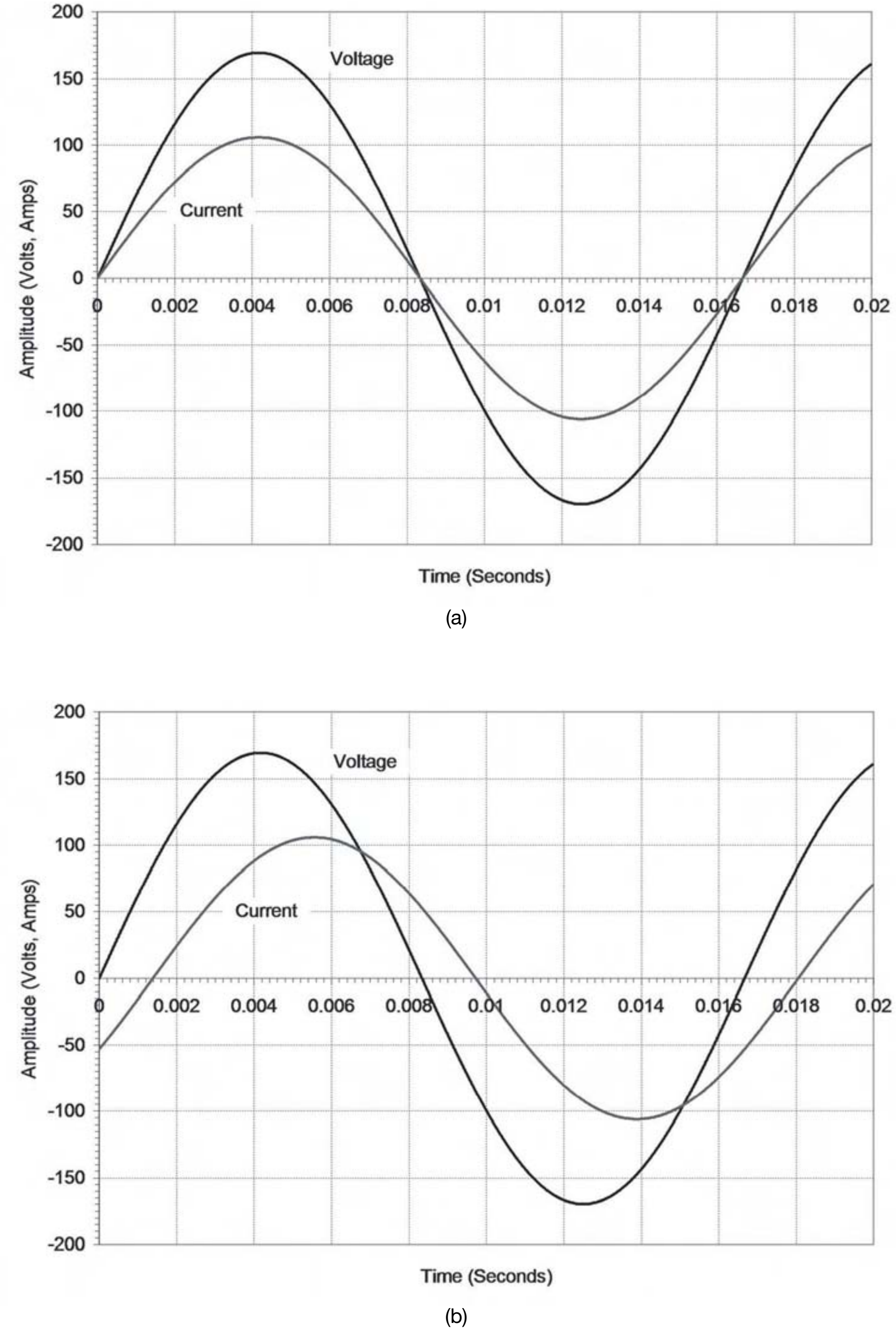
Example 2.25 Find the total rms current if the first (fundamental) through seventh harmonics are 10, 1, 0, 3, 3, 0, and 1 A, respectively.

Squares of each component = 100, 1, 0, 9, 9, 0, 1
Sum of the squares = 100 + 1 + 0 + 9 + 9 + 0 + 1 = 120 A^2
Square root = 10.95 A

Other terms are of interest when discussing ac voltage and current amplitudes are peak-to-peak and crest factor. *Peak-to-peak* amplitude is the total amplitude of an ac waveform measured from maximum positive to maximum negative peaks. The *crest factor* of an ac waveform is the ratio of its peak (crest) to its rms value. Crest factor affects the measurements of distorted waveforms with an average value responding meter. Analog meter movements and inexpensive digital meters respond to the average value of an ac voltage or current but typically are calibrated to display the rms value. While this calibration is accurate for an undistorted sine wave, the meter will incorrectly indicate the rms value of a distorted waveform. True rms meters are available for measuring distorted waveforms but most only are able to accurately display the rms amplitude for waveforms with a crest factor less than approximately 1.1 to 2.0 for handheld multimeters and 5.0 for laboratory instruments. The crest factor of a pure sine wave is 1.414 (or $\sqrt{2}$) and of a triangular wave is 1.732 (or $\sqrt{3}$).

2.10.3 Phase

Voltages and currents in an ac circuit have the same fundamental frequency (60 Hz), but they may not necessarily pass through their corresponding zero values at the same instant in time. Figure 2.27(a) shows 60 Hz voltage and current sine waves with rms amplitudes of 120 V and 75 A (peak values of 169.7 V and 106.1 A, respectively). Both the voltage and



(a)

(b)

Fig. 2.27 Phase relationship of 60-Hz ac voltage and current: (a) in-phase and (b) out-of-phase by 30° or 0.00139 s.

current pass through zero amplitude at the same instant, increasing positively, and, therefore, are said to be in phase with each other. Figure 2.27(b) shows the same voltage and current combination but not passing through zero at the same instant. The current waveform passes through zero, increasing positively, later than the voltage waveform. Therefore, the voltage and current are not in phase and, further, the current *lags* the voltage.

The time lag between the voltage and current shown in Figure 2.27(b) is 0.00139 s, which corresponds to 30° of phase. Phase is represented by the angle θ. The relationships between the various parameters are

$$t = \frac{\theta}{360}\left(\frac{1}{f}\right) \text{ seconds} \tag{2.25}$$

or

$$\theta = 360 ft \text{ degrees} \tag{2.26}$$

For example, at a frequency of 60 Hz, the time corresponding to 25° is

$$\left(\frac{25}{360}\right)\left(\frac{1}{60}\right) = 0.00116 \text{ s}$$

2.10.4 Power in Alternating Current Circuits

2.10.4.1 Voltage and Current In-Phase Calculating the power in a dc circuit is simple—take the product of the dc voltage and dc current. In an ac circuit, the situation is slightly more complicated. In an ac circuit, the product of the *instantaneous* voltage and current determines the power at that instant (the *instantaneous power*). The *peak power* occurs when the peak voltage and current occur at the same time, that is, when the voltage and current are in-phase. The voltage and current in a circuit are in-phase when there is only resistance in the circuit and, under this condition, the average power is given by

$$P = VI \text{ watts} \tag{2.27}$$

2.10.4.2 Voltage and Current Out-of-Phase by Angle θ If the voltage and current differ in phase by an angle θ that lies between –90° and +90°, the average power is given by

$$P = VI \cos\theta \text{ watts} \tag{2.28}$$

The quantity cos θ (trigonometric cosine function of angle θ) is called the *power factor* (PF) of the circuit. The power factor can never be greater than 1.0 and can be leading or lagging based on the phase difference between the voltage and current. A lagging power factor indicates the current lags the voltage wave and the circuit has more inductive reactance than capacitive reactance. A leading power factor indicates the current leads the voltage wave and the circuit has more capacitive reactance than inductive reactance. Solving Eq. (2.28) for the power factor gives

$$\text{PF} = \cos\theta = \frac{P}{VI} \tag{2.29}$$

Example 2.26 The phase angle between the voltage and current in a circuit is 30°. Determine the power factor.

$$\mathrm{PF} = \cos\theta = \cos(30°) = 0.866$$

Inductive reactance can be thought of as the ac resistance of an inductor. An inductor can be a coil of wire (with or without a magnetic core) or regular circuit wiring. When current flows through the inductor it stores electrical energy in the resulting electromagnetic field. With a steady dc current, the inductance has no effect, but with an alternating or changing current, it opposes the change. An inductor acts like a short circuit (has low impedance) at low frequencies and an open circuit (has high impedance) at high frequencies. Inductance is measured in henrys[13] (millihenry, microhenry). Inductive reactance, X_L, is proportional to the frequency f and inductance L and is given by

$$X_L = (2\pi f L)\text{ ohms} \tag{2.30}$$

Similarly, capacitive reactance can be thought of as the ac resistance of a capacitor. A capacitor acts on the principle that when there is a voltage difference between two electrical conductors, there is some charge storage on them. This sets up an electric field in the space between the conductors. With a steady dc voltage applied to the plates, the capacitance has no effect, but with an alternating voltage, the capacitance opposes the change. A capacitor acts like an open circuit (has high impedance) at low frequencies and a short circuit (has low impedance) at high frequencies. Capacitance is measured in farads[14] (microfarads, nanofarads, picofarads). Capacitive reactance, X_C, is inversely proportional to the frequency f and capacitance C and is given by

$$\text{Capacitive reactance } X_C = \frac{1}{2\pi f C}\text{ ohms} \tag{2.31}$$

Example 2.27 A 10-μF capacitor and 10-mH inductor are used in a circuit operating at 60 Hz. Determine the reactance of each component.

$$X_L = 2\pi f L = 2\pi \times 60 \times 10 \times 10^{-3} = 3.77\ \Omega$$

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 60 \times 10 \times 10^{-6}} = 265.2\ \Omega$$

2.10.5 Alternating Current Circuits

2.10.5.1 Circuit with Resistance Only Figure 2.28 shows an ac circuit containing only resistance. The instantaneous current and voltage are

$$i = I_m \sin(2\pi f t)\text{ amperes} \tag{2.32}$$

$$v = Ri = RI_m \sin(2\pi f t)\text{ volts} \tag{2.33}$$

---

[13] The unit of inductance, henry (H), was named after Joseph Henry, an American scientist, in 1893.

[14] The capacitance unit, farad (F), is named after Michael Faraday, an English electrical experimentalist, who developed the concept of electric and magnetic forces in 1845.

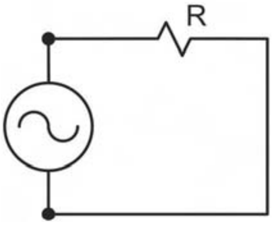


Fig. 2.28 Circuit with resistance only.

The relationship between the effective (rms) voltage and current is

$$V = IR \text{ volts} \tag{2.34}$$

When the circuit has resistance only, $\theta = 0°$ and $\cos\theta = 1.0$ (power factor is 1.0). For the in-phase case, Eq. (2.28) reduces to Eq. (2.27) and

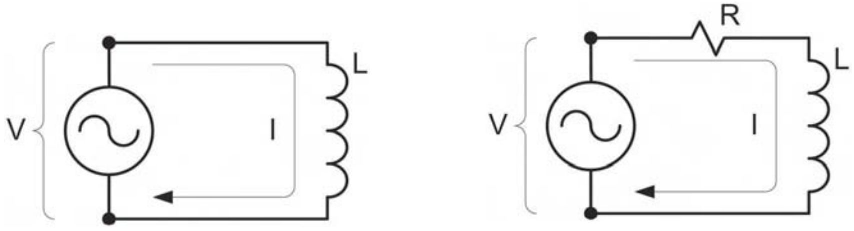
$$P = VI = I^2R \text{ watts}$$

Note that with resistance only, the ac circuit follows the same laws as a dc circuit in regard to the relationships between the voltage, current, resistance, and power.

2.10.5.2 Circuit with Inductance Figure 2.29(a) shows a circuit with inductance only. The current waveform in this circuit lags the voltage waveform by exactly 90°. During those periods when the current is increasing from zero to maximum, the energy received from the power source is stored in the magnetic field of the inductance; during those periods when the current is decreasing from its maximum value to zero, all the stored energy is returned to the source. Therefore, over a complete cycle, the net energy taken by a pure inductance is zero.

Practical inductors have some amount of resistance, as shown in Figure 2.29(b), so the phase difference between the current and voltage is not quite 90°. All power expended in such a circuit is accounted for in the resistance. The total impedance of this circuit is

$$Z = \sqrt{R^2 + X_L^2} \text{ ohms} \tag{2.35}$$



(a) (b)

Fig. 2.29 (a) Circuit with inductance only and (b) circuit with inductance and resistance.

Note that in the case of a pure inductance (in which case $R = 0$), Eq. (2.35) reduces to

$$Z = X_L \text{ ohms}$$

The voltage across a circuit with inductance and resistance is

$$V = I\sqrt{R^2 + X_L^2} = IZ \text{ volts} \tag{2.36}$$

and

$$I = \frac{V}{\sqrt{R^2 + X_L^2}} = \frac{V}{Z} \text{ amperes} \tag{2.37}$$

Equation (2.37) corresponds to Ohm’s law for the ac circuit—the current in an ac circuit is *directly* proportional to the voltage across the circuit and *inversely* proportional to the impedance of the circuit. Note also that the angle by which the current lags the voltage, and thus the power factor of the circuit, is given by

$$\text{PF} = \cos\theta = \frac{R}{\sqrt{R^2 + X_L^2}} = \frac{R}{Z} \tag{2.38}$$

2.10.5.3 Circuit with Capacitance Figure 2.30 shows a circuit with capacitance only. The current waveform in this circuit leads the voltage waveform by exactly 90°. During those periods when the current is increasing from zero to maximum, the energy received from the power source is stored in the electric field of the capacitance; during those periods when the current is decreasing from its maximum value to zero, all the stored energy is returned to the source. Therefore, over a complete cycle, the net energy taken by a pure capacitance is zero.

2.10.5.4 Circuit with Resistance, Inductance, and Capacitance Figure 2.31 shows a circuit with resistance, inductance, and capacitance. The current waveform in this circuit leads the voltage waveform by between +90° and –90° as determined by the relative amounts of inductive and capacitive reactance.

The total impedance of this circuit is

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \text{ ohms} \tag{2.39}$$

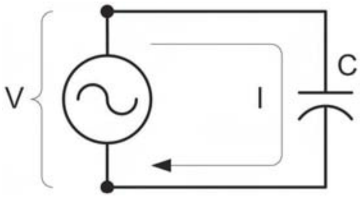


Fig. 2.30 Circuit with capacitance only.

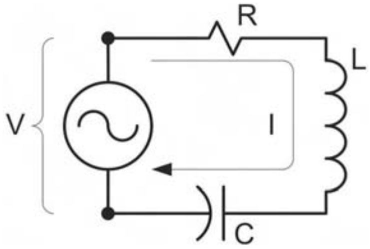


Fig. 2.31 Circuit with resistance, inductance, and capacitance.

The voltage across the circuit is

$$V = I\sqrt{R^2 + (X_L - X_C)^2} = IZ \text{ volts} \tag{2.40}$$

and the current is

$$I = \frac{V}{\sqrt{R^2 + (X_L - X_C)^2}} = \frac{V}{Z} \text{ amperes} \tag{2.41}$$

The power factor of the circuit is given by

$$\text{PF} = \cos\theta = \frac{R}{\sqrt{R^2 + (X_L - X_C)^2}} = \frac{R}{Z} \tag{2.42}$$

Note that when $X_L = X_C$, the power factor is 1.0 because the net of the inductive and capacitive reactances is zero.

Example 2.28 Determine the 60-Hz power factor of a series circuit consisting of a 20-mH inductor, 15-μF capacitor, and a 100-Ω resistor.

First, calculate the inductive and capacitive reactances:

$$X_L = 2\pi \times 60 \times 20 \times 10^{-3} = 7.54\ \Omega$$

$$X_C = \frac{1}{2\pi \times 60 \times 15 \times 10^{-6}} = 176.8\ \Omega$$

The total impedance is

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{100^2 + (7.54 - 176.8)^2} = \sqrt{10{,}000 + 28{,}649} = 196.6\ \Omega$$

and

$$\text{PF} = \frac{R}{Z} = \frac{100}{196.6} = 0.509$$

2.10.6 Other Forms of Alternating Current Power

There are three types of power in ac circuits:

$$P_{\text{Apparent}} = VI \text{ volt-amperes (VA)} \tag{2.43}$$

$$P_{\text{Real}} = VI \cos \theta \text{ watts (W)} \tag{2.44}$$

$$P_{\text{Reactive}} = VI \sin \theta \text{ volt-amperes-reactive (VAR)} \tag{2.45}$$

Equation (2.43), which is the product of rms voltage and current, has a measurement unit of *volt-amperes,* or *VA.* It is called the *apparent power* because it may not indicate the actual power used or delivered if the circuit contains capacitance or inductance. Eq. (2.44) is the *real* or *active* power in *watts,* or *W.* It is called real power because it is the power that actually does work (causes an incandescent lamp to glow, charges a battery, or powers load equipment). Finally, Eq. (2.45) is called *reactive power.* It indicates the power that is stored in the circuit's capacitance and inductance and is given in *volt-amperes-reactive,* or *VAR.* The three types of power are related by

$$P_{\text{Apparent}} = \sqrt{(P_{\text{Real}})^2 + (P_{\text{Reactive}})^2} \tag{2.46}$$

Equation (2.46) may be written using a more formal nomenclature:

$$S = \sqrt{P^2 + Q^2} \tag{2.47}$$

where S = apparent power
P = real power
Q = reactive power

Another way of defining power factor is the ratio of real to apparent power:

$$\text{PF} = \frac{P_{\text{Real}}}{P_{\text{Apparent}}} \tag{2.48}$$

While Eq. (2.48) is equivalent to the definitions already given in terms of the phase angle between the voltage and current (*displacement power factor*), the power ratio provides clearer insight into the power factor correction used in all modern ferroresonant and switch-mode rectifiers. In these rectifiers, the ac current drawn by the rectifiers normally would be highly distorted and, as a result, would introduce relatively high harmonic currents into the ac power system. These harmonics distort the shape of the current waveform, which leads to what is called *distortion power factor.* Distortion power factor is the ratio of 60-Hz current magnitude to the effective (rms) current magnitude. The total rms current includes harmonics and will be larger than the current at the 60-Hz powerline fundamental frequency.

An ac load with high harmonic currents causes numerous problems in electric utility transformers and building wiring, so all modern rectifiers have power factor correction circuits that reduce the harmonics and thus improve the distortion power factor.

Example 2.29 The rms voltage across a circuit is 120 V and the rms current through it is 10.5 A. The current lags the voltage by 29°. Determine the apparent, real, and reactive power and the power factor.

$$P_{\text{Apparent}} = VI = 120 \times 10.5 = 1260 \text{ VA}$$

$$P_{\text{Real}} = VI \cos \theta = 120 \times 10.5 \cos(29°) = 1102 \text{ W}$$

$$P_{\text{Reactive}} = VI \sin \theta = 120 \times 10.5 \sin(29°) = 611 \text{ VAR}$$

$$\text{PF} = \frac{P_{\text{Real}}}{P_{\text{Apparent}}} = \frac{1102}{1260} = 0.875 \text{ lagging}$$

2.10.7 Single-Phase and Three-Phase Voltages

The phase angle concept applies to voltages in a multiphase system, such as a three-phase electric service, and in a single-phase service as well. In the three-phase system, the voltages have exactly 120° phase difference, and the voltages on the two legs of a single-phase electric utility service have 180° phase difference.

Electric power is delivered through a service transformer or bank of transformers located on or near the facility property. A simple transformer has a primary winding and a secondary winding (Fig. 2.32, upper). The voltage transformation depends on the primary and secondary turns ratio. For example, if the primary has 30 times more turns than the secondary, or $N/M = 30$, the turns ratio is 30 : 1. If a voltage of 7200 V is applied to the primary (a common distribution voltage), the secondary voltage will be 7200/30 = 240 V (a common service voltage). In this type of service transformer, the secondary winding has a center tap, so the ratio on each half of the secondary effectively is 60 : 1 and the voltage from the center tap to each outer leg is 120 V (Fig. 2.32, lower).

The service transformers are step-down types that reduce the electric utility distribution voltage to a much lower *utilization* voltage. The voltages used in modern distribution systems vary from 12,700 to 34,500 V line-line. These voltage levels are classified as medium voltages. The typical line-neutral voltages of 7200 and 14,400 V have corresponding line-line voltages of 12,470 and 24,940 V, respectively. In older areas, many

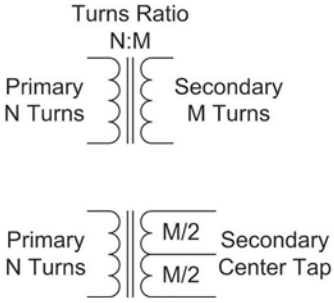


Fig. 2.32 Transformer schematics: *upper,* Simple transformer with N : M turns ratio; *lower,* transformer with center-tapped secondary.

distribution lines still use line-line voltages of 2400 and 4800 V. Many other voltages have been used over the years. Single-phase services use one step-down transformer and three-phase services may use one transformer with three integral windings (i.e., a three-phase transformer) or two or three individual transformers (i.e., single-phase transformers) depending on the configuration.

The service voltages at the service transformer secondary windings may be measured from line-to-neutral or from line-to-line. With most single-phase services, there are two lines (L1 and L2) and a neutral (total of three wires) and the voltages have a 180° phase relationship (Fig. 2.33). The most common voltages are 240 V line-line and 120 V line-neutral. The nomenclature "120/240 V" indicates the service voltage for a typical single-phase service.

The general relationship between line-line (L-L) and line-neutral (L-N) voltages for a single-phase service is

$$V_{L\text{-}L} = 2V_{L\text{-}N} \quad \text{or} \quad V_{L\text{-}N} = \tfrac{1}{2}V_{L\text{-}L} \tag{2.49}$$

The advantage of a three-phase electrical service is in the efficiency of generation and distribution of large amounts of power compared to single phase. However, most ac loads in telecommunications facilities are single phase and are connected line-neutral or line-line. To maintain *load balance,* the individual loads are spread as evenly as possible across the three phases.

Three-phase services may be connected in a delta or wye configuration, which refers to the way the windings in the service transformers are presented schematically. Several variations of the delta configuration have been used over the years, including ungrounded and corner grounded delta. These normally are found only in industrial installations. One variation of the delta configuration that uses a center-tapped transformer to serve line-neutral loads may be found in many older telecommunications facilities. Either two or three transformers may be used (Fig. 2.34). The nomenclature for a three-phase, four-wire delta service is "240/120 V" to differentiate it from a 120/240 V single-phase service.

The three-phase, four-wire delta combines the characteristics of a single-phase service for serving line-neutral loads such as lighting with the characteristics of a three-phase service for serving three-phase loads such as motors and large rectifier systems. Line-neutral

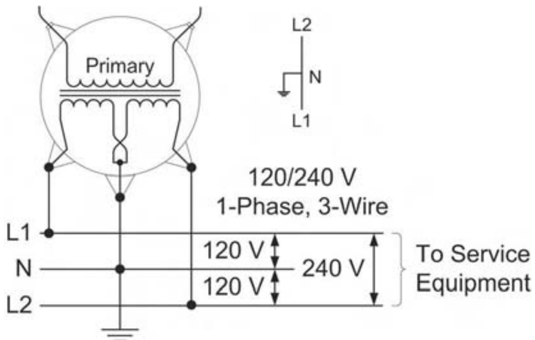


Fig. 2.33 120/240 V, one-phase, three-wire service. The small schematic to the right of the transformer shows the phase relationship between the two legs L1 and L2.

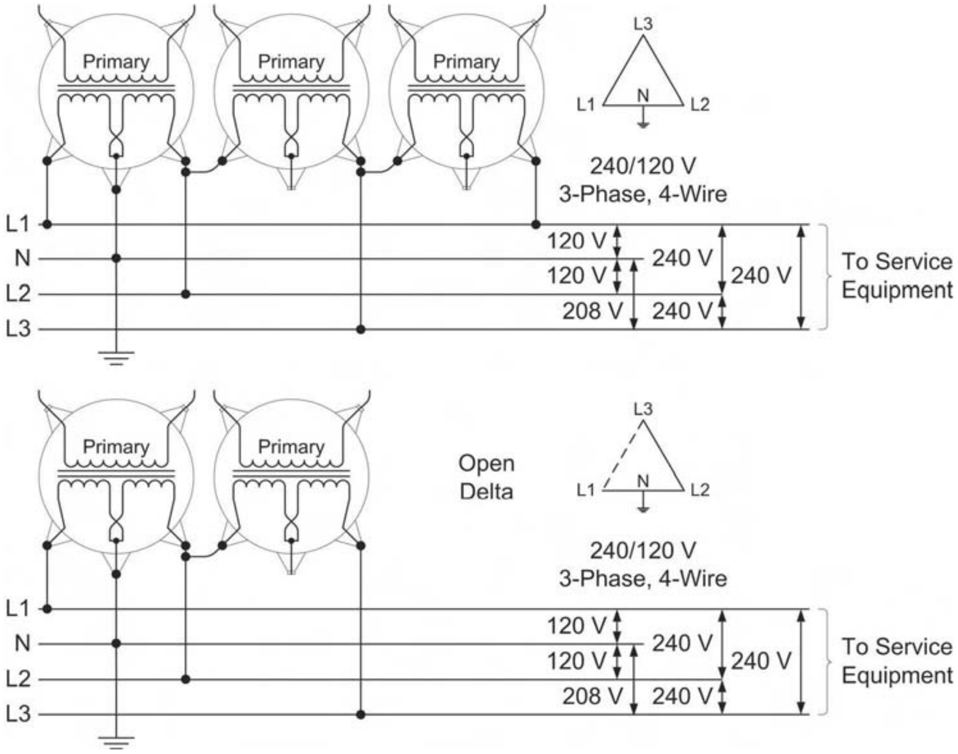


Fig. 2.34 Three-phase, four-wire delta services.

loads are connected L1-N and L2-N and line-line loads are connected L1–L2, L2–L3, and L1–L3.

The advantages of the three-phase, four-wire delta service voltage configuration is the ease with which an existing single-phase service may be upgraded to three-phase by adding one or two single-phase transformers and the fact that the added transformers almost always are smaller than the original single-phase transformer, thus providing some cost savings to the electric utility. The disadvantages are the inherently unbalanced load on the primary distribution lines and the potential problems and damage due to certain types of electrical faults. Also, the voltages from line-neutral depend on the phase leg in question. For L1-N and L2-N, the voltage is 120 V but for L3-N, the voltage is 208 V. The latter is called the "wild" leg or high leg. All line-line voltages (L1–L2, L2–L3, and L1–L3) are 240 V.

With a wye-connected three-phase service (the most common type of three-phase service), there are three lines (L1, L2, and L3) and a neutral (a total of four wires), and the voltages have a 120° phase relationship. There are two common service voltages with 208 V line-line and 120 V line-neutral and 480 V line-line and 277 V line-neutral (the latter typically found in larger installations) (Fig. 2.35). The nomenclatures used to indicate these service voltages are "208Y/120 V" and "480Y/277 V," respectively. The general relationship between line-line (L-L) and line-neutral (L-N) voltages for a three-phase wye-connected services is

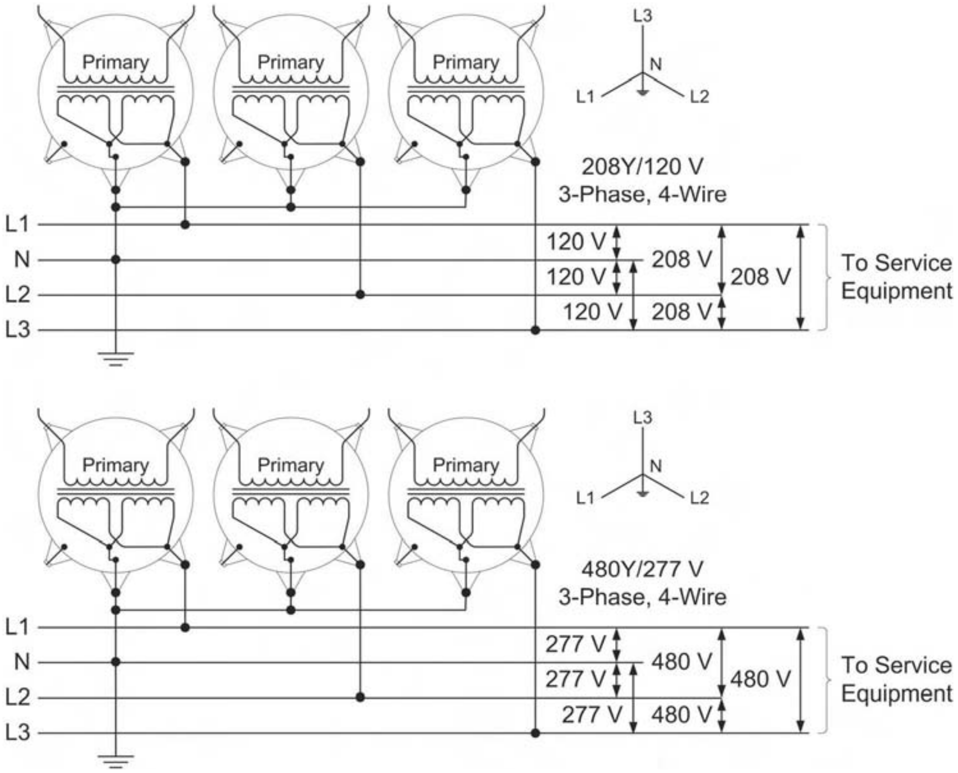


Fig. 2.35 Three-phase, four-wire, wye service configurations.

$$V_{L\text{-}L} = \sqrt{3}V_{L\text{-}N} \quad \text{or} \quad V_{L\text{-}N} = \frac{1}{\sqrt{3}}V_{L\text{-}L} \tag{2.50}$$

A variation of the three-phase, four-wire service, called a network service, is used to derive one-phase, three-wire services from a three-phase transformer installation (Fig 2.36). In this case, the one-phase services are connected to any two phases and neutral, and the line-neutral voltages on both legs are 120 V and the line-line voltage is 208 V. Such an installation is convenient and inexpensive to the electric utility that has an existing three-phase service and needs to connect one-phase services nearby.

The load power on a single-phase service is the sum of the power on the individual legs, or

$$P_{1-\Phi} = (V_{A\text{-}N}I_A\text{PF}_A) + (V_{B\text{-}N}I_B\text{PF}_B) \tag{2.51}$$

For a balanced single-phase load (equal line currents, line voltages, and power factors)

$$P_{1-\Phi} = 2V_{L\text{-}N}I_L\text{PF} = V_{L\text{-}L}I_L\text{PF} \tag{2.52}$$

The calculations of power in three-phase circuits are straightforward if the loads on each phase are known. Assuming the loads are perfectly balanced, and in terms of line-neutral

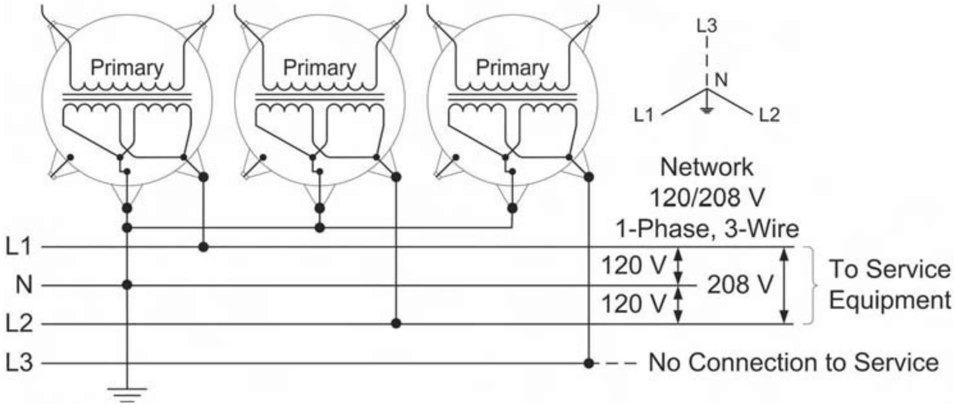


Fig. 2.36 Network service derived from a three-phase transformer installation.

voltages, the power is

$$P_{3-\Phi} = 3V_{L\text{-}N}I_L\text{PF} \tag{2.53}$$

or, in terms of line-line voltages,

$$P_{3-\Phi} = \sqrt{3}V_{L\text{-}N}I_L\text{PF} \tag{2.54}$$

Power can be calculated based on a single-phase representation of each of the three phases. If the loads are not balanced

$$P_{3-\Phi} = (V_{L1\text{-}N}I_{L1}\text{PF}_{L1}) + (V_{L2\text{-}N}I_{L2}\text{PF}_{L2}) + (V_{L3\text{-}N}I_{L3}\text{PF}_{L3}) \tag{2.55}$$

2.10.8 Alternating Current Wiring

Wiring in ac circuits has slightly different electrical characteristics than the same wiring in dc circuits because of skin effect and proximity effect and the inductive and capacitive effects on ac current. Skin effect is the tendency for alternating currents to flow closer to the surface of a wire with higher current density than in the center. Proximity effect is the interaction of the alternating magnetic fields of conductors in close proximity. Skin effect and proximity effect increase the resistance of the wire at power frequencies (60 Hz) and is most noticeable in large wire sizes (> 250 kcmil).

The type of conduit, whether magnetic such as steel or nonmagnetic such as aluminum, used to enclose the wiring also affects the electrical characteristics. The power factor of the load itself will affect the voltage drop in the wiring. However, except in multifloor or large sprawling buildings, ac voltage drops are small and detailed calculations seldom are needed.

In those cases where it is desirable to perform ac circuit analysis of the type applicable to rectifier and inverter wiring, the process can be simplified by assuming certain conditions and using approximations. However, it is helpful to first look at a vector diagram of the voltage and current relationships in an ac circuit (Fig. 2.37). A vector dia-

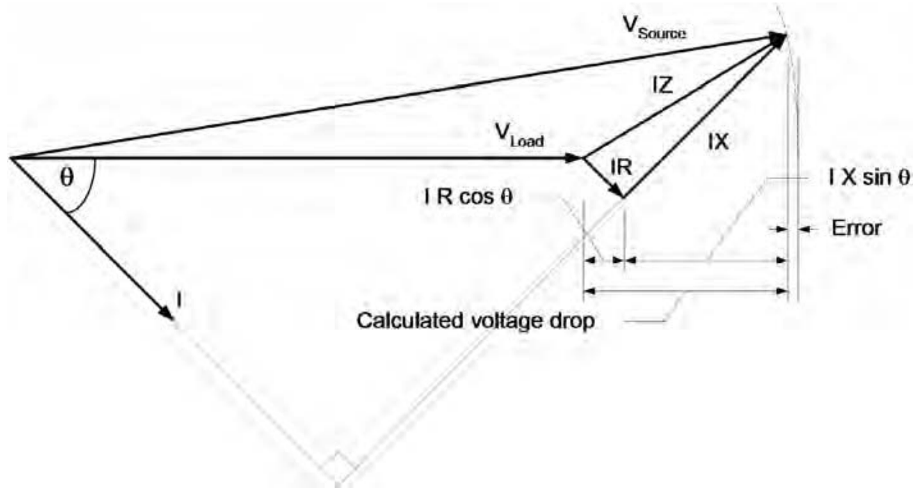


Fig. 2.37 Vector diagram of ac circuit voltages and currents with lagging power factor.

gram shows the magnitude and phase angle of the source and load voltages and the line current (the lengths are exaggerated in the illustration for clarity). The vector arrow lengths are proportional to the magnitudes and the angles are shown directly. The exact formula for the voltage at the load end of the circuit, which can be derived from the vector diagram, is

$$V_{\text{Load}} = \sqrt{V_{\text{Source}}^2 - (IX \cos\theta - IR \sin\theta)^2} - (IR \cos\theta + IX \sin\theta) \tag{2.56}$$

Usually, the parameter of interest is the actual voltage drop itself, which is approximated by

$$V_{\text{Drop}} = IR \cos\theta + IX \sin\theta \tag{2.57}$$

where V_{Drop} = line-neutral voltage drop in the circuit (V)
I = line current (A)
R = line ac resistance in one conductor (Ω)
X = line reactance in one conductor (Ω)
θ = angle between the load voltage and load current
$\cos\theta$ = load power factor
$\sin\theta$ = load reactive factor

The voltage drop calculated above is the drop in one conductor. For single-phase circuits, V_{Drop} must be multiplied by a factor of 2, and for three-phase circuits, must be multiplied by $\sqrt{3} = 1.732$ as in

$$V_{1-\Phi\text{Drop}} = 2(IR \cos\theta + IX \sin\theta) \tag{2.58}$$

$$V_{3-\Phi\text{Drop}} = \sqrt{3}(IR \cos\theta + IX \sin\theta) \tag{2.59}$$

From the above formulas, the resistive voltage drop is in-phase with the line current and is given by the term $IR \cos \theta$. The reactive voltage drop component, or $IX \sin \theta$, is 90° out of phase with the current. The sign of $\sin \theta$ depends on whether the load power factor is lagging, in which case it is positive, or leading, in which case it is negative. Lagging power factor is more common.

Example 2.30 The resistance in a single-phase circuit is 0.01 Ω and the reactance is 0.02 Ω. The line current is 9.1 A and the load power factor is 0.9. Determine the voltage drop.

First, determine the phase angle between the load voltage and current and then use that to calculate the voltage drop. Since the power factor is 0.9, then $\cos \theta = 0.9$. Therefore, angle θ is the inverse cosine of 0.9 and

$$\theta = \cos^{-1}(0.9) = 25.8^\circ$$

and

$$\sin(25.8^\circ) = 0.436$$

The voltage drop is

$$V_{1-\Phi\text{Drop}} = 2(IR \cos \theta + IX \sin \theta) = 2[(9.1 \times 0.01 \times 0.9) + (9.1 \times 0.02 \times 0.436)] = 0.322 \text{ V}$$

To simplify voltage drop calculations, wiring characteristics, including the effects of conduit, are summarized in tables in terms of voltage drop per 10,000 A-ft of wire with multiplication factors to adjust between single-phase and three-phase systems. The table values are then scaled to the actual circuit conditions being analyzed. Chapter 5 (System Design) provides a table for this purpose and its use is described there.

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CHAPTER 3

dc POWER SYSTEM COMPONENTS

Telecommunications dc power systems are made from numerous components and equipment groups, including rectifiers, powerboards with charge and discharge busbars, primary and secondary distribution systems (including overcurrent protection), batteries, and voltage conversion devices. This chapter describes all of these components in detail except batteries, which are described in Chapter 4, Telecommunications Batteries.

3.1 NOMINAL SYSTEM AND OPERATING VOLTAGES

Modern telecommunications dc power systems in the United States are 60 Vdc class and operate at nominal 24 or 48 V, although some equipment still exists in networks that operates at a nominal voltage of 12 or 130 Vdc. Nominal system voltages and operating voltage ranges are shown in Table 3.1.

A number of factors affect the dc power system operating voltage ranges including battery technology (VLA or VRLA), voltage drops in the circuit segments, rectifier output regulation, and equipment voltage limits. Specific details and rationale behind the ranges shown are provided in Chapter 5 (System Design).

Because the thinner air at higher altitudes reduces the convection and forced-air cooling capability of equipment, the power output of most dc power system components must be derated when operated at altitudes exceeding 3300 ft (1000 m) above sea level. There also is additional derating at 6600 ft (2000 m) for circuit interrupting devices (such as circuit breakers). For interrupting devices, the thinner air is a poorer dielectric, thus reducing their interrupting capability. Derating applies to mountaintop sites as well as high-altitude regions in the United States. Power producing equipment such as rectifiers, converters, and inverters generally have a lower maximum current output capability or a lower maximum ambient operating temperature at altitude than at sea level. A typical temperature derating requires a linear decrease in ambient operating temperature from +50°C (122°F) at sea level to +40°C at 10,000 ft (3000 m).

Table 3.1 Nominal System Voltages and Voltage Ranges[a]

Nominal System Voltage (Vdc)	Operating Voltage Range (Vdc)	Remarks
12	10.7–15.0	
24	20.0–28.3	
48	42.75–56.7	Applies to load equipment that provides network-to-user interfaces for dc signaling[b]
48	40.0–56.7	Applies to load equipment that does not provide network-to-user interfaces for dc signaling[c]

[a] Source: ANSI T1.315 [1]. See Chapter 5 for explanation of how ranges are derived.

[b] Network-to-user interfaces that use dc signaling include loop-start and ground-start analog line circuits (the former often referred to as POTS, or plain old telephone service), loop-reverse battery (LRB) analog trunk circuits, and E&M analog trunk circuits. The design of some switching systems that use these circuits is such that the lower end of the operating voltage range has to be increased to achieve the desired supervision distances on metallic twisted-pair access network facilities [2–5].

[c] Not all equipment can meet the lower and upper limits.

3.2 NOISE AND TRANSIENTS IN dc POWER SYSTEMS

3.2.1 Noise Characteristics

Noise is any undesired signal and can take many forms. Of particular importance in dc power systems are noise voltages and currents that interfere with load equipment operation or even the operation of the dc power system itself. The noise can be coupled into equipment via power and signal circuit conductors (conductive coupling) and via electromagnetic (inductive and capacitive) coupling caused by improper or inadequate shielding, bonding, and grounding.

It is impractical to build rectifiers, converters, and rotating electrical generating machinery and transformers that are entirely free of harmonic voltages and currents in their input and output waveforms. The dc output from rectifiers contains many ac components called *ripple,* and their input ac current waveforms can be distorted. The term ripple indicates what the dc voltage looks like on an oscilloscope (Fig. 3.1). The distorted voltages and currents (noise) are electromagnetically coupled into telecommunications systems through outside plant cables and signal and power cables in central offices.

The coupled noise can be measured with or without a filter. When measured with a filter, it commonly is called *weighted* noise, and, when measured without a filter, it is called *unweighted* noise. It should be noted that all noise measuring test sets have limited frequency response even when in the unweighted, or “wideband,” mode, but the response usually is flat throughout the desired band rather than specially shaped as in the *weighted* mode. In either case, the measured noise power is determined from the root mean square (rms) voltage of the ac components within the frequency band or bands of interest.

Weighted measurements indicate the interfering or annoying effects of specific frequencies on human telephone conversations. Certain frequencies are more or less filtered by the combination of the telecommunications channel, telephone set, and human ear and have different annoying effects. Frequencies that are heavily filtered by the system or are not annoying have less weighting while unfiltered and annoying frequencies have more weighting. Frequencies outside of the voice band (below approximately 200 and above approximately 3400 Hz) are already heavily filtered by analog circuit transmission inter-

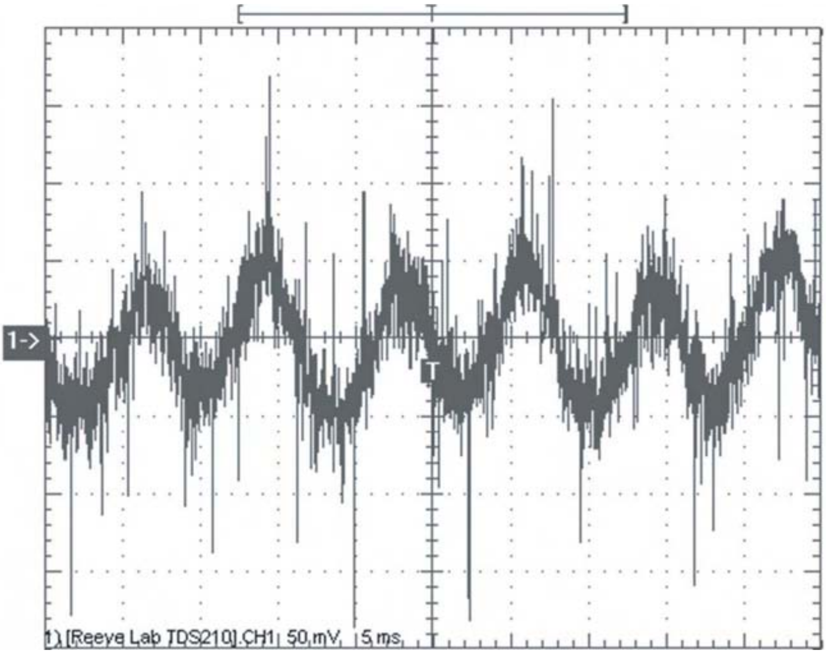

Fig. 3.1 Ripple voltages in a dc power system. The oscilloscope screen capture was taken with a ground reference at a –48-Vdc secondary distribution bus about 100 ft from the primary distribution. The waveform shows noise and small spikes superimposed on 120-Hz ripple. The peak–peak amplitude of the ripple is around 100 mV.

faces and have less interfering effect so are completely excluded from voice-band measurements.[1]

The C-Message filter is the standard filter for voice-band measurements (Fig. 3.2). It is based on the 500-type telephone set manufactured by Western Electric in the 1950s. Although this type of telephone set has not been manufactured for many decades, the C-Message filter still is widely used for noise measurements in the telecommunications industry. Noise measured with this filter is given in units of dBrnC (decibels with respect to reference noise using the C-Message filter). Reference noise is defined as 1 picowatt, or 0 dBrnC, which is equivalent to a power level of –90 dBm. Reference noise voltage in a 600-Ω circuit impedance is 0.0245 mV (0.0000245 V). Noise measured with a C-Message filter is lower than noise measured over the voice band with no filter (unweighted).

The major noise sources in dc power systems are rectifiers and load equipment, but noise may come from external sources as well. Many types of external equipment, such as electric motors, and other external noise sources, such as lightning and ac power distribution and transmission systems, influence overall noise performance especially if the

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[1] Frequencies in the band from approximately 200 to 3400 Hz are called *voice frequencies* and the band is called the *voice band*. Analog telecommunications channels that operate in this band are called *voice-grade* circuits. The noise requirements for voice-grade circuits are specified in [6]. Voice-grade circuits can carry not only human speech but also analog voice-band data from fax machines and dialup modems. For a more complete discussion of analog transmission, see [2,7].

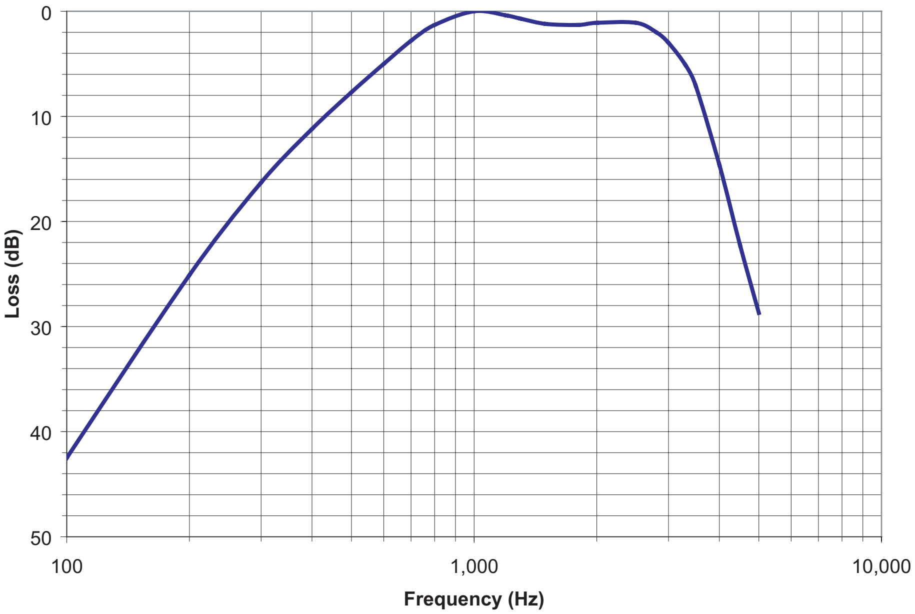

Fig. 3.2 C-message filter curve, voltage–frequency, or current–frequency response.

telecommunications facility is inadequately bonded and grounded. Rectifiers have fairly large capacitors and inductors for output noise filtering, but this has little effect on noise induced into power and signal cabling by other sources. To reduce noise from these other sources, it is common to use individual *powerline filters* located as close to the loads as possible (e.g., in the fuse or circuit breaker panel located in an equipment frame).

The typical noise output specification for rectifiers is based on industry experience and normally is 32 dBrnC (1.6 nW, or 0.975 mV across 600 Ω). Reduction below this value at the rectifier output through additional internal filtering has little effect on the noise at the loads, and additional filtering adversely affects the rectifier's response to step loads and other transients caused by load equipment.

So-called wideband (unfiltered) noise is specified in volts or millivolts with and without a battery (as a filter) in the measuring circuit. Fully charged batteries look electrically like very large capacitors so they have a significant filtering effect. Wideband noise measurements usually specify a battery ampere-hour (Ah) capacity that is four times (4×) the load current. For example, the wideband noise from a 50-A rectifier would be measured with a 200-Ah battery connected to its output. Typical values for modern modular rectifiers are 100 to 500 mV peak to peak in any 3-kHz interval over a 20-MHz bandwidth. Table 3.2 shows various noise parameters that apply at the system level. Individual components may operate at different noise levels and dc powerline filters located close to load equipment may be required to meet operating requirements.

3.2.2 Transients

Transients are temporary deviations of the steady-state voltage to higher and lower values (Fig. 3.3). Transients that decrease the voltage can cause equipment dropouts; transients

Table 3.2 Maximum System Noise Levels

Nominal System Voltage (Vdc)	Voice-Band Noise (dBrnC at 600 Ω)	Wideband Noise (mV_{rms})	Peak–Peak Noise (mV_{pp})
12	—	—	—
24	56	100	240
48	56	100	480

Source: ANSI T1.315 [1].

that increase the voltage can damage power supplies and electronic components. The opening of overcurrent protection devices, component failures, and online or offline switching of older rectifiers can cause transients. Transients in a circuit can cause nuisance tripping of overcurrent devices. All modern rectifiers have a current *walk-in* feature that eliminates transients during online switching.

Transients in telecommunications dc power systems are not well studied or documented, but values for testing 48-V equipment have been specified (Table 3.3).

3.2.3 Direct Current Powerline Filters

Powerline filters are used to reduce ripple voltages and currents on the power conductors. Although they frequently are called *battery filters,* powerline filters do not filter battery noise (batteries do not generate noise). Powerline filters are located close to loads or groups of loads and are used to reduce noise that is electromagnetically coupled into the dc power circuits. Such filters usually are an L- or π-filter topology (Fig. 3.4) and are connected in series with primary or secondary distribution circuits (Fig. 3.5).

Powerline filters usually have input overcurrent protection (component CB in Fig. 3.4). Inductor L_1 carries the full load current and is made from heavy magnet wire wrapped on an iron core. Typical values are 1 mH. The L filter has only one high-value electrolytic capacitor (C_1), whereas the π filter has two capacitors (C_1 and C_3). Typical values for C_1 and C_3 are 6300 μF. Since electrolytic capacitors are ineffective at higher frequencies, a small value capacitor (C_2, typically 0.01 μF) suitable for high frequencies is used in the output circuits. All components have a voltage rating of 150 to 200%, the

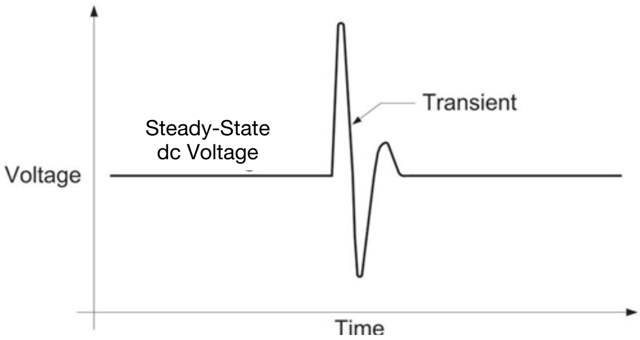

Fig. 3.3 Transient on a dc power system.

highest operating voltage. For example, a nominal 48-V filter has components rated 75 to 100 V. Resistor R_1 drains the charge from the capacitors when power is removed from the filter. It usually is sized to discharge the capacitors in 1 min or less and typically is 30 kΩ to 1 MΩ.

Since electrolytic filter capacitors have limited life (5 to 10 years) and almost always fail shorted, the capacitors may be connected in series with a fuse (Fig. 3.6). When the capacitor fails, the fuse opens and isolates the short from the rest of the power system, thus preventing a capacitor explosion or other catastrophic circuit failure. When the capacitor fails and the fuse opens, the filter loses its effectiveness. The capacitor fuse usually is

Table 3.3 Transients in dc Power Systems

Nominal System Voltage (Vdc)	Maximum Amplitude (V_{pk})	Maximum Duration (ms)	Remarks
12	—	—	Not specified
24	—	—	Not specified
48	75	10	Maximum rate of rise and fall 10 V/ms

Source: ANSI T1.315 [2].

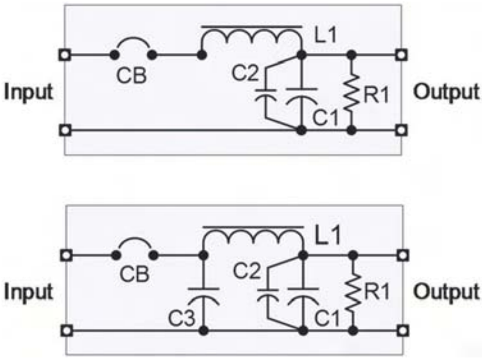

Fig. 3.4 dc powerline filter topologies (*upper,* L-filter; *lower,* π filter) .

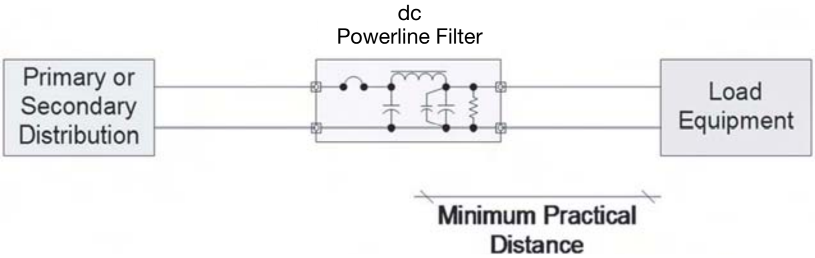

Fig. 3.5 Powerline filter connections.

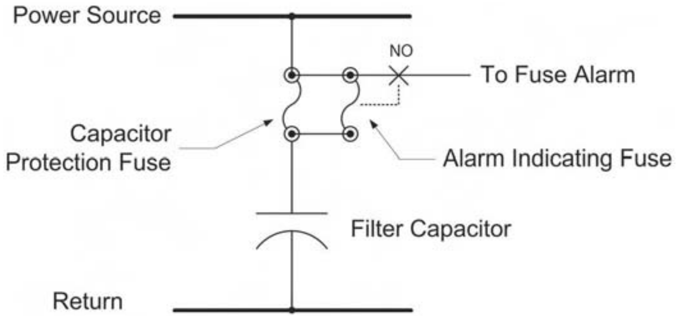

Fig. 3.6 Capacitor fuse. If the capacitor fails shorted, the protection fuse opens. The protection fuse is large enough to withstand capacitor charging current when voltage is first applied. The alarm indicating fuse is a small value fuse that opens immediately after the protection fuse opens.

wired in parallel with an alarm indicating fuse so that operating personnel are alerted to the problem.

3.3 RECTIFIER SYSTEMS

Rectifiers convert the source ac voltage to a direct voltage and supply direct current to the load equipment. During normal operation, the rectifiers determine the voltage accuracy and regulation and can heavily influence the noise on dc power circuits. Rectifiers always are provided in an $N + 1$ redundant configuration giving a minimum of two rectifiers in any given system (Fig. 3.7).

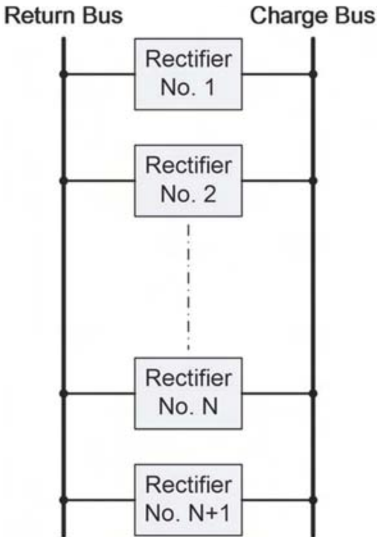

Fig. 3.7 Rectifiers are equipped for $N + 1$ redundancy: N rectifiers are required to serve load and battery recharge requirements and one rectifier is added as a spare.

3.3.1 Technology

Three basic technologies have been used in telecommunications rectifiers since the 1970s:

- Silicon-controlled Rectifier (SCR)
- Controlled ferroresonant transformer
- Switch-mode rectifiers

A typical rectifier consists of a power section and a control section (Fig. 3.8). The power section can use various types of semiconductor switches. The SCR is a unidirectional semiconductor device that, when used in rectifiers, acts as a phase-controlled electronic switch. Another name for an SCR is thyristor. When the SCR is turned on, it conducts current in one direction. SCRs usually are arranged in a full-wave or bridge circuit and are turned on and off as required to regulate the dc output voltage. The power section in-

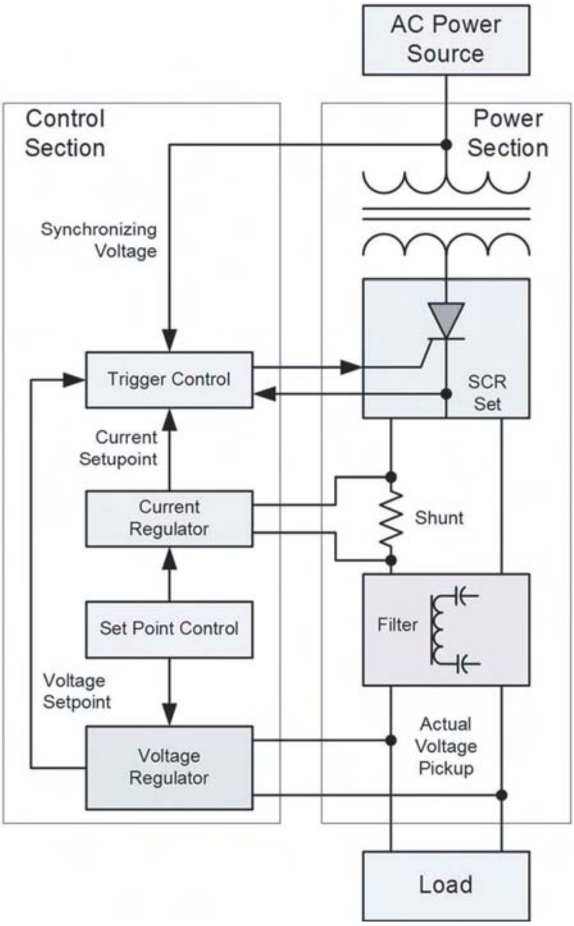

Fig. 3.8 SCR rectifier simplified block diagram.

cludes an input transformer, SCRs, and output filters. The control section includes the SCR trigger circuits and current and voltage regulator functions.

A conceptual schematic of a simple SCR rectifier is shown in Figure 3.9(a) to illustrate its operation. Two SCRs (SCR1 and SCR2) and two power diodes (D1 and D2) form a bridge circuit. The trigger control circuit delivers two trigger pulses per period of the ac input voltage waveform, one for each half-wave. The pulses are mutually phase shifted by

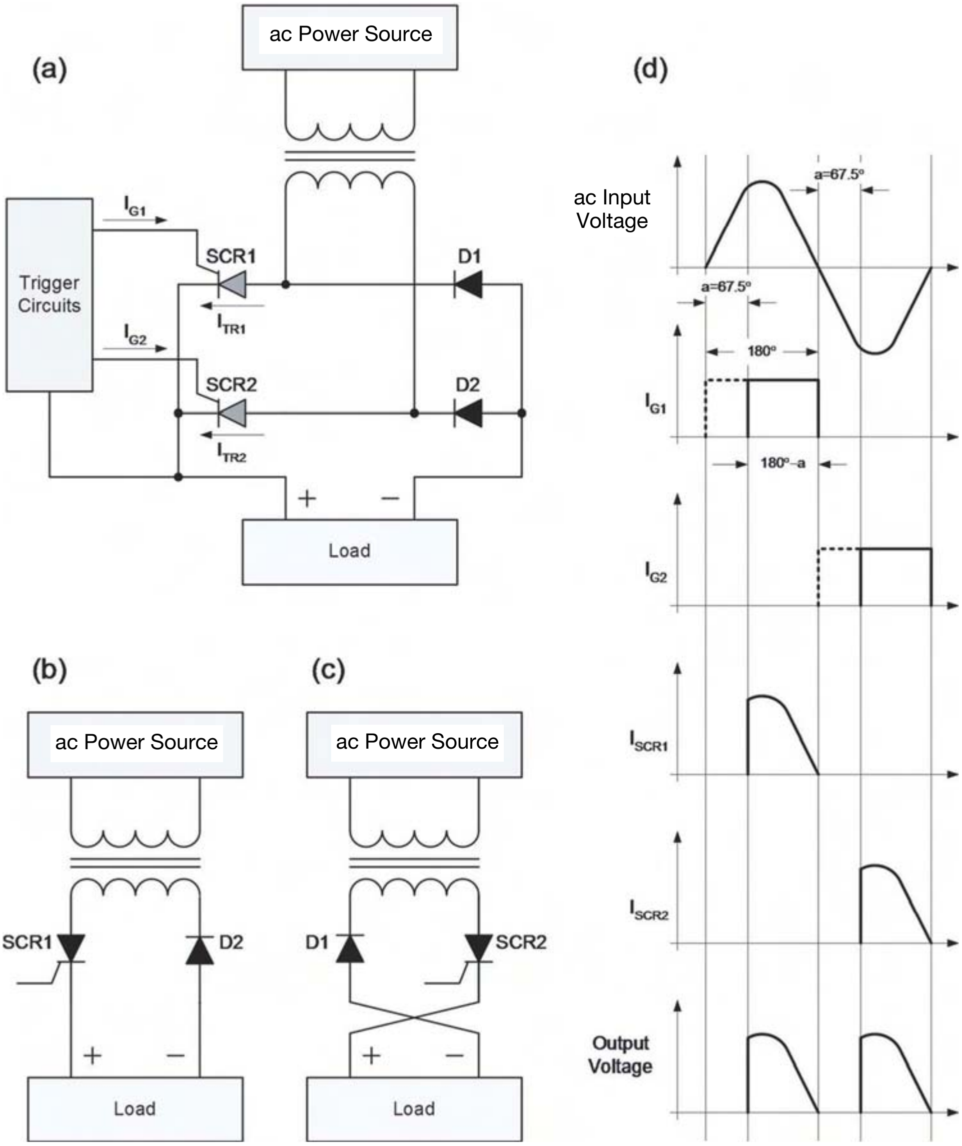

Fig. 3.9 SCR rectifier conceptual schematic: (a) conceptual schematic, (b) circuit with SCR1 turned on and SCR2 off, (c) circuit with SCR2 turned on and SCR1 off, and (d) waveforms at various circuit locations.

180° and have a duration of 180° – a, where a is the amount of phase shift. Both half-waves are rectified and phase controlled by the trigger pulses. For example, if a = 67.5°, then the half-waves are on for 180° – 67.5° = 112.5° of their total period and off for the rest of the time.

When a positive trigger pulse is applied to the gate of SCR1, it turns on and the resulting circuit is shown in Figure 3.9(b). Current flows through both SCR1 and D2. SCR1 turns off after the zero crossing of the input voltage waveform because, with a negative-going ac input voltage at its cathode, the SCR's anode has a negative voltage compared to its cathode. At this point, SCR2 can be turned on. When SCR2 receives a trigger pulse and conducts, the resulting circuit is shown in Figure 3.9(c). Current flows through both SCR2 and D1. The voltages at various points in the circuit are shown in Figure 3.9(d). The output of the SCR/diode bridge consists of a series of truncated half-waveforms, the duration and rms voltage of which depend on the trigger time and duration. The output voltage is then filtered to remove the ac components and leave only the dc component. By delaying or advancing the trigger time with respect to the phase of the input waveform, the output voltage can be varied from 0 to 100% or regulated within tight boundaries.

Controlled ferroresonant transformer rectifiers use a specially designed transformer (sometimes called a controlled-output or constant-voltage transformer) that operates in a saturated mode and uses a resonant circuit as the regulation stage (Fig. 3.10). Energy circulates between the capacitor and the inductance in the transformer secondary winding to maintain the transformer core in saturation. With the core saturated, the secondary (output) winding develops an almost constant voltage even though there may be relatively large changes in the voltage across the primary (input) winding.

SCRs or triacs may be used to control the resonant winding. Triacs are front-to-back SCRs and thus are bidirectional (e.g., CR1 in Fig. 3.11). When the triac is switched on, it allows current to flow in either direction. The triac is self-commutating in that it turns itself off at the waveform zero crossing (end of each half-cycle). When the triac is off, the resonant winding circuit is capacitive (C_1). The capacitance resonates with the winding inductance and tends to raise the secondary output voltage. If the triac is continuously switched on at the beginning of each ac cycle, the inductor (L_1) is effectively connected across the capacitor and the net reactance is designed to be inductive, which effectively lowers the secondary output voltage. By varying the point in the waveform at which the triac is turned on, the resonant winding circuit can be made to vary from capacitive to inductive, thus varying the secondary output voltage up or down. The phase control circuit determines when the triac is turned on and maintains the desired output voltage and current. This control overcomes some of the sensitivity to input frequency that older ferroresonant transformer rectifiers have.

Rectification of the ac waveform in SCR and controlled ferroresonant transformer rectifiers produces large ripple components on the dc output, and filtering the ripple out requires large and heavy filter inductors and capacitors. Also, the switching action generates spikes and electromagnetic interference (particularly radio frequency interference, or RFI) that requires additional filtering. SCR rectifiers are particularly noisy. Since phase-controlled rectifiers discontinuously draw power from the ac supply, rather than continuously, the input current waveform is highly distorted. This results in an inherently low distortion power factor and the need for additional electronics in the rectifier to improve it.

Switch-mode rectifiers are the most common technology used in new systems. When switch-mode rectifiers were introduced, they were relatively expensive but offered size and weight advantages not possible with other technologies. Several generations of

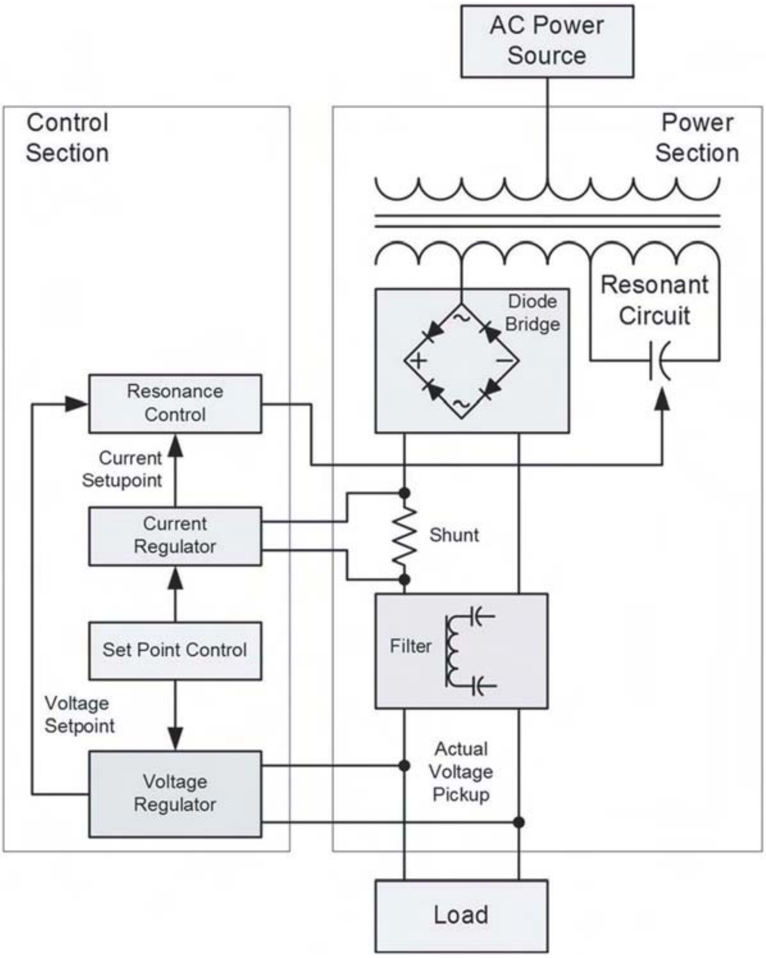

Fig. 3.10 Controlled ferroresonant transformer rectifier conceptual schematic.

switch-mode rectifiers have been deployed in telecommunication networks, each generation smaller and lighter than the previous generation.

While SCR and controlled ferroresonant rectifiers operate at the fundamental powerline frequency (60 Hz), switch-mode rectifiers convert the powerline frequency to much higher frequencies—tens of kilohertz. At higher frequencies, transformers and reactive components (inductors and capacitors) are much smaller than at lower frequencies, thus allowing the size and weight of the rectifier to be significantly reduced. As each generation was deployed, the frequencies got higher and the rectifiers got smaller.

Another advancement that led to smaller size and weight was the development of circuit integration and later very large scale integration (VLSI). Such circuits allowed the replacement of many discrete components (capacitors, resistors, and transistors) with a single chip that usually does the same job better and more reliably.

The switch-mode rectifier consists of three stages (Fig. 3.12). The first stage rectifies the input voltage (converts it to dc). The dc powers the high-frequency dc–ac inverter in

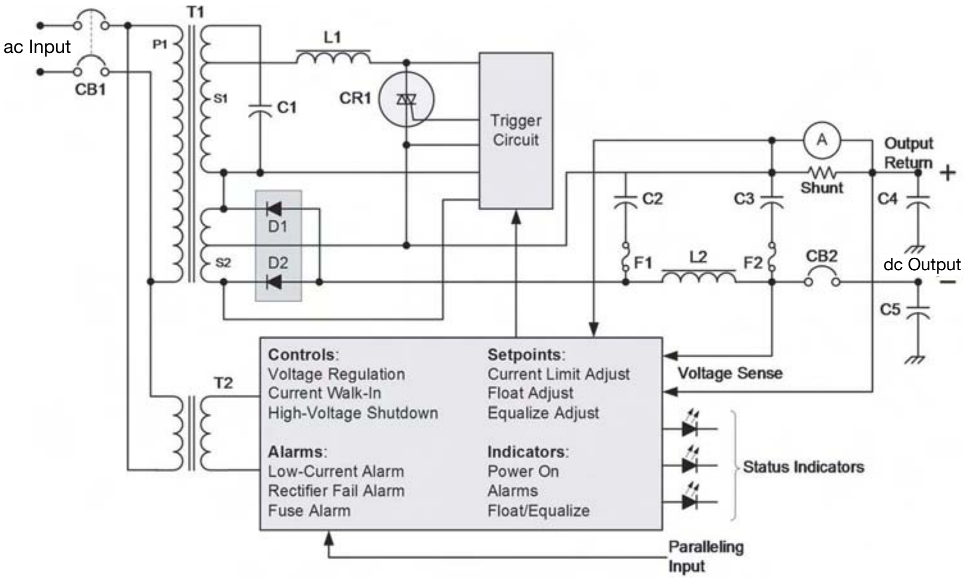

Fig. 3.11 Triac-controlled ferroresonant transformer rectifier simplified schematic.

the second stage. The output of the high-frequency inverter feeds the third stage, which rectifies the high-frequency ac and provides the regulated and filtered dc output. Since the inverter operates at a high frequency, relatively small filter components can be used to eliminate high-frequency ripple on the output. The inverter block may use field-effect transistors (FETs) in a push–pull arrangement (Fig. 3.13).

One of the design challenges associated with switch-mode rectifiers is the reduction of high-frequency emissions to acceptable levels. All modern rectifiers must meet FCC emission requirements.[2] In addition, most rectifiers marketed for telecommunications applications are designed to meet Telcordia Network Equipment Building Systems (NEBS) requirements as well as the applicable NEMA standard, which includes performance requirements, and ANSI T1 standards, which include, among other things, vibration, temperature, and fire spread and ignition.[3]

There are three most noticeable differences between current generation rectifier products and previous generations:

Modularity All current generation rectifiers are modular and are installed as plug-in units in equipment shelves. Modular telecommunications rectifiers must be hot swappable; that is, the rectifiers can be removed from the shelf and replaced without affecting the dc power system. These rectifiers are easily replaceable, whereas previous generations were fixed mounted and fixed wired in equipment frames. Replacing one of these older units requires that all wiring be disconnected.

Compact Size Previous generation rectifiers were large and heavy, providing a current output capacity of a few to several hundred amperes at 48 V in a 23-in. × 7-ft

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[2] Federal Communications Commission, Part 15, Subpart B, Class A (commercial) [8].

[3] For example, see [9,10,11,12,13,14].

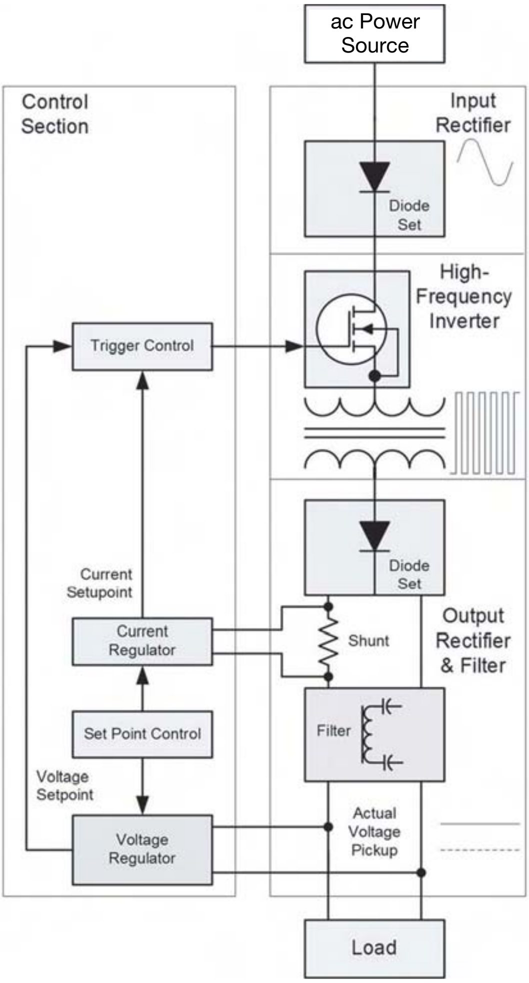

Fig. 3.12 Basic switch-mode rectifier block diagram.

equipment frame. Current generation rectifiers are very compact and provide as much as 1200 to 1400 A at 48 V in the same frame size.

Cooling All current generation modular rectifiers, because of their compact size and limited capability to dissipate heat through convection, use fan cooling. Most previous rectifier generations use convection cooling. The addition of rotating machinery (fans) to rectifiers has reduced their overall reliability and increased their maintenance. In some rectifiers, fan failure shuts down the rectifier, but in others it activates an alarm and reduces the rectifier output current to prevent overheating. The fairly loud buzzing noise made by older rectifier technologies (usually caused by transformer vibration) has been replaced by a fairly loud fan noise from switch-mode rectifiers.

Table 3.4 compares the characteristics of various rectifier technologies.

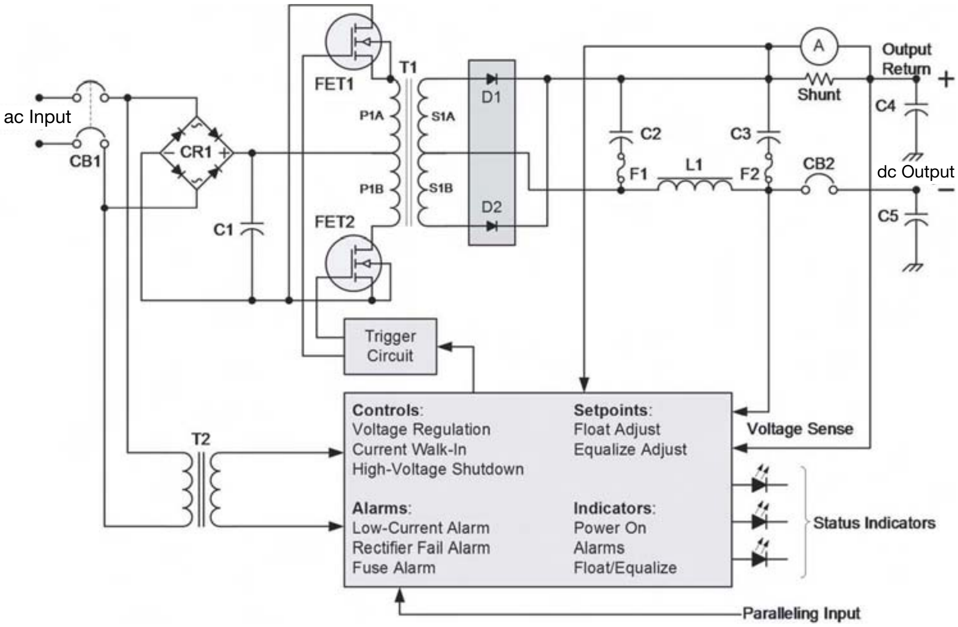

Fig. 3.13 Switch-mode rectifier simplified schematic. FET1 and FET2 are very efficient electronic switches that are alternately turned on and off to chop the dc input and convert it to a high-frequency ac. The chopped dc is coupled to the secondary of transformer T1 where it is subsequently rectified by D1 and D2 and then filtered by the output filter circuit.

Table 3.4 Rectifier Technology Comparison

Parameter	SCR	Controlled Ferroresonant	Switch Mode
Output regulation	± 0.5–1%	± 0.5%	± 0.5%
Current limit	125%	125%	100–105%
Input surge immunity	Poor	Excellent	Excellent
Output ripple, rms	30 mv	30 mV	10 mV
Output ripple, peak–peak	500 mv	100 mV	100 mV
Output noise	32 dBrnC	32 dBrnC	32 dBrnC
Efficiency, 40% load	78%	81%	80–85%
Efficiency, 100% load	80%	87%	88%
Power factor, 40% load	0.70	0.94	0.97
Power factor, 100% load	0.70	0.99	0.97
EMI emission	Poor	Excellent	Good
EMI susceptibility	Poor	Good	Good
AC system noise	Bad	Excellent	Excellent
Performance, 57–63 Hz	Okay	Excellent	Excellent
Audible noise	Buzz	Buzz	Fan noise

3.3.2 Rectifier Features

Telecommunications rectifiers have features that are characteristic of their application in high-reliability telecommunications systems. Some features in older rectifiers were optional and were only provided if specified at the time of purchase. Newer rectifier products generally are fully featured at no extra cost.

Operation Mode Rectifiers may operate in two modes—float and equalize. With VLA batteries, the float mode operates load equipment and float charges the batteries during normal operation, and the equalize mode operates load equipment and recharges the batteries after an ac power failure or equalizes the cells in a battery when maintenance data indicates that such a charge should be applied. The equalize mode normally is not used with VRLA batteries because the float mode normally recharges the battery. The actual float and equalize voltages depend on the battery technology. Most rectifiers have a switch on their front panel to control the mode and an associated indicator lamp; other rectifiers just have a control input from an external controller or switch.

Load Sharing and Parallel Operation The minimum number of rectifiers in a dc power system is two (one active and one backup). Multiple rectifiers must coexist, that is, operate in parallel. Unfortunately, field experience has shown that such operation is not guaranteed with all rectifier brands, although it should be. For example, rectifiers from one manufacturer may not properly operate in parallel with rectifiers from another manufacturer.

Load sharing is different than parallel operation, although in order for rectifiers to load share they must also operate in parallel. With load sharing, each rectifier supplies current proportional to its rating. For example, three 50-A rectifiers serving a 100-A load each would supply 33 A, and two 50-A rectifiers and one 100-A rectifier serving the same load would supply 25 A from each 50-A rectifier and 50-A from the 100-A rectifier. Load sharing is not particularly accurate, being around 10%. Load sharing requires that the rectifier load sharing control circuits be connected together, usually in a controller or terminal block in the powerboard.

Remote Control In some installations, it is desirable to turn rectifiers on and off from a remote location. The remote control can be from a fire or smoke detection system, an alarm control system, or a network operations center (NOC). The control may be by closing a dry (i.e., no voltage) relay contact or by applying a ground to the rectifier control input.

Voltage Sensing Rectifiers regulate their output voltage by automatically adjusting it up or down to maintain the desired value. The sensing can be done locally at or near the rectifiers or rectifier frame or remotely at the battery terminals (Fig. 3.14). If remote voltage sensing is used, the sensing is done at or close to the battery terminals. Remote sensing provides the most accurate voltage control at the point where it is required—the batteries. However, under float conditions, the battery current is very small, and the voltage drop in a properly designed circuit from the rectifiers to the battery terminals is very small. Therefore, local sensing is sufficiently accurate in most installations, and the added expense of running sense leads to the batteries is not justified. However, where many battery strings are operated in parallel or where the float current causes a significant voltage drop (more than approximately 100 to 200 mV), then remote sensing is recommended. With parallel strings, a logical sensing point is a collector bar near the batteries.

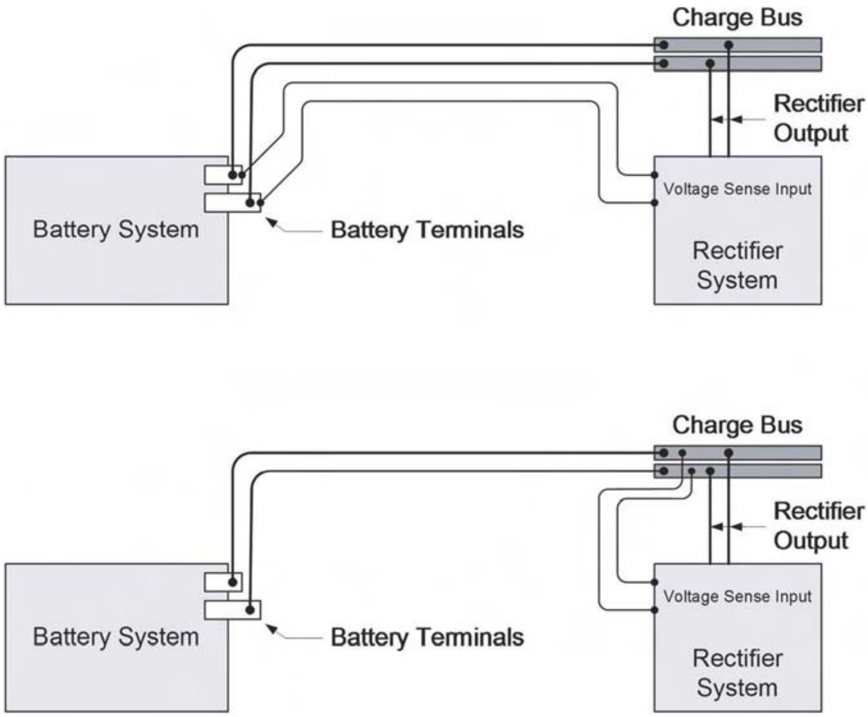

Fig. 3.14 Remote (*upper*) and local (*lower*) voltage sensing. The rectifiers regulate the voltage at the sensing point.

Temperature-Compensated Charging Related to voltage sensing and of particular importance to VRLA batteries is temperature-compensated charging. With temperature-compensated charging, a temperature sensor on the battery controls the rectifier output voltage through the remote voltage sense leads (Fig. 3.15). The compensation reduces the chances of thermal runaway in VRLA batteries and is not required with VLA batteries. Many existing rectifier systems can be retrofitted with an external temperature compensation module (Fig. 3.16); new systems have temperature compensation built-in.

With no temperature compensation in Figure 3.15(a), the rectifier output voltage is adjusted to the battery float voltage (54.5 V in this example) and is regulated by the sense voltage input; there is no temperature sensor and no compensation. With temperature compensation in Figure 3.15(b), the rectifiers initially are adjusted to a lower voltage because of the voltage drop across the temperature compensation module. In this example, the voltage drop of the temperature compensation module at the normal operating temperature of 25°C (77°F) is 6.0 V, so the rectifiers initially are adjusted to 48.5 V without the module in the circuit. When the module is inserted in the circuit, the rectifier sense leads are 6.0 V lower than the output voltage, and the rectifier output automatically increases by 6.0 V to 54.5 V to compensate for it. If the battery temperature increases, the voltage drop across the temperature compensation module in Figure 3.15(c) decreases by, say, 0.6 V to 5.4 V at 30°C (86°F). The rectifier sense voltage input sees this as a voltage increase from 48.5 to 51.1 V. However, because the rectifier is adjusted for 48.5 V at the

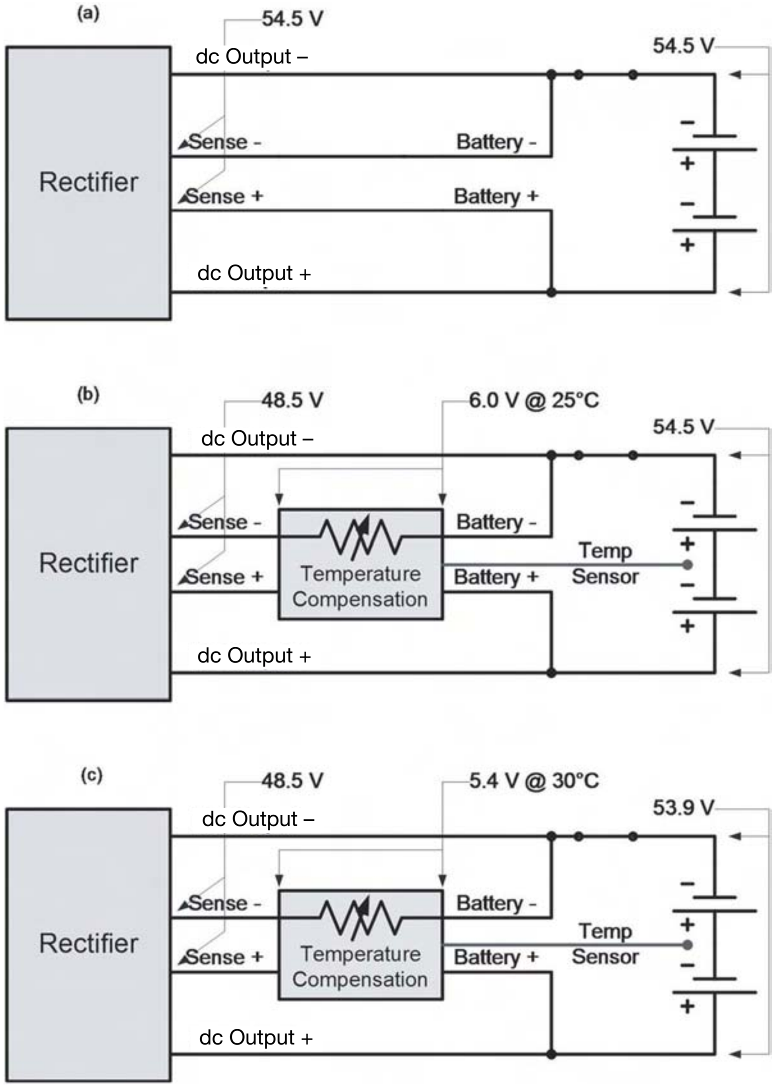

Fig. 3.15 Conceptual diagrams of 48-V temperature-compensated charging setup: (a) no temperature compensation, (b) with temperature compensation at normal operating temperature, and (c) with temperature compensation at elevated operating temperature.

sense voltage input, it automatically decreases the output voltage by 0.6 V to 53.9 V in order to maintain the sense voltage input at 48.5 V.

The relationship between battery temperature and battery voltage usually is a linearly decreasing voltage with increasing temperature (Fig. 3.17). In the other direction, with decreasing temperature, the rectifier output voltage is increased with falling temperature but not indefinitely. Typical temperature coefficients are –2.5 to –4.5 mV/cell/°C. This range works out to be 30 to 54 mV/°C for a 12-cell battery (24-V system) and 60 to 108 mV/°C for a 24-cell battery (48-V system).

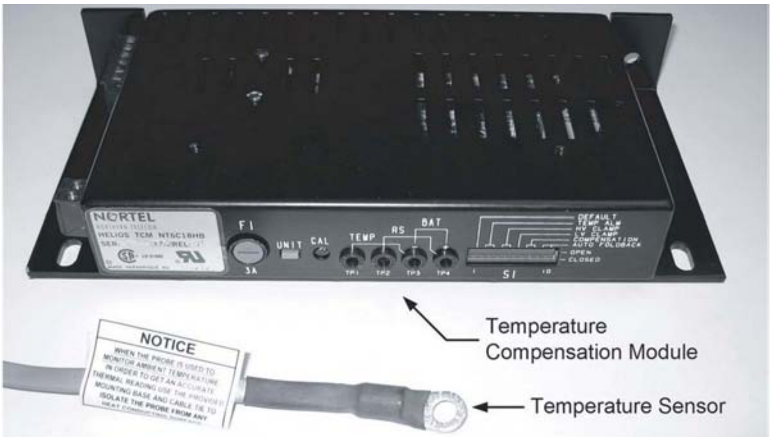

Fig. 3.16 Temperature compensation module suitable for retrofit applications.

Rectifier Current Limitation Modern switch-mode rectifiers are constant-power devices, and their output current capability is inversely related to their output voltage. For example, a 3000-W rectifier can deliver 65 A at 46 V and 55 A at 54.5 V. This means the rectifiers can provide more recharge current to a discharged battery, when system voltage is low, and potentially recharge it faster. However, the higher recharge current can increase the risk of thermal runaway in VRLA batteries.

Rectifier current limitation can be used to minimize the chance of thermal runaway and also to increase system efficiency. This usually is a programmable function that controls rectifier current to some predetermined value. It also can be used to turn off unneed-

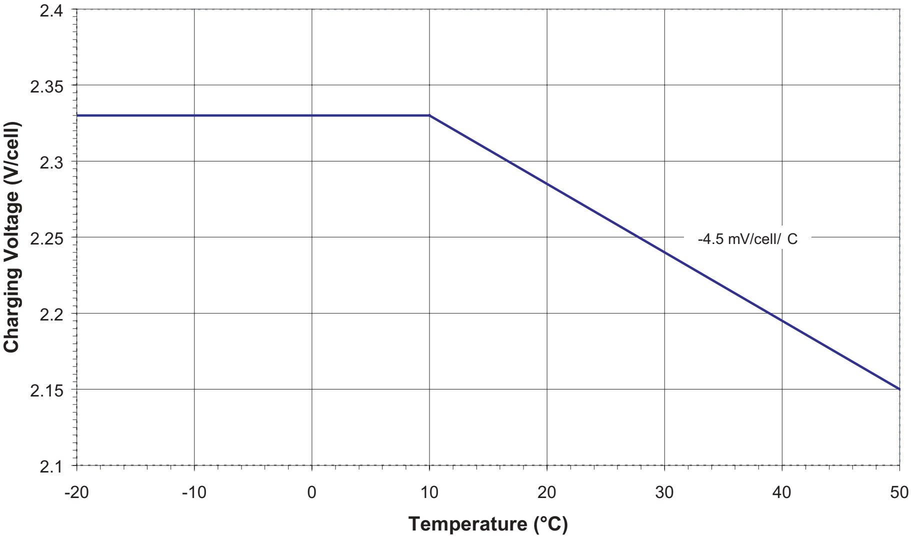

Fig. 3.17 Battery cell voltage as a function of battery temperature for temperature-compensated charging (typical).

ed rectifiers (or place them in a hibernate state) and to limit the number of rectifiers (and thus the charging current) that are available to recharge the battery. This would be used when a rectifier system is initially oversized for the initial load or battery capacity. The unneeded rectifiers can be left plugged in. If there are any rectifier module failures, the controller automatically brings a hibernating rectifier back online. The added benefit of this scheme is the overall rectifier system operates much more efficiently, potentially reducing the electricity consumption at the facility.

Voltage Regulation Voltage regulation is defined as

$$\text{Regulation (\%)} = \frac{V_{\text{NL}} - V_{\text{FL}}}{V_{\text{FL}}} \times 100 \tag{3.1}$$

where V_{NL} = no-load voltage (V)
V_{FL} = full-load voltage (V)

In telecommunications rectifiers regulation is ±0.5% under all load and input conditions. The relatively tight regulation is required for long battery life. The regulation at various operating voltages is shown in Table 3.5.

Efficiency Efficiency is defined as the ratio of the input power to the output power, expressed as a decimal fraction or in percent and is around 0.85 to 0.9 (85 to 90%) for modern rectifiers at full load. As a percentage

$$\text{Efficiency (\%)} = \frac{P_{\text{Output}}}{P_{\text{Input}}} \times 100 \tag{3.2}$$

where P_{Output} = Output Power (W)
P_{Input} = Input Power (W)

Switch-mode rectifier efficiency is fairly constant at around 80 to 85% at loads above 25% of rated current. The efficiency of controlled ferroresonant rectifiers peaks at around 90% at full-load current. Below full load the efficiency drops to around 80% at 25% load (Fig. 3.18). For example, a fully loaded rectifier that delivers 3000 W to network equipment at 90% efficiency actually draws 3333 W from the ac power system. The rectifier dissipates the difference (333 W) as heat. Rectifiers are seldom intentionally operated at 100% rated current except during battery recharge. In a properly designed dc power system, rectifiers spend most of their time at 25 to 50% of rated current.

Table 3.5 Rectifier Voltages at ±0.5% Regulation

Nominal System Voltage (V)	Cell Voltage (V/cell)	Operating Voltage (V)	Regulation at 0.5% (V)	Regulation Range (V)
24	2.17[a]	26.04	±0.130	25.91–26.17
24	2.27[b]	27.24	±0.136	27.10–27.38
48	2.17[a]	52.08	±0.260	51.82–52.34
48	2.27[b]	54.48	±0.272	54.21–54.75

[a] Typical VLA cells.
[b] Typical for VRLA cells.

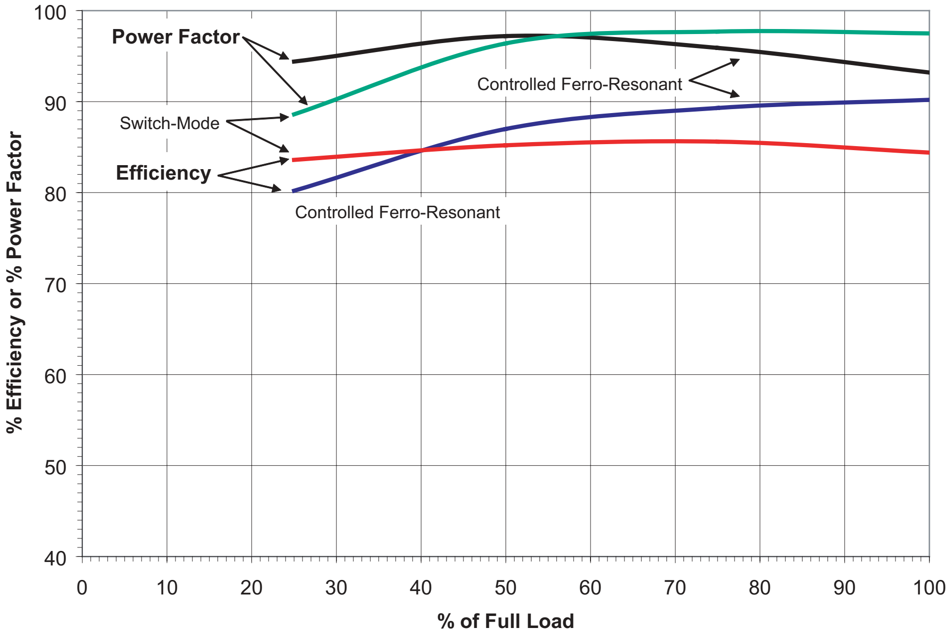

Fig. 3.18 Typical rectifier efficiency and power factor versus load.

Rectifier operating costs are directly related to their efficiencies and are especially important in areas where electricity costs are high.

Example 3.1 A 24-V system is equipped with six 50-A rectifiers and the total load is steady at 75 A. Determine (1) the yearly electrical energy costs for ferroresonant and switch-mode rectifiers when the rate is 2.5 cents/kWh, 5.0 cents/kWh, 10.0 cents/kWh, 20.0 cents/kWh, 40.0 cents/kWh, and 80.0 cents/kWh, and (2) the yearly costs of losses at the same energy rates. Assume the system operates at 27.0 V.

In this example, the load on each rectifier is 12.5 A (50 A × 75 A/300 A) so they are operating at 25% of rated load. The output power of each rectifier is 338 W (12.5 A × 27 V). Assuming the efficiency is 80% for ferroresonant rectifiers and 85% for switch-mode rectifiers, the input powers are 422 W (338 W ÷ 0.8) and 397 W (338 W ÷ 0.85), respectively. The energy consumed by each rectifier in one year is 3697 kWh (0.422 kW × 8760 h) and 3478 kWh (0.397 kW × 8,760 h). Operating costs are tabulated below.

Unit Energy Cost ($/kWh)	Yearly Operating Cost per Ferroresonant Rectifier ($)	Yearly Operating Cost per Switch-Mode Rectifier ($)	Difference ($)
0.025	92	87	5
0.05	185	174	11
0.10	370	348	22
0.20	739	696	43
0.40	1479	1391	88
0.80	2958	2782	176

The power losses for the ferroresonant and switch-mode rectifiers are 84 W (422 W – 338 W) and 59 W (397 W – 338 W), and the yearly energy losses are 736 and 517 kWh, respectively. The costs of the energy losses are tabulated below.

Unit Energy Cost ($/kWh)	Yearly Cost of Losses per Ferroresonant Rectifier ($)	Yearly Cost of Losses per Switch-Mode Rectifier ($)
0.025	18.40	12.92
0.05	36.80	25.85
0.10	73.60	51.70
0.20	147.20	103.40
0.40	294.40	206.80
0.80	588.80	413.60

The foregoing analysis can be taken one additional step by calculating the present worth of the energy savings. Assuming 5% annual cost of money over a 10-year study period (7.857 present worth factor assuming monthly payouts), the present worth of the energy savings of the switch-mode rectifier is shown below. Where energy costs are high and the study period is fairly long (10 to 20 years), the savings per rectifier approximately equal the purchase price of one or two switch-mode rectifiers. A similar analysis can be made at other costs of money, time periods, and rectifier efficiencies.

	Per Rectifier		Per Rectifier System
Unit Energy Cost ($/kWh)	Switch-Mode Advantage ($)	Present Worth (5%, 10 Years)	Present Worth (5%, 10 Years)
0.025	5.48	43	258
0.05	10.95	86	516
0.10	21.90	172	1032
0.20	43.80	344	2065
0.40	87.60	688	4130
0.80	175.20	1377	8259

Power Factor Correction The rectifier load in telecommunications facilities can represent the majority of the total ac load, so it is important to use high power factor rectifiers. Current or voltage distortion caused by low-load power factor leads to numerous problems in electric utility service transformers, power and energy metering equipment, and building electrical circuits. Most electric utilities have a penalty clause in their tariffs for low power factor, so it is in the end-user's interest to maximize power factor to minimize this penalty. Also, overheating from low distortion power factor can damage building electrical wiring and step-up and step-down transformers. *Power factor correction* in rectifiers reduces the distortion on the ac input voltage and current waveforms and thus improves the performance of ac electrical systems. The power factor of ferroresonant and switch-mode rectifiers is approximately 0.9 and higher for most load levels (Fig. 3.18).

Input Voltage Range Modern switch-mode rectifiers have a wide input voltage range, typically 176 to 264 Vac or 96 to 264 Vac at 47 to 63 Hz.[4] A wide input voltage range allows operation with 120/240 Vac single-phase systems and 208Y/120 Vac three-phase systems without adjustment. Older technologies require taps on the input transformer to be changed for operation at different service voltages. When the taps are properly set, the rectifiers will meet the specified output voltage regulation with as much as 10% variation in the ac input voltage. Large ferroresonant rectifiers (400 A and larger) require 480Y/277 Vac service voltage or a step-up transformer where lower service voltages are used.

High-Voltage Shutdown All modern rectifiers have internal selective high-voltage shutdown circuits. These circuits sense a high-voltage condition in the rectifier, possibly due to internal failure, and shut it down by tripping the input circuit breaker to prevent the rectifier from damaging load equipment and other rectifiers. Many rectifiers also have remote high-voltage shutdown capability so that a high-voltage condition may be sensed at a different location and the rectifiers shutdown through an external control circuit. The high-voltage shutdown controls, both local and remote, are nonrevertive (i.e., reset is not automatic) and require manual intervention to bring the rectifier back online.

Visual Indicators and Controls Some manufactures eliminate visual indicators from rectifiers and put them in a controller (Fig. 3.19), while others provide a full range of operational indicators on the rectifier front panel itself. A full range includes

- Light-emitting diode (LED) bar graph, liquid-crystal display (LCD), or meter to indicate output current
- LED bar graph, LCD, or meter to indicate output voltage (this meter may also measure current as determined by a selector switch; bar graphs have low resolution and are only used to indicate voltage or current within a range)
- Power on/off
- Equalize/float mode
- Test
- Rectifier fail alarm (RFA)
- Low-current alarm (LCA)
- High-voltage alarm (HVA)

Many types of rectifiers are stand-alone devices that have user-adjustable controls on the rectifier front panel but others require a cover or door to be opened. Other types require a separate controller module installed in the shelf assembly with the rectifier modules (Fig. 3.20). Still other types of modular rectifiers use a separate controller chassis that connects to the rectifier shelf assembly by a control cable. Most modern types do not have potentiometer-type adjustments but are set through a craft user interface. User-adjustable controls typically include

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[4] Rectifiers used in the United States only need to operate over the range from 57 to 63 Hz, but many rectifier products also are sold in countries where the fundamental powerline frequency is 50 Hz, which requires a range from 47 to 53 Hz.

- *Float voltage adjustment* Used to adjust rectifier float voltage output
- *Equalize voltage adjustment* Used to adjust rectifier equalize voltage output. In most rectifiers, the float and equalize voltage settings are interdependent. Usually, the float voltage is set first and then the equalize voltage may be set.
- *Current limit adjustment* Rectifiers will go into current limiting under several conditions, including short circuit on the discharge or charge bus or associated circuits, overload caused by load equipment failure that is not cleared by an overcurrent protection device, and battery recharge after restoration of an ac power failure or after a load test. To the rectifier, overload and battery recharge conditions are indistinguishable. Many switch-mode rectifiers do not have an adjustable current limit control. Some rectifiers can operate indefinitely under overload conditions but rectifier life generally will be reduced. Ferroresonant rectifiers have inherent current limiting, which may be supplemented by an adjustable control.
- *Load simulate adjustment* This is very useful in testing the rectifier over its full current range; otherwise, external power supplies or special procedures are required to fully test and adjust rectifier load sharing and overload controls. Load simulation is missing from older rectifiers.
- *Load sharing adjustment* This control calibrates the rectifier for proper load sharing.
- *High voltage alarm and shutdown adjustment* Typical high-voltage alarm settings are 56.0 V for a 48-V system and 28.0 V for a 24-V system, but this varies with the installation and load equipment tolerance.
- *Low-current alarm adjustment* The low-current alarm (LCA) usually is activated if the rectifier carries less than 10% of rated load current. There can be many reasons for an LCA and not all are actual alarm conditions. For example, the load current may be very low compared to rectifier capacity and under normal float conditions the rectifiers are very lightly loaded. This situation is encountered where long battery reserve times are needed and the resulting ampere-hour capacity is large rel-

Fig. 3.19 Typical rectifier front panel. The dimensions of this switch-mode rectifier module are 3.94 in. wide × 3.30 in. high × 9.25 in. deep and it is rated 1.6 kW at 24 V. The LED indicators on the upper right side of the front panel are ac, dc, and alarm. (Photo courtesy of Argus Technologies, Inc.)

Fig. 3.20 Rectifier shelf assembly with controller and rectifier modules (same type as in Fig. 3.19 but 48 V in this case). The shelf assembly mounts in a standard 19-in. equipment frame. The controller (*bottom photo*) plugs into the left-hand slot of the rectifier shelf assembly and is required for rectifier operation. LED indicators on the upper-left are OK, minor alarm, and major alarm, and there is a reset button just below the LEDs. At the bottom left of the controller is a 10BaseT Ethernet jack for connecting the controller to the central office local area network. The dimensions of the shelf assembly are 17.4 in. wide × 3.4 in. high × 12.0 in. deep. (Photos courtesy of Argus Technologies, Inc.)

ative to the normal equipment load. Another situation is where rectifier load sharing or float voltage is slightly out of adjustment and the rectifiers do not properly share at low load levels. In many installations, this is not cause for alarm because the lower rectifier will pick up the load upon failure of another rectifier in the system.

- *Filter capacitor charge* Rectifiers are equipped with relatively large output filter capacitors, which draw considerable charging current when voltage is applied to them in an uncharged condition, such as when a rectifier is first turned on. The large current draw can trip rectifier overload circuits or open overcurrent devices in the capacitor circuit. Well-designed rectifiers have a precharging control switch that allows the capacitor to be safely charged before the output circuit breaker is turned on.

Internal Protection and Control Functions Internal protection functions are inherent to most modern rectifier designs and operate without user intervention. Typical internal controls are

- *Walk-in circuit* When a rectifier is turned on, the output current increases gradually. This reduces transients on the dc bus and prevents overshoot of the rectifier output that could lead to a high-voltage shutdown. A typical walk-in circuit requires 5 to 10 s to start picking up the load and another 5 to 10 s to reach the required value.
- *Low line voltage shutdown* If the ac input voltage to the rectifier falls below the

preset threshold, the rectifier will automatically shut down to prevent rectifier damage or to prevent the rectifier from operating outside its specified limits. Normally, this is a revertive control, and the rectifier automatically restarts when the input voltage returns to normal.

- *Line phase loss or unbalance shutdown* This applies to three-phase rectifiers and shuts them down to prevent damage from unbalanced input conditions.
- *Voltage sense lead protection* Remote voltage sense leads are much smaller than battery circuit conductors and usually are run on the same cable racks with them. The leads may be damaged during the installation or removal of conductors or accidentally disconnected. To prevent runaway rectifier output circuits, internal rectifier controls will either force the rectifier output to a low voltage or shut it down completely. This type of control is nonrevertive.

3.4 POWERBOARD

A powerboard consists of one or more equipment frames that support the charge and discharge busbars, rectifier system, monitoring and control system, and primary distribution system. Small single-bus powerboards with ratings up to approximately 1600 A are conveniently packaged with charge/discharge busbars, monitoring and control, and primary distribution in one frame. In sizes 400 A and smaller, the rectifier system may be packaged in the same frame (Fig. 3.21). In sizes larger than 400 A, a second frame, sometimes called a *supplemental* frame but more often just a *rectifier frame,* holds the rectifier system.

Common bus ratings for small powerboards are 50, 100, 200, 400, 600, 800, 1200, and 1600 A (actual values vary with the manufacturers). Above 1600 A, powerboard bus ratings increase in approximately 800- to 1000-A increments. In some systems, the charge and discharge busbars are hung from the ceiling or attached to the tops of frames (Fig. 3.22), and only the primary distribution system is located in equipment frames. Rigid copper busbars are used in telecommunications powerboards for convenience of construction, standardization of mounting arrangements and economy. However, small powerboards (< 50 A) may use cables to connect components. Very small power systems, up to approximately 15 A, may have all components and limited primary distribution in one equipment shelf (Fig. 3.23).

Busbar mounting arrangements must be designed to withstand mechanical forces due to shipping and installation, seismic forces during earthquakes, forces from contraction and expansion of components due to temperature changes, and magnetic reaction forces during electrical faults. Short circuits between the current-carrying conductors (feed and return) or between the ungrounded current-carrying conductor (feed) and ground can cause large magnetic reaction forces. Two current-carrying conductors in close proximity will repel or attract each other depending on the relative current directions. For thin busbars, the force is approximately [15][5]

$$F = \frac{2 \times 10^{-7} \times i_1 i_2 L}{d^2}\left[2d \tan^{-1}\left(\frac{d}{s}\right) - s \ln\left(\frac{d^2 + s^2}{s^2}\right)\right] \text{ newtons} \qquad (3.3)$$

---

[5] This expression for force between two conductors assumes that the bars are thin with respect to their width and is a simplified version of a more detailed expression by H.B. Dwight in Chapter 37 of *Electrical Coils and Conductors, Their Electrical Characteristics and Theory,* McGraw-Hill, 1945.

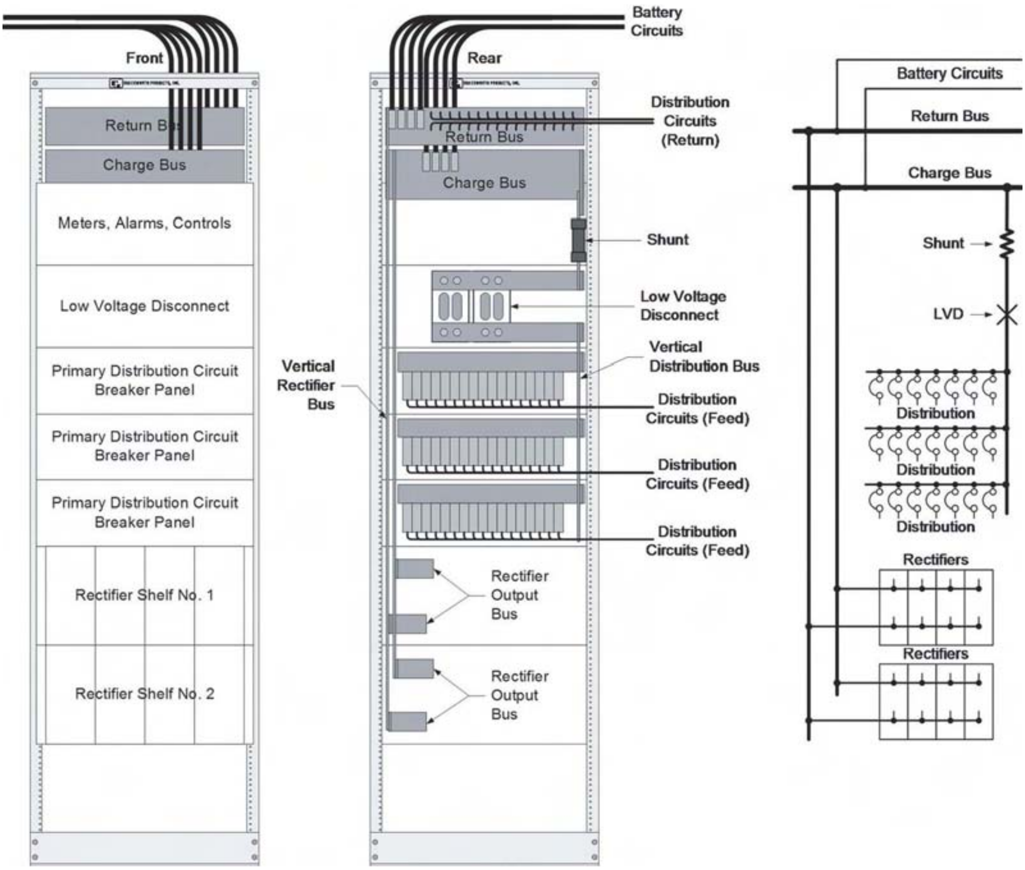


Fig. 3.21 Powerboard: front and rear view of a powerboard in one frame with termination busbars, shunts, controls, meters, and rectifiers, and corresponding schematic.

where F = force (N)
i_1 = current in one conductor (A)
i_2 = current in other conductor (A)
L = length (m)
s = spacing between conductors (m)
d = busbar width, long side (m)

The force is small for normal operating currents but can be quite large for fault currents. For example, assume 4-in. (102-mm) busbars are spaced 1 in. (25 mm) apart, are 10 ft (3 m) long, and carry 100 A. For a paired circuit in which the two currents have the same magnitude and flow in opposite directions, the force tends to push the two conductors apart. Using Eq. (3.3) the force is about 0.12 N (0.0266 lb).

Short-circuit currents from batteries in dc power systems can be quite high and can last for several minutes. The resulting magnetic reaction forces also can be quite high. For example, if the paired conductors of the previous example are shorted and the fault currents are 10,000 A in each conductor, the repulsive force is about 1150 N (258 lb) using Eq.

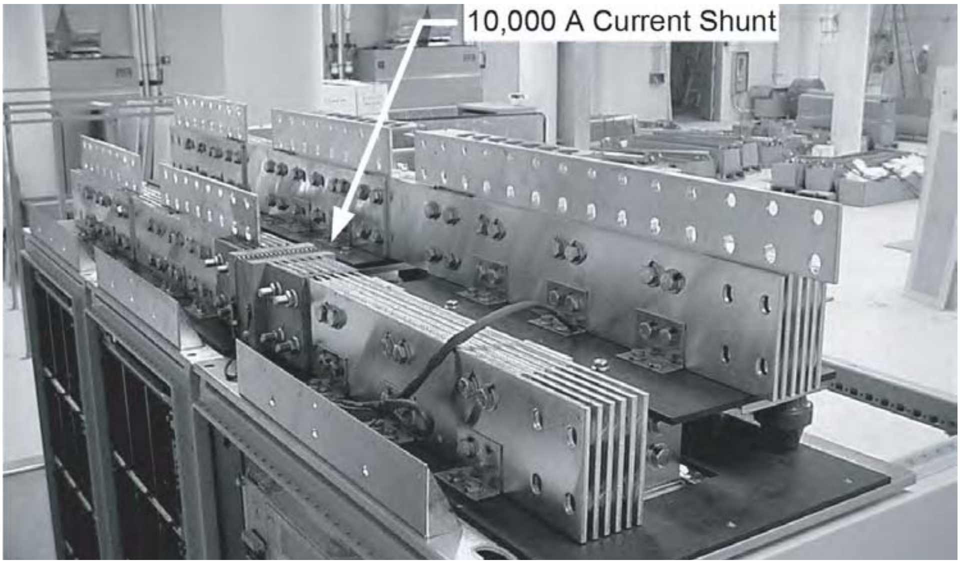


Fig. 3.22 Busbars mounted at the top of equipment frames, ready for connection to batteries. This bus is rated 10,000 A (note 10,000 A shunt in middle left of picture). (Photo courtesy of Power-One, Inc.)

(3.3). This force is applied almost instantly (rise time limited by the ratio of circuit resistance to inductance) and forces the conductors apart.

3.4.1 Charge and Discharge Busbars

The charge and discharge buses consist of one set of busbars that operates at the system voltage and another (return bus) that is bonded to the earth electrode or grounding system. The charge and discharge buses at system voltage may be one and the same bus but, in

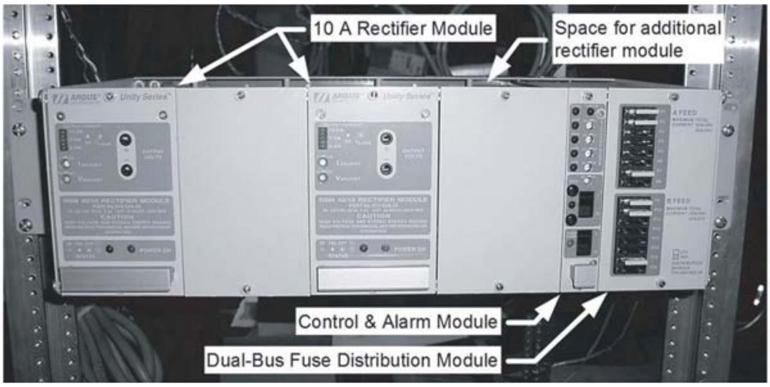


Fig. 3.23 Small 48-V power system with rectifiers and primary distribution in a single equipment shelf mounted in a 23-in. channel-type equipment frame. Up to four rectifier modules may be installed. Shelf dimensions are 17.5 in. wide × 7 in. high × 12 in. deep.

many systems, they are separated by a low-voltage disconnect (LVD) contactor, current shunt, or both (Fig. 3.24). The charge and discharge segments of the return bus usually are combined.

In small, low-current systems, the busbars are relatively small and do not have enough physical space for terminating all the cables from the rectifiers and batteries, in which case separate cable termination busbars are used (Fig. 3.25).

Copper busbars are used in powerboards because of their rigidity, strength, and high current-carrying capability. For example, a single 2-in. × ¼-in. busbar mounted vertically in free air can safely carry slightly more than 700 A when the ambient temperature is 30°C and the bar is allowed 40°C temperature rise, and a 4-in. × ½-in. busbar mounted vertically in air can safely carry almost 1900 A under the same conditions. When busbars are paralleled, they are spaced equal to their thickness (e.g., parallel ¼ in. busbars are spaced ¼ in. apart). The maximum current density normally is in the range of 1 A per 1000 CM to 1 A per 1600 CM. Table 3.6 shows the busbar sizes used in typical powerboards.

Current shunts used in dc powerboards are low-resistance, high-power resistors connected in parallel with a high-impedance voltmeter. They are designed to carry almost all of the current so that only a negligible portion flows through the voltmeter (Fig. 3.26). Although the indicator actually is a voltmeter, it is calibrated in amperes with full-scale equal to the shunt's current rating. The most common shunt voltage drop is 50 mV at rated load current, but other values such as 25, 40, and 100 mV have been used in some systems.

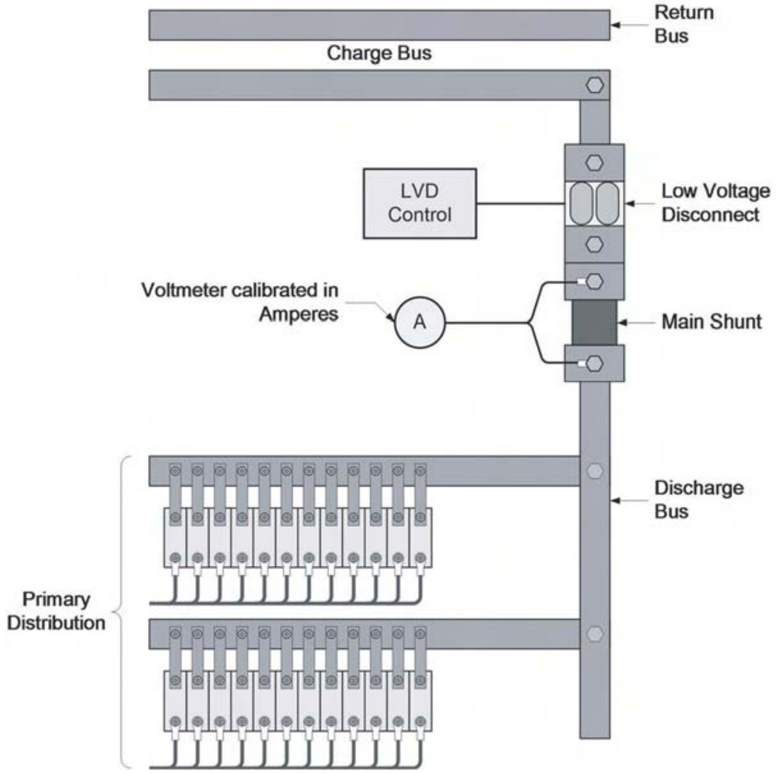


Fig. 3.24 Charge and discharge buses with low-voltage disconnect and current shunt.

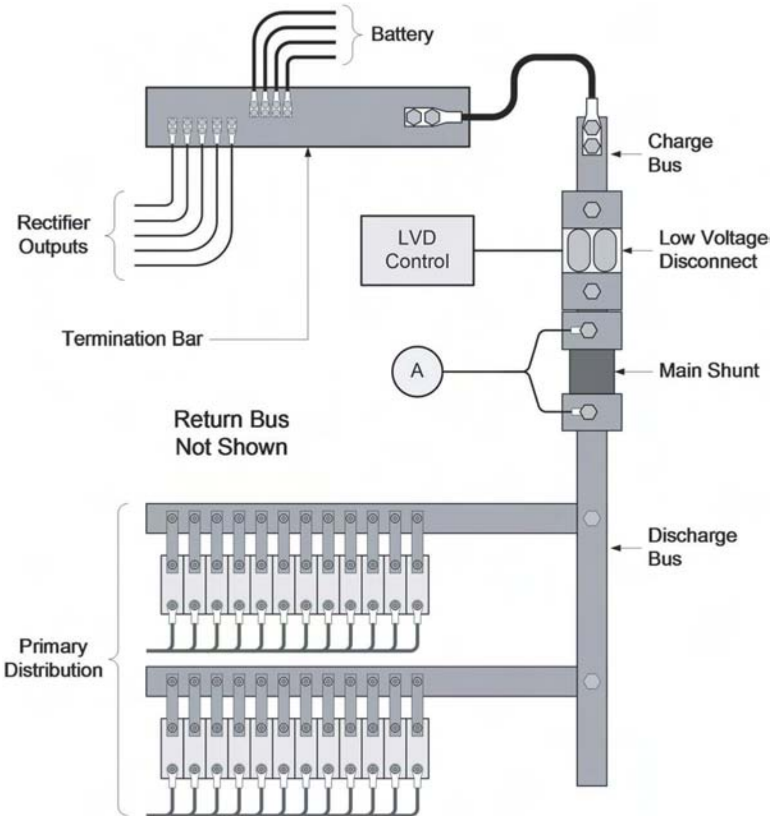


Fig. 3.25 Rectifier and battery cable termination busbar (return bus not shown).

Example 3.2 The main shunt in an 800-A powerboard has a voltage drop of 50 mV at rated load. Determine the shunt resistance and power dissipated at rated load. The resistance of the shunt is

$$R = \frac{V}{I} = \frac{0.050}{800} = 62.5 \times 10^{-6}\ \Omega = 62.5\ \mu\Omega$$

The power dissipated at full load is

$$P = VI = 0.050 \times 800 = 40\ \text{W}$$

Most shunts consist of parallel resistance components to provide more surface area for heat dissipation (Fig. 3.27). This minimizes heating of the resistive element and improves its accuracy over the full operating current range.

When a shunt is connected between the charge and discharge buses and measures the total system load, it is called a *main* shunt. Shunts also may be used on individual primary or secondary distribution circuits or to measure the load on circuit breaker and fuse panels (Fig. 3.28). In some powerboards, there is no main shunt, in which case the

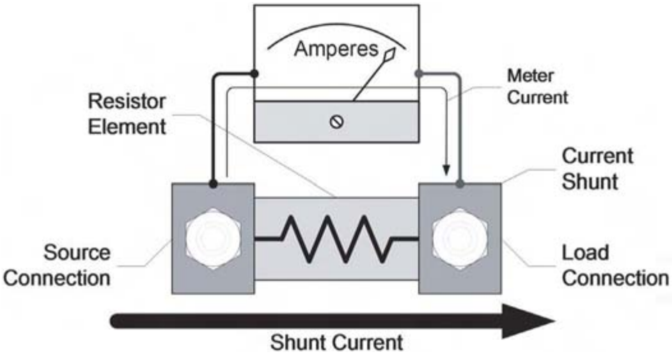


Fig. 3.26 dc current shunt application.

Table 3.6 Typical Powerboard Busbar Sizes

Powerboard Rating (A)	Busbar Size (in.)	Area (kcmil)	Current Density (CM/A)
50, 100, 200	$\frac{1}{4} \times 1$	318.3	1592
400, 600	$\frac{1}{4} \times 2$	636.6	1061
800	$\frac{1}{4} \times 2\frac{1}{2}$	795.8	995
1200	$\frac{1}{4} \times 4$	1273.2	1061
1600	$(2)\ \frac{1}{4} \times 4$	2,546.5	1592

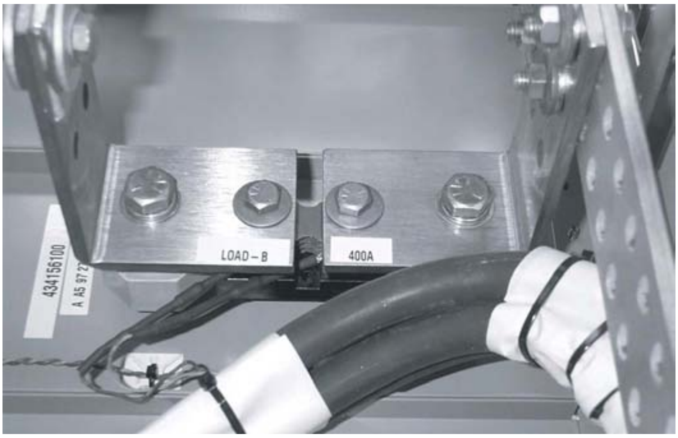


Fig. 3.27 400-A current shunt consisting of four parallel resistance elements in center of photo (note small leads to current indicator).

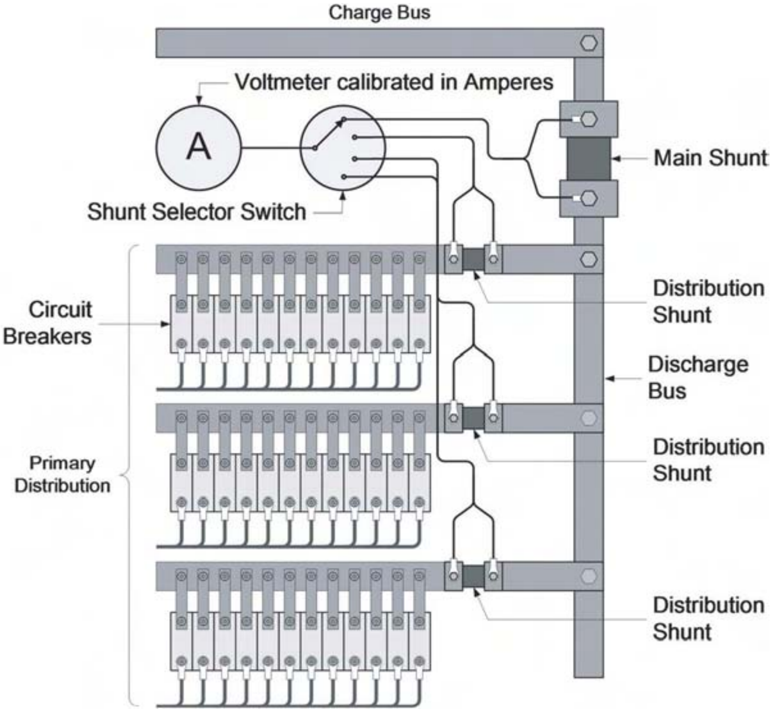


Fig. 3.28 Shunt applications: an analog ammeter would have two or more scales or the selector switch would select different ranges in a digital ammeter to accommodate different current ratings in the main and distribution shunts.

controller automatically adds the individual distribution loads to arrive at the total current.

Low-voltage disconnects are high-current relays (contactors) that may be connected between the discharge bus and the primary distribution system (Fig. 3.29). Their voltage and current ratings are the same as the busbars on which they are mounted. In high-current applications or where redundancy is needed, two LVDs may be wired in parallel. Where this is not practical, the loads are split across more than one discharge bus to lower the individual LVD current rating. A low-voltage disconnect may be installed to

- Prevent overdischarge of the battery
- Provide a means to shed loads to prolong battery reserve time
- Prevent damage to load equipment from low voltage

The arguments against using low-voltage disconnects are

- They are an electromechanical element that is subject to failure.
- They are subject to accidental operation.
- The low-voltage disconnect may open due to an initial dip in the battery voltage

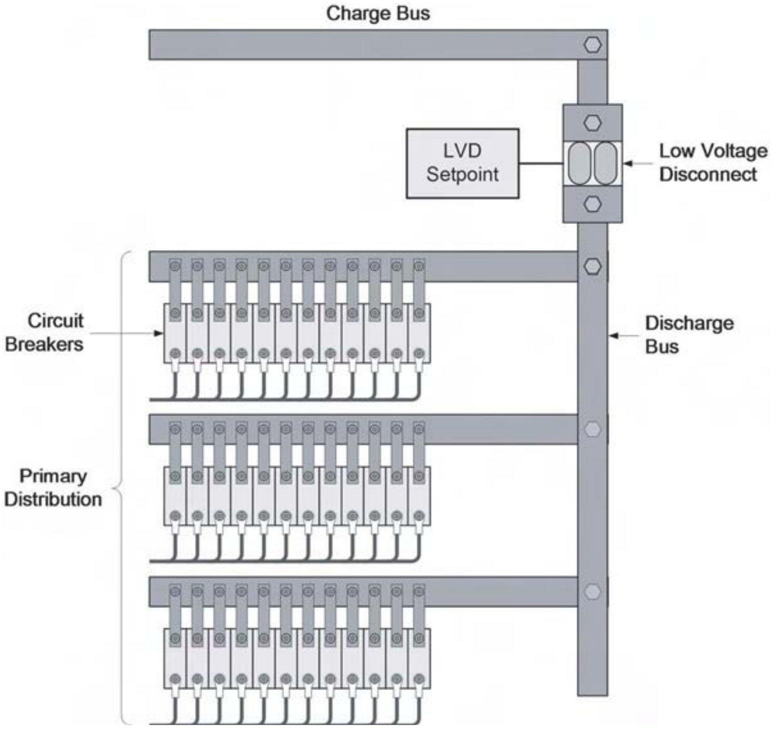


Fig. 3.29 Low-voltage disconnect on the main bus.

> (so-called *coupe de fouet*) when a fully charged battery first starts to discharge. Although the battery voltage probably recovers, the LVD already has interrupted the discharge bus. This phenomenon is more fully described in Chapter 6, Part III, Battery Maintenance.

Low-voltage disconnect contactors are electrically held; that is, when the system bus voltage is greater than the disconnect threshold, the LVD contactor is in the operated state (closed) and is electrically held in the closed condition by the contactor solenoid. As the battery discharges and the system bus voltage drops, the disconnect threshold is reached where the contactor releases and disconnects the circuit. Battery discharge is stopped, and the battery is protected from overdischarge when the load is disconnected from it by the LVD. The LVD does not disconnect the rectifier circuits. When the rectifier power source is restored, all available rectifier current initially is available to recharge the battery via the charge bus. As the battery voltage rises, the LVD reconnect threshold eventually is reached, which causes the LVD contactor to close, thus restoring current to the load. At this time, the rectifier system provides current to both the battery and load equipment.

Low-voltage disconnects normally are set with hysteresis such that they disconnect (drop-out) at a lower voltage than they reconnect. For example, the disconnect voltage threshold may be set to 44.0 V and the reconnect voltage to 48.0 V. As the battery discharges, it will be disconnected when the voltage at the LVD sensing point reaches 44.0 V. As the battery recharges the LVD will reconnect the load when the voltage at the sensing point reaches 48.0 V. The actual set-point voltages used in any given system depend on a number of factors. More details can be found in Chapter 5, System Design.

Low-voltage disconnects are used primarily to protect battery systems from overdischarge, but they also may be used in load-shedding schemes and to prevent load equipment from operating at low voltages that may damage them.

A load-shedding scheme allows less important or lower priority loads to be disconnected first, which reduces the discharge current and extends the discharge time. For example, in a three-step load-shedding scheme (Fig. 3.30), the first LVD (LVD1) may be set to disconnect at 46.0 V, the second (LVD2) to disconnect at 45.0 V, and the third (LVD3) at 44.0 V. When the discharge bus voltage reaches the first threshold, LVD1 will disconnect the low-priority loads thus reducing the battery current. The battery will continue to discharge but at a slower rate. When the second threshold is reached, LVD2 will disconnect the second load group, and so on.

3.5 MONITORING AND CONTROL

Monitoring and control systems can include simple analog metering for voltage and current and dry relay contact closures and indicating lamps for alarms, or they can be more

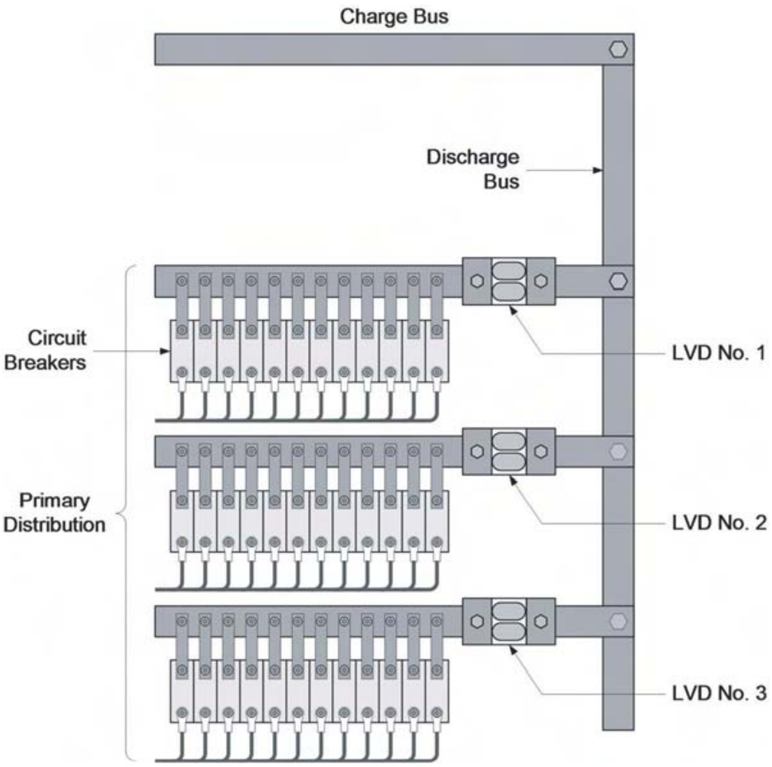


Fig. 3.30 Low-voltage disconnect in a three-circuit load shedding application.

complex digital metering, data logging, and alarm collecting systems with various types of local and remote connectivity (e.g., EIA-232 or 10/100BaseT Ethernet using Internet Protocol, IP). Figure 3.31 shows typical functions.

3.5.1 Alarm Circuits

Typical monitoring, alarm sending, and alarm indicating functions include

- High-voltage alarm
- Low-voltage alarm
- High or overcurrent alarm
- Rectifier system minor alarm (operates upon failure of one rectifier in an $N+1$ system)
- Rectifier system major alarm (operates upon failure of more than one rectifier in an $N+1$ system)
- Fuse/circuit breaker alarm
- Low-voltage disconnect (LVD) alarm
- Emergency or fire alarm disconnect control
- Automatic and manual rectifier equalize control

The high or overcurrent alarm setting is based on the powerboard bus (or main shunt) rating and the rating of the largest rectifier in the system as follows

$$I_{\mathrm{OCA}}\ (\%) = \frac{I_{\mathrm{Alarm}}\ (\%)(I_{\mathrm{Capacity}} - I_{\mathrm{Rectifier}})}{I_{\mathrm{Shunt}}} \tag{3.4}$$

where I_{OCA} (%) = setting of overcurrent alarm (%)
I_{Alarm} (%) = percent of full load desired for overcurrent alarm (A)
I_{Capacity} = total capacity of the power system (A)
$I_{\mathrm{Rectifier}}$ = current rating of largest rectifier in the system (A)
I_{Shunt} = main shunt current rating (A)

Alarm circuits may be “dry” or “wet” and may be based on solid-state electronic switches or electromechanical relays. A dry circuit has no voltage or ground on the alarm contacts, whereas a wet circuit has either battery or ground. Sensing circuits associated with dry contacts supply battery and ground for indicating lamps or LEDs (light-emitting diodes) and alarm sending systems. A typical alarm output circuit consists of one or more form-C relay contact sets, each of which includes a normally open and normally closed contact (Fig. 3.32). Depending on the function, separate sets of contacts are provided for minor, major, and catastrophic alarms.

Alarm circuits can indicate minor (MIN), major (MAJ), or catastrophic (CAT) conditions. A minor alarm indicates a fault that is not service affecting or affects only a small percentage of the total service. An example of a minor alarm is the failure of one rectifier in an $N+1$ redundancy rectifier system. A major alarm is more severe and affects a larger percentage of the total service. The failure of two or more rectifiers in a rectifier system normally is a major alarm. A catastrophic alarm indicates total service failure. The failure of all rectifiers and battery discharge to where the low-voltage disconnect opens is a cata-

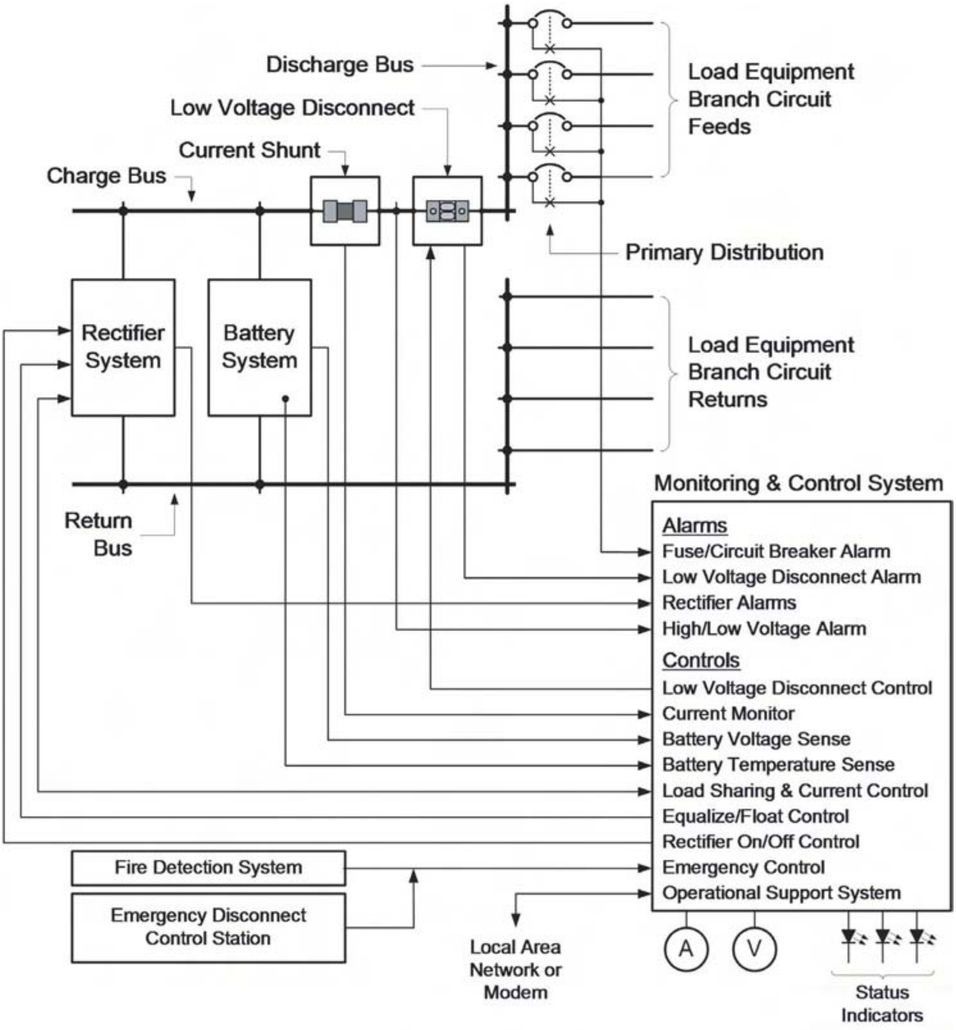


Fig. 3.31 Monitoring and control.

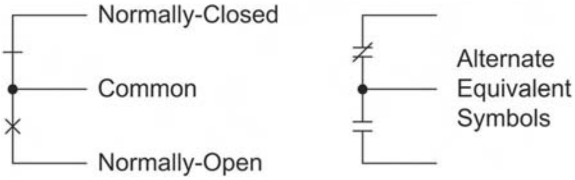


Fig. 3.32 Form-C relay contact set. The symbols for normally closed and normally open relay contacts on the left are unique to the telecommunications industry. The contact position shown in schematics usually is the position of the contacts when the device is "on-the-shelf" and not powered.

strophic alarm condition. In modern programmable equipment, many types of alarms can be classified in software according to their perceived severity.

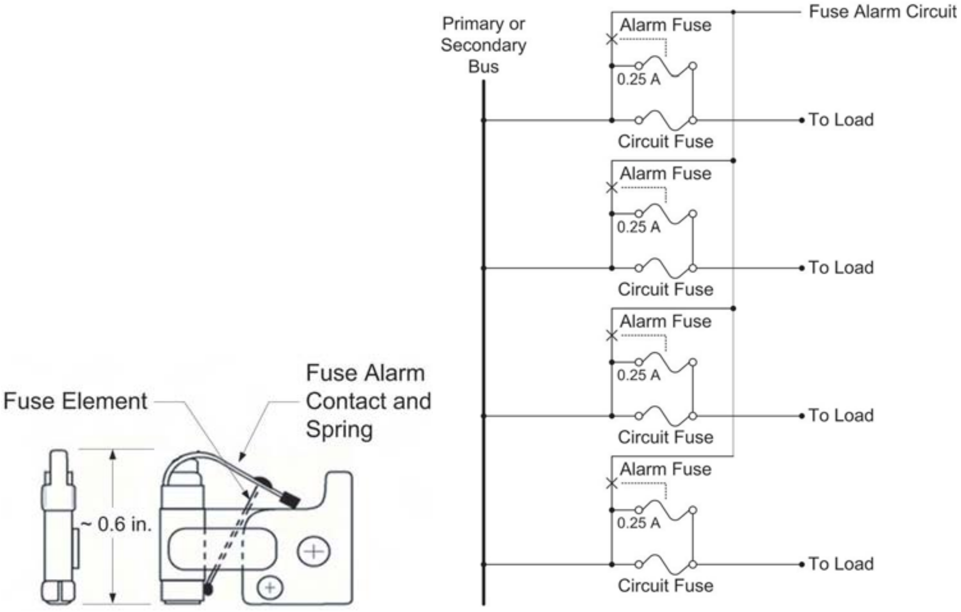
Fuse and circuit breaker alarms usually are operated in parallel and, on a system basis, are detected as a group. Small circuits (less than 15 A) use alarm indicating fuses [Fig. 3.33(a)] that have integral means of closing an alarm contact when the fuse burns open. Alarm indicating fuses also are connected in parallel with larger cartridge fuses to provide the indicating function [Fig. 3.33(b)].

Circuit breakers used in telecommunications power systems include an auxiliary set of form-C contacts to indicate circuit breaker handle position—opened or closed (Fig. 3.34). In this case, the normally closed contacts are connected in parallel to the alarm detecting system.

3.5.2 Battery Equalize Control

The equalize control may be manual or automatic. Older rectifier systems have an equalize control switch on each rectifier. The rectifiers also may be manually controlled as a group from the powerboard with a single toggle switch. More modern systems use a central controller in the powerboard to control all rectifier functions, including equalize.

Automatic equalize controllers monitor the system voltage (Fig. 3.35). The rectifier equalize control circuit is armed if the voltage falls below a programmable threshold, which indicates the rectifiers are not supplying current and the battery is discharging. Thresholds typically are 24.0 or 48.0 V depending on the system voltage. When ac power



(a) (b)

Fig. 3.33 Fuse alarm circuits. (a) Alarm indicating fuses are connected in parallel with a larger cartridge fuse. When the larger fuse burns open, so does (b) the alarm indicating fuse.

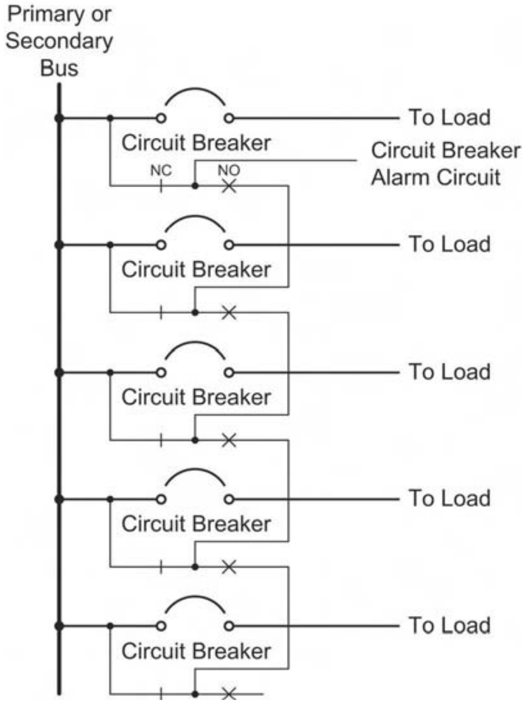


Fig. 3.34 Circuit breaker alarm circuits (alarm contacts are shown with the circuit breaker in off/tripped position). When the circuit breaker is in the on position, the normally closed (NC) contacts are mechanically held open, and the bus voltage is blocked from the alarm circuit. When a circuit breaker trips or is turned off, the normally closed contacts connect the bus voltage to the alarm circuit.

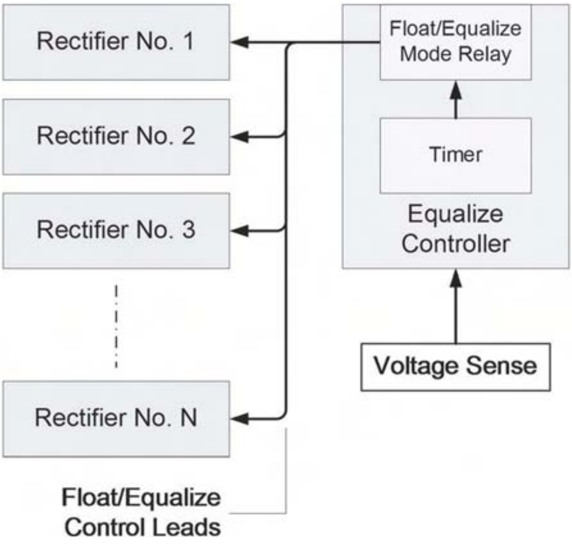


Fig. 3.35 Automatic equalize controller.

returns and the rectifiers are able to deliver output current, they switch to the equalize mode for a selectable time period, typically from 0 to 99 h. When the timer expires, the rectifiers automatically are reset to the float mode. Equalize controllers normally are not used with VRLA batteries but are found in many powerboards used with VLA batteries.

3.5.3 Capacitor Precharge Circuit

Some load circuits have large capacitances associated with them. When voltage is applied to a discharged capacitor, it acts like a short circuit and may trip upstream overcurrent devices. Some powerboards contain circuits that precharge the capacitors prior to the distribution circuit breaker closing. Precharging prevents the circuit breaker from tripping when it is initially closed due to the current transient from the capacitors in the circuit load equipment. Each large circuit breaker position (typically larger than 125 A) is equipped with a precharge push-button and associated circuit (Fig. 3.36).

3.6 PRIMARY AND SECONDARY DISTRIBUTION SYSTEMS

The primary distribution system includes the first overcurrent protection device after the discharge bus and normally is located with or close to the discharge bus. Primary overcurrent devices usually feed equipment groups such as switching systems or secondary distribution systems. The secondary distribution system includes intermediate overcurrent protection devices after the primary and may be located adjacent to the primary or in any other location.[6]

Overcurrent protection devices such as circuit breakers and fuses in the primary and secondary distribution systems protect all branch circuits on the load side of the discharge bus. The overcurrent protection is located at the point closest to where conductors are powered (Fig. 3.37) and also at any point in a circuit where the conductor size is reduced unless an upstream overcurrent device also is suitable for protecting the smaller conductor.

3.6.1 Overcurrent Protection

System protection is “the detection and prompt isolation of the affected portion of the system whenever a short circuit or other abnormality occurs that might cause damage to, or adversely affect the operation of any portion of the system or the load that it supplies” [16 (page 39)]. Overcurrent caused by an overload or a short circuit results in overheating, burning, or other damage to circuit wiring and equipment if it is allowed to persist.

The primary objective of electrical system protection is to prevent human injury. Secondary objectives are to minimize load equipment and circuit component damage, and to limit service interruptions caused by equipment failure, human error, or adverse natural events. Achieving the primary objective in many cases means achieving the secondary objectives. Equipment damage and service continuity are traded off according to the operating requirements and importance of the equipment being protected. The primary and secondary objectives can be achieved only by the correct combination of cir-

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[6] Primary distribution centers and secondary distribution centers are sometimes called battery distribution fuse bays (BDFB) or battery distribution circuit breaker bays (BDCBB).

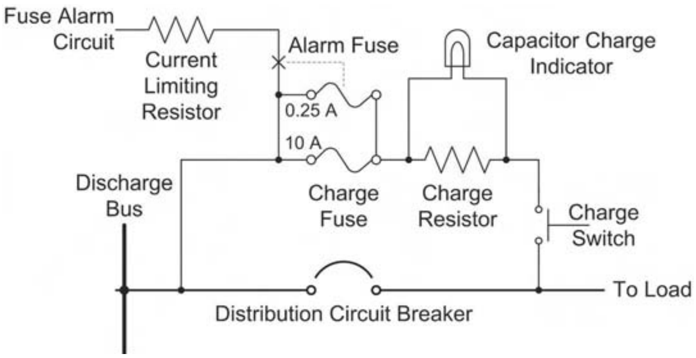

Fig. 3.36 Capacitor precharge circuit. Prior to closing the circuit breaker the push-button is pressed and current flows through the charging resistor, charging fuse, and indicating lamp to the load capacitors. When the lamp extinguishes, the capacitors in the circuit are charged. At this time, the circuit breaker can be closed and the button is released. The charge resistor is sized to limit the current through the charge fuse.

cuit overcurrent protection, wire size and insulation, and physical protection. The nominal current rating of a device refers to the maximum current it can carry during normal operation.

Properly sized overcurrent protection devices open the circuit before any damage occurs. The total of the individual primary or secondary distribution overcurrent device ratings almost always is greater than the powerboard bus rating. This is because the individual distribution circuits usually operate at a 50% load factor (the actual circuit operating current is no more than 50% of the overcurrent protective device rating) although they are designed to continuously carry 80% of circuit current-carrying capacity. Telecommunications dc circuits normally are not designed to carry more than 80% of the conductor current rating during normal operation. As long as the actual total load does not exceed the bus rating there will be no problems.

Overloads are overcurrents between 1× and approximately 6× the nominal current rating while short circuits are overcurrents above approximately 10× nominal current. Currents between approximately 6× and 10× are considered transition currents. Overload currents do not leave the normal current-carrying circuit path from the source through the load, whereas short circuits bypass the load. Short circuits usually result from line-to-line or line-to-ground faults. Overcurrent protection devices react differently to overload and

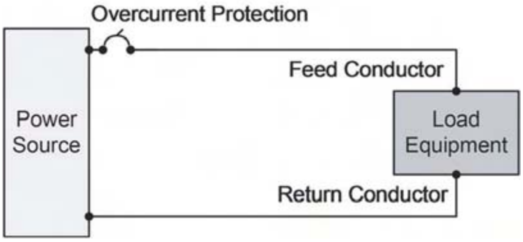

Fig. 3.37 Overcurrent protection device for a circuit is located where the circuit receives its power.

short-circuit currents because of their current–time (*IT*) or *delay characteristic* curves. It is possible the delay characteristic curve for a given device is different for dc than ac currents, thus it is necessary to confirm their basis before use.

Overloads are caused by connecting larger or additional load equipment to the circuit or failure in the load equipment that causes higher than normal current. Short circuits in low-voltage dc circuits usually are caused by mechanical damage to wire insulation during installation, removal, or replacement, accidental contact with tools, or catastrophic failure of load equipment.

Besides protecting the conductors and equipment, the overcurrent protective device isolates the fault from the power source so that nonfaulted circuits can continue working in a normal manner. The entire electrical system, including the power source, wire, electrical circuit components, and load equipment must be protected from faults.

Protection devices must be coordinated. The ratings of all devices connected between the current source and load are selectively coordinated when the device nearest to the fault is the only one that opens and only the affected equipment is disconnected from the electrical system. For example, a fault in the primary or secondary distribution circuits should not affect the battery circuit (Fig. 3.38).

The selective coordination process compares the delay characteristic curves of the protection devices connected in series. Circuit breakers and fuses are available with various delay characteristic curves. Figure 3.39 shows a typical circuit breaker delay characteristic curve, and Table 3.7 provides tabular information corresponding to this curve. These characteristics apply to any circuit breaker with the delay 51 curve shown. Figure 3.40 and Table 3.8 provide similar information for a typical fuse. Note that a separate curve is provided for each fuse value because different fuse link masses and shapes affect the melting characteristics. Fuse curves such as these normally represent average conditions and do not show minimum melt or total clearing conditions.

As an example of a circuit breaker delay curve application, consider a 50-A circuit breaker and a fault that draws 200 A (4× or 400% of circuit breaker rating). The opening mechanism in a circuit breaker with a delay 51 trip characteristic will unlatch in as little

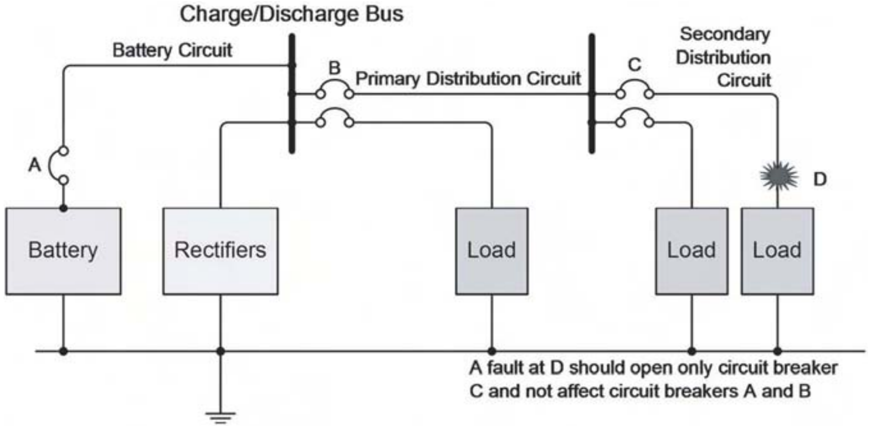

Fig. 3.38 Coordination of overcurrent devices. A fault at *D* should open the overcurrent protection device at *C* only and not the devices at *A* or *B*.

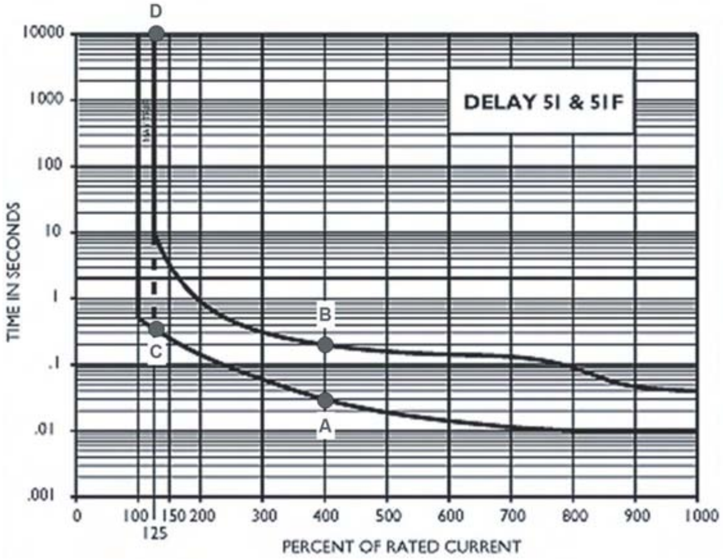

Fig. 3.39 Example of delay 51 circuit breaker trip points. (underlying graph with permission of Airpax Corporation, Power Protection Products.)

as 0.03 s (point *A* in Fig. 3.39), but the circuit will not completely open until as much as 0.2 s has elapsed (point *B*). If the load on the delay 51 circuit breaker in this example is 62.5 A (125% of rating), it may trip anywhere between 0.3 s (point *C*) and 3 h (point *D*) or more (it may never open).

Coordination of circuit breaker *interrupt* ratings (as opposed to *overload* ratings) can be complicated. A short circuit can occur at the load terminals of the distribution protection device or almost anywhere in the battery or distribution circuits. Some locations are higher risk than others (e.g., exposed terminals), and locations closer to the battery will experience higher fault currents. Coordination should ensure that the first device to interrupt the fault has an interrupt rating greater than the available short-circuit current.

In modern telecommunications dc power systems, two conductors carry current from the power source to the load (feed and return conductors). The return conductor is connected to a return bus, which may be in a powerboard or other convenient location. In modern systems, the return bus is intentionally bonded to the earth ground system at only one location. A third conductor (equipment grounding conductor, EGC, or frame ground) is used to bond equipment frames and structures to the earth ground system. In modern systems, the return conductors and EGCs are separate conductors, and the EGC is meant

Table 3.7 Delay Characteristics for Delay 51 Circuit Breaker

Delay	100%	125%	150%	200%	300%	400%	600%	800%	1000%
51 & 51F	No trip	0.5–10 s	0.25–3 s	0.15–0.9 s	0.05–0.3 s	0.03–0.2 s	0.015–0.15 s	0.01–0.09 s	0.01–0.04 s

Data provided by Airpax Corporation, Power Protection Products.

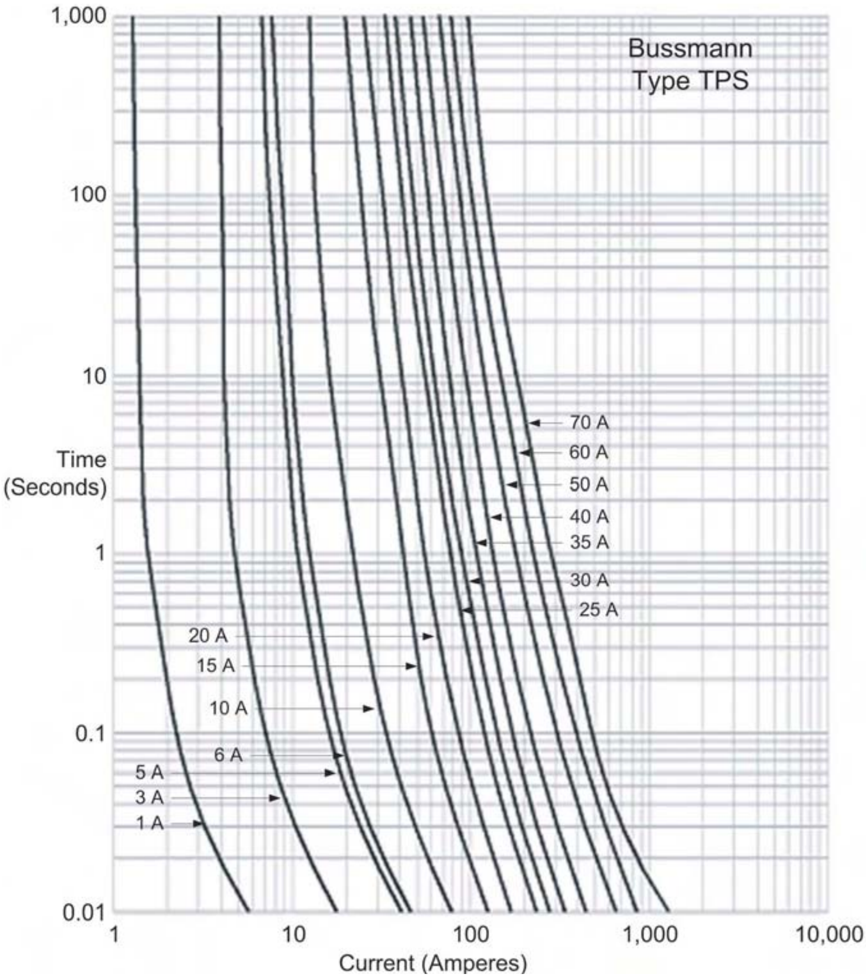

Fig. 3.40 Example of TPS fuse delay characteristic curve. (Underlying graph with permission of Bussmann.)

to carry only fault currents and does not carry any operating current. Older systems may have different bonding configurations (Table 3.9).

Short circuits can occur between the feed conductor and return conductor or between the feed conductor and the EGC or other grounded metallic part. In low-voltage systems, short circuits usually are low impedance (terms used are solid, bolted, or welded) rather than high impedance from arcing or flashover. However, high-impedance faults can occur in battery systems where a cell container fails and electrolyte leaks to a grounded metallic component.

The type of overcurrent protection device—fuse or circuit breaker—used in any particular application is determined by cost, preference, available space, bus configurations, and maintenance, environmental, and circuit performance requirements. Proper selection results in a device with the lowest rating that will not inadvertently open (false trip or nuisance trip).

Table 3.8 Delay Characteristics for 30-A TPS Fuse

Delay	100%	125%	150%	200%	300%	400%	600%	800%	1000%
Typical	No trip	> 1000 s	~ 130 s	~ 80 s	~ 0.7 s	~ 0.09 s	~ 0.03 s	~ 0.012 s	< 0.01 s

Data from the corresponding delay characteristic curve.

Table 3.9 Comparison of Return Conductor and EGC Configurations for Modern and Older Systems

Component	Modern	Older
Return bus	Intentionally bonded to the earth ground system at only one location	Intentionally and incidentally bonded to ground at many points or locations
Equipment grounding conductor (EGC)	Separate from the return conductor and meant to only carry fault currents	Not always separate from the return conductor—may be shared with the return conductor

The overcurrent device must sense the fault and disconnect the circuit from the power source before injury or damage occurs. Only the feed conductor is disconnected by the overcurrent device. Fuses and circuit breakers provide both sensing and disconnecting functions in one device.

A fuse depends entirely on thermal effects for its operation—the fuse element melts and opens the circuit. The time it takes to open depends on the length of time the overcurrent has been flowing and the magnitude of the overcurrent. Fuses are single-use devices (not resettable) that are discarded and replaced after they have opened.

Circuit breakers are electromechanical devices that may be reset and reused after an overload or low-value short circuit, but most manufacturers recommend replacement if the device ever interrupts a short circuit with a fault current close to its interrupt rating. Circuit breakers depend on thermal effects or magnetic effects, or both, for their operation. Thermal operation is similar to fuses in that the current magnitude required to open the device depends on how long it has been flowing. Circuit breakers that are designed to protect only against short circuits use an electromagnet to sense and quickly actuate the opening mechanism. Thermal-magnetic circuit breakers combine the advantages of sensing and protecting against overloads as well as sensing and quickly opening on short circuits. Circuit breakers used in telecommunications are trip-free, which means they cannot be held on with an overload or short circuit present on the circuit.

Circuit components, such as rectifiers, filters, regulators, and electronic circuits, have significantly different overload withstand characteristics compared to wire and cable. Many electronic circuits and components require extremely fast fault clearing to adequately protect them from thermal damage.

3.6.2 Fuses

Fuses are the most common overcurrent protective devices used in telecommunications systems, especially older systems—they are low cost and reliable. A fuse operates by melting an internal, shaped-metal link, typically a lead alloy (fast-acting fuses may use a silver wire link). Since a fuse depends on its self-destruction to protect a circuit, the fuse must be replaced after it opens [replaceable element fuses (type RL) have been used in telecommunications but all new applications since the early 1980s use one-time fuses]. When a fuse burns opens, the melting current and the circuit interrupting current may be different. Fuse-clip size and condition and the size of the conductor attached to it can influence fuse performance (large conductors act as heat sinks). In addition, fuse and clip corrosion can cause heating due to the higher resistance of the corroded surface and can lead to nuisance interruption. Also, if a fuse holder is overheated, the fuse contract springs may relax, leading to poor contact and increased resistance.

Fuse elements may deteriorate over time due to chemical and physical stresses in the element during repeated short duration overloads. For example, some power supplies produce a short high-current inrush (capacitor charging current) followed by a relatively low running current. The short duration inrush current warms and thermally stresses the element but does not last long enough to melt it. Cyclical expansions and contractions of the fuse element can lead to eventual mechanical fatigue and premature failure.

Fuses must not be used where the circuit operating voltage is higher than the fuse voltage rating. On the other hand, a fuse may be operated at a lower than rated voltage but the arcing and clearing times may be different than at rated voltage. Fuses should not be used in direct current circuits unless they are rated for dc.

3.6.2.1 Fuse Operating Parameters The operation of all fuse types is defined by several parameters:

- Melting time
- Arcing time
- Total clearing time (sum of melting and arcing time)
- Peak let-through current
- Voltage rating

The time required to melt the fuse element on a specified overcurrent is the melting time, whereas arcing time is the elapsed time from the melting of the fuse element to the final interruption of the current. The peak let-through current is the maximum instantaneous current through the fuse during the total clearing time (Fig. 3.41).

Fuses are available in two basic configurations—small value, alarm indicating fuses, Type 70 and type GMT, and cartridge fuses (Fig. 3.42). Several fuse panel types are available for telecommunications applications depending on the fuse type and required current rating (the following are modern and not historical)[7]:

- Type 70 fuse panels with individual fuse position ratings up to 20 A
- Type GMT fuse panels with individual fuse position ratings up to 15 A
- Type TPL and TGL, cartridge fuse panels with individual fuse position ratings from 70 to 800 A
- Type TPN, TLN, and TGN, cartridge fuse panels with individual fuse position ratings from 1 to 600 A

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[7] TPx fuses are manufactured by Bussmann, TLx fuses by Littelfuse, and TGx fuses by Ferraz-Shawmut.

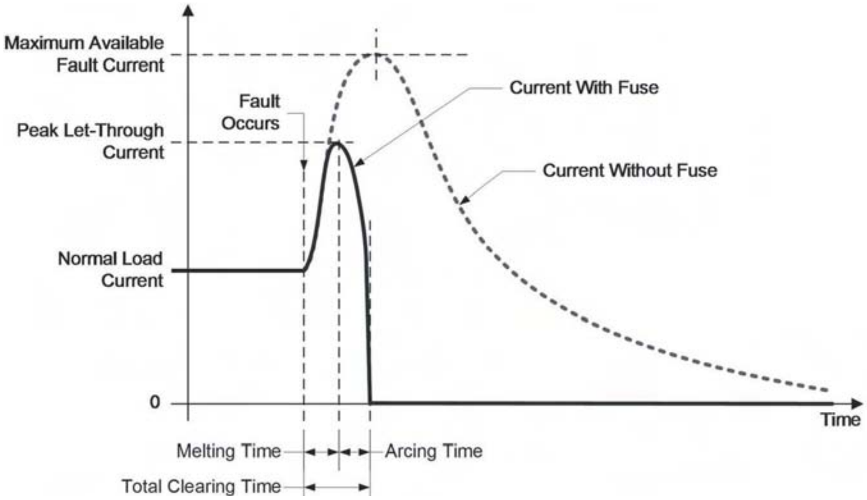


Fig. 3.41 Typical fuse current limitation curve.

- Type TPS, TLS, and TGS, cartridge fuse panels with individual fuse position ratings from 1 to 70 A

Fuse positions rated more than 600 or 800 A are seldom used in telecommunications dc power systems. Loads are split in such a way to reduce the rating of individual circuits to less than 600 or 800 A, typically 100 to 200 A.

3.6.2.2 Time Delay Characteristics The thermal energy required to melt the fuse element is specified by its *melting integral,* which is represented in fuse catalogs by time–current (current–time) or delay characteristic curves (Fig. 3.43). The delay characteristic curve is determined by the element construction and material. To minimize false opening, fuses are selected such that their minimum opening energy is greater than the maximum inrush energy. Some load equipment requires a fast-blow fuse while others require a slow-blow fuse. Slow-blow fuses have an inherent thermal delay that allows them to withstand large inrush currents for short durations without burning open.

Because there is no overlap between fuse curves shown, these fuses appear to provide selective coordination; however, the curves represent average values and do not show the possible ranges due to manufacturing tolerances. Curves generally are considered to be accurate to ±10%, but for selective coordination purposes an accuracy of ±20% is a more conservative assumption.

As a rule of thumb, for a given fuse family, selective coordination can be achieved when the fuse ratings have a 2:1 ratio. For example, a 100-A fuse will coordinate with a downstream 50-A fuse. The 2:1 ratio may not apply when different fuse families are involved. Also, when fuses and circuit breakers are connected in series, selective coordination generally cannot be ensured by rules of thumb but only by more detailed analysis (Chapter 5, System Design).

3.6.2.3 Short-Circuit Capability Cartridge fuses have good short-circuit interrupt capability. The TxN (TPN, TGN, TLN depending on manufacturer), TxS, and TPL series

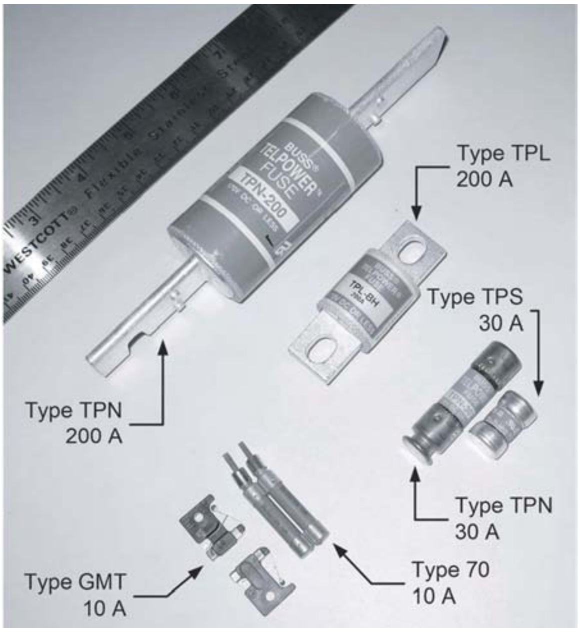


Fig. 3.42 Telecommunications fuses. Type TPN, TPL, and TPS are cartridge fuses and type GMT and 70 are alarm indicating fuses.

all have 100,000-A interrupt rating. Type NON fuses used in older dc power systems have 50,000-A interrupt rating up to 60 A and 10,000 A at higher values. Smaller alarm-indicating fuses have much lower ratings because they are used on relatively low-current circuits whose resistance limits the available fault currents to low values. The type 70 fuses have 1000-A interrupt rating and type GMT have 450-A interrupt rating when used in 60-Vdc class systems.

3.6.2.4 Direct Current Resistance Small value alarm-indicating fuses have significant dc resistance and can introduce significant voltage drop (Table 3.10). On the other hand, cartridge fuses have very low resistance and do not introduce significant voltage drop.

3.6.3 Circuit Breakers

A circuit breaker provides manual on–off switching and automatic operation during overcurrent conditions. Overcurrent trip is indicated by the handle moving to the off or midtrip position.

3.6.3.1 Thermal Circuit Breakers Thermal circuit breakers depend on temperature rise in a thermal sensing element for actuation. When an overcurrent condition exists, the thermal sensing element deflects and trips a spring-loaded switch to open the circuit. The most common thermal elements consist of a laminate of two or three different metals.

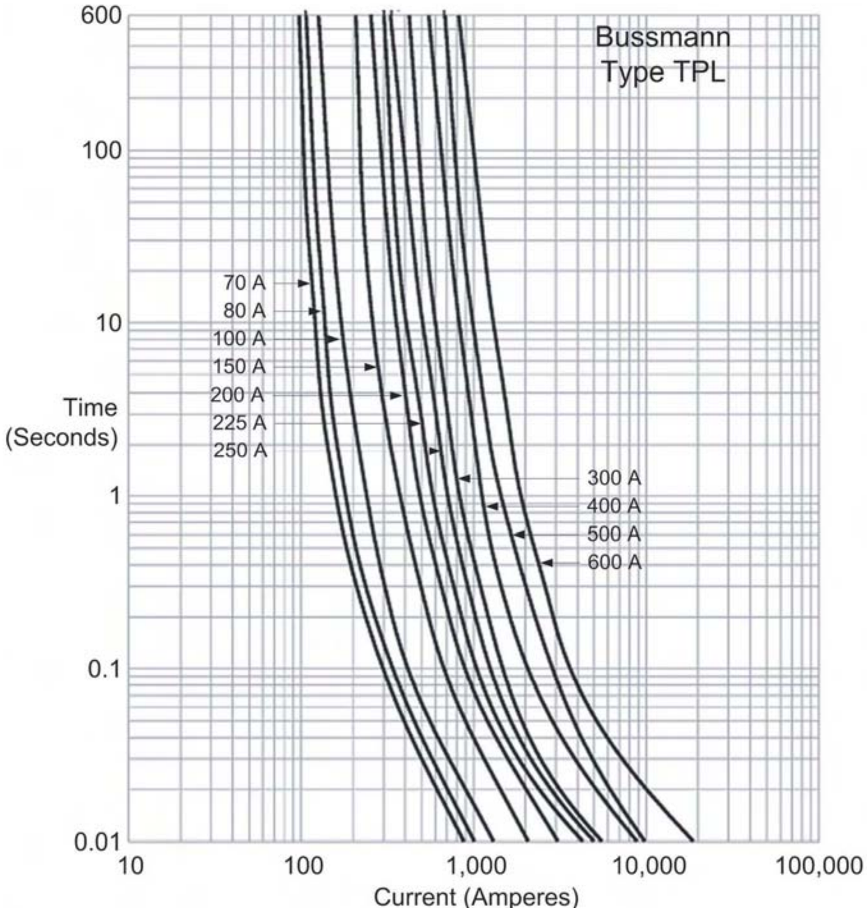


Fig. 3.43 Time delay characteristic curves, type TPL fuse. (Underlying curve provided by Bussmann.)

The low expansion side may be the metal alloy Invar, the center may be copper for low resistivity or nickel for high resistivity. Metals used in the high expansion side vary considerably.

Temperature rise in the sensing element is caused principally from internal resistance heating due to the load current through the circuit breaker (I^2R heating). However, the heating or cooling effects from external sources also affects the thermal element by altering its room temperature calibration. The physical size, shape, configuration, and electrical resistance of the thermal element determine the circuit breaker current rating. In some cases, a heater coil is placed adjacent to, and electrically in series with, the thermal element to augment self-heating of the thermal trip element. This is especially true in circuit breakers rated below 5 A.

3.6.3.2 Thermal-Magnetic Circuit Breaker To protect wiring, upstream components and the breaker itself from unnecessarily long thermal and mechanical stress during

Table 3.10 Type GMT Fuse dc Resistance and Voltage Drop

Ampere Rating (A)	Nominal Cold Resistance (Ω)	Voltage Drop @ 50% Load Factor (V)	Voltage Drop @ 100% Load Factor (V)
0.18	6.25	0.56	1.13
0.20	5.70	0.57	1.14
0.25	4.20	0.53	1.05
0.375	2.00	0.38	0.75
0.5	1.52	0.38	0.76
0.65	1.25	0.41	0.81
0.75	0.980	0.37	0.74
1	0.665	0.33	0.67
1.33	0.480	0.32	0.64
1.5	0.385	0.29	0.58
2	0.120	0.12	0.24
2.5	0.0904	0.11	0.23
3	0.0670	0.10	0.20
3.5	0.0415	0.07	0.15
4	0.0350	0.07	0.14
5	0.0285	0.07	0.14
7.5	0.0113	0.04	0.08
10	0.00840	0.04	0.08
12	0.00660	0.04	0.08
15	0.00580	0.04	0.09

high fault currents, an electromagnet may be added to decrease the tripping time of the thermal breaker (Fig. 3.44). This magnetic circuit usually consists of a few turns of a large cross-section magnet wire in series with the thermal element.

The magnetic-assist mechanism usually has a trip point well above the normal overload trip range. This has little effect on the normal thermal trip response time, but under high overcurrent conditions the current produces sufficient magnetic force to trip the circuit breaker without waiting for the bimetal thermal element to heat up and deflect.

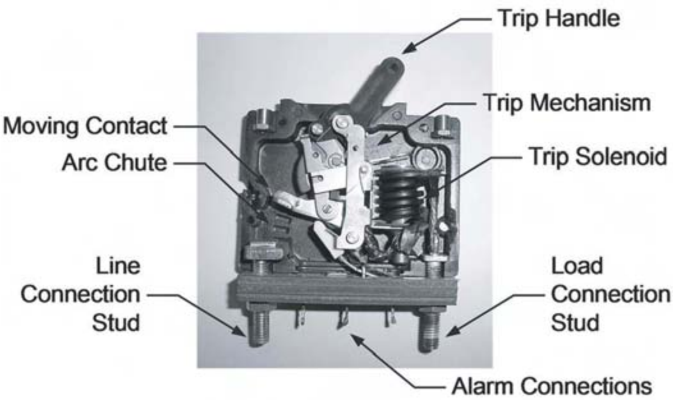


Fig. 3.44 Thermal-magnetic circuit breaker.

3.6.3.3 Magnetic Circuit Breakers A magnetic circuit breaker (also called instantaneous trip circuit breaker) is similar to a thermal-magnetic circuit breaker except it does not have the thermal element. It uses a solenoid in which a movable core, held with a spring in a tube and damped with a fluid, is moved by the magnetic field of a series coil that is carrying fault current. The movable core trips the spring-loaded contacts.

Magnetic circuit breakers are designed to open quickly ("instantaneously") under short-circuit conditions. The instantaneous trip current usually is on the order of 6 to 10 times (6×, or 600%, to 10×, or 1000%) the current rating of the circuit breaker. A typical thermal circuit breaker will open a 10,000-A fault in about 40 or 50 ms, but a magnetic circuit breaker will open the same fault in about 10 ms. Under higher short-circuit current conditions, the operating speed of magnetic circuit breakers may be as fast as 3 to 4 ms. The time-to-trip of a typical magnetic breaker is illustrated in Figure 3.45.

A magnetic breaker can be reset immediately after tripping, although the delay mechanism itself does not immediately reset. If the fault is still present, the circuit breaker will

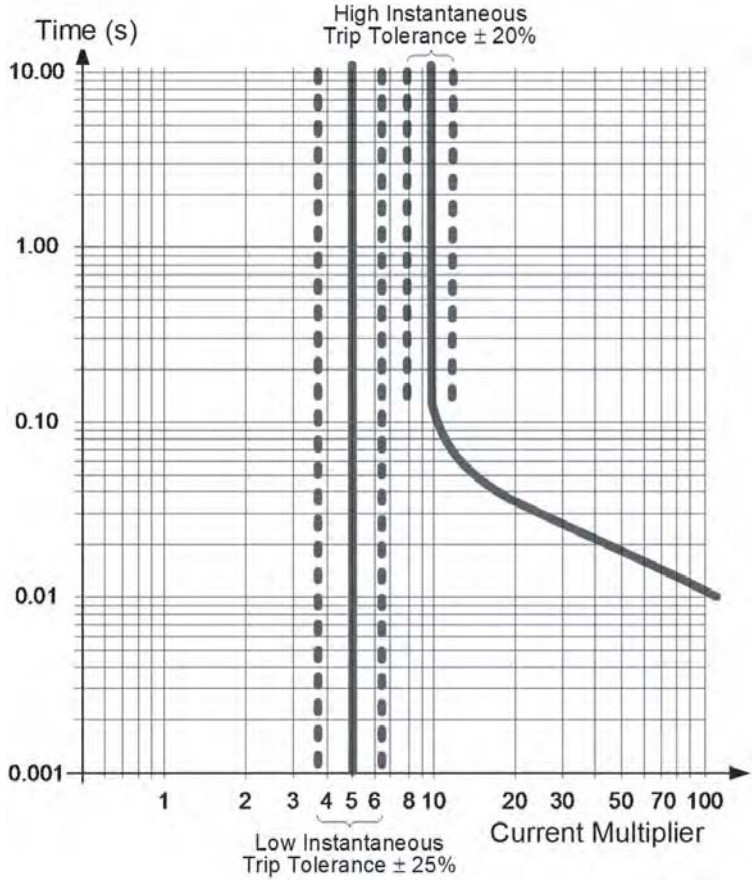


Fig. 3.45 Time–current curve for a magnetic circuit breaker. The circuit breaker shown will not respond to currents less than 5 times (5×) its current rating. The minimum opening time for very large faults (100×) is limited by the mechanical inertia of the circuit breaker components. The dotted lines indicate the time ranges due to mechanical and electrical tolerances.

trip again but with reduced time delay. Thermal breakers cannot be reset until their heating elements cool down.

3.6.3.4 Short-Circuit Capability

It is important that the fault current available at the overcurrent device not exceed the current that the device can safely interrupt. Circuit conductor resistances and fault resistance affect the available fault current at any location in a circuit. In a properly designed circuit, short-circuit currents do not destroy the circuit breaker.

The primary factors that determine the available fault current are the battery capacity and its internal resistance, rectifier capacity, resistance of the circuit conductors, and connection resistances. These factors, in addition to the fault resistance, determine the actual fault current.

The effective current capacity of a circuit can be computed roughly by a simple differential measurement of the circuit output voltage from no load to full load. For example, if a 50-V circuit supplying 30 A has a 2-V drop, the total resistance back to the power source is $R = 2/30 = 0.067\ \Omega$, and the short-circuit current at the load end of this circuit is limited to the power source voltage divided by the total circuit resistance, or 50 V/0.067 Ω = 750 A. The interrupting capacity for typical circuit breakers is shown in Table 3.11.

3.6.3.5 Transient (False or Nuisance) Tripping

The fast operating speeds of magnetic circuit breakers can cause nuisance tripping on high-amplitude transients. When a transient of sufficient energy flows through a circuit breaker, it responds in an instantaneous trip mode and trips. If the transient is nondamaging to load and circuit equipment, as it is in many cases, the trip is classified as a nuisance trip or false trip.

Inrush transients are most severe when the power source has low impedance and the circuit voltage is high. Transient-tolerant protectors must accept the first surge of current without tripping, while still providing maximum circuit protection. This is accomplished either by shunting high magnetic flux peaks away from the circuit breaker internal armature or using an inertial device to dampen the armature. Both methods affect the delay characteristic curves.

3.6.3.6 Time Delay Characteristics

Trip delays must be long enough to avoid nuisance tripping caused by harmless transients, yet fast enough to open the circuit when a real fault exists. Basic trip delay characteristics are:

- **Instantaneous** Usually trips in under 100 ms but more typically within approximately 15 ms, for very sensitive circuits where low overloads of short duration may be harmful, or where high fault currents should not be allowed to persist.

Table 3.11 Circuit Breaker Interrupting Capacity

Current Range (A)	Maximum Voltage (Vdc)	Interrupting Capacity (A)	Third-Party Approval
100–250	65	65,000	UL 489
100–250	65	65,000	UL 489A
275–1200[a]	65	65,000	UL 489A

[a] Parallel poles.

- **Fast Delay** Trips in less than 10 s, for circuits and electronic applications where temporary overloads of 200% cannot be tolerated for more than a few seconds.
- **Slow Delay** Trips in 10 to 100 s, for most large transformer-coupled loads where brief overloads can be tolerated without damage. Slow delays allow turn-on surges to pass without tripping.
- **Very Slow Delay** Trips in more than 100 s, for protection of wiring where a limited overload will not cause damage.

As the fault current increases, the time delay decreases to a point where the circuit breaker's mechanical inertia and arc quenching capability determine the circuit interrupting time. At very high fault currents (10 times the rated current), the practical limit for magnetic circuit breaker is about 4 to 10 ms.

Circuit breakers used in telecommunications usually are available in three delay variations: 51, 52, and 53, with 52 being the most common (Fig. 3.46 and Table 3.12). Delay 51 is a relatively short delay device for general-purpose applications in distribution circuits. Delay 52 and 53 have much longer delays and are useful in circuits where inrush currents and false tripping are potential problems. Using a long delay circuit breaker incurs some risk because conductor insulation may melt or the conductor itself may be damaged before the circuit breaker opens.

3.6.3.7 Direct Circuit Resistance Circuit breakers typically have very low resistances and, therefore, low-voltage drops at rated load. However, the voltage drop may be a significant factor if the load voltage is critical, particularly for low-amperage circuit breakers (5 A and less). Typical resistance values and corresponding voltage drops at 50 and 100% load factors are shown in Table 3.13.

3.6.3.8 Trip and Switching Configurations Molded case disconnect switches and circuit breakers can be equipped with a shunt trip mechanism that allows the device to be opened from a remote location (Fig. 3.47). When used on a battery disconnect switch or circuit breaker, a push-button switch usually is located near the door to the battery room so that firefighters or others can operate it to disconnect the battery during an emergency. The shunt trip usually is powered directly by the battery with fuses providing overcurrent protection for the push-button circuit wiring. Light-emitting diodes (LED) or lamps can be provided to indicate switch or circuit breaker states. Figure 3.48 and Table 3.14 show some possible combinations.

3.7 VOLTAGE CONVERSION

Two basic voltage conversion devices are used in telecommunications power systems: DC–DC converters and inverters.

3.7.1 DC–DC Converters

Most telecommunications switching and transmission equipment operates from –48 V but the radio frequency (RF) equipment used in many wireless base stations operates from +24 V. Some older RF equipment used in paging and land mobile radio (LMR) installa-

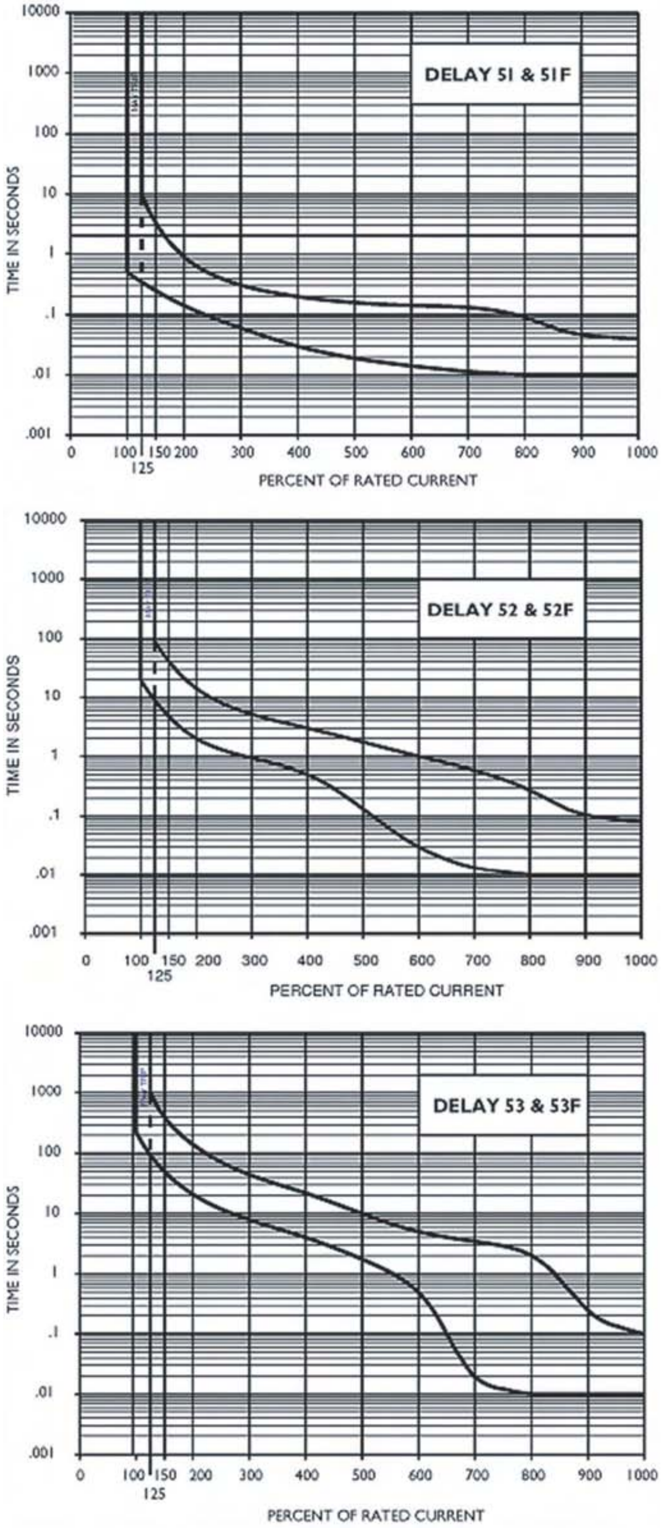


Fig. 3.46 A dc circuit breaker IT characteristics. (Graph with permission of Airpax Corporation, Power Protection Products.)

Table 3.12 dc Circuit Breaker Current–Time Characteristics Comparison

Delay	100%	125%	150%	200%	300%	400%	600%	800%	1000%
51 & 51F	No trip	0.5–10 s	0.25–3 s	0.15–0.9 s	0.05–0.3 s	0.03–0.2 s	0.015–0.15 s	0.01–0.09 s	0.01–0.04 s
52 & 52F	No trip	9–90 s	5–40 s	2–15 s	0.9–5 s	0.5–3 s	0.03–1 s	0.01–0.28 s	0.01–0.08 s
53 & 53F	No trip	100–1000 s	50–400 s	22–150 s	8–45 s	4–25 s	0.5–5 s	0.01–2 s	0.01–0.1 s

Data provided by Airpax Corporation, Power Protection Products.

tions operates from +12 V. Equipment requiring other voltages and polarities has been deployed over the years, for example, +130 Vdc, –130 Vdc, and +48 Vdc for network-controlled payphones (coin phones).

If a site has a mixture of equipment, a separate battery plant may be provided for each voltage or polarity but, depending on the load currents, it may be more economical to use dc–dc converters instead. While voltage conversion is the most common application for dc–dc converters, it is not the only one. Converters may be used to

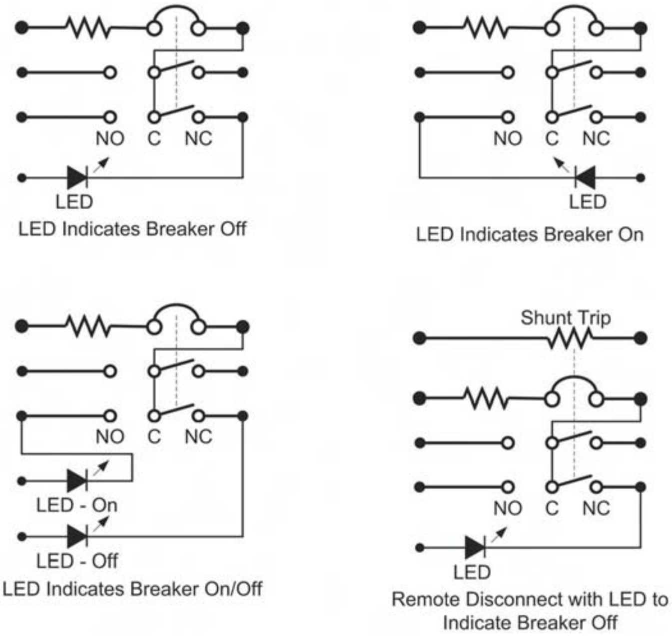
- Change voltage (e.g., from +24 Vdc to –48 Vdc)
- Change polarity (e.g., from +24 Vdc to –24 Vdc)
- Isolate ground systems or reference planes (note: DC–DC converters have been marketed in the telecommunications industry that do not have isolated inputs and outputs and obviously cannot be used for this purpose.)

Table 3.13 Typical Circuit Breaker Resistance and Voltage Drop[a]

Rated Current (A)	DC Resistance (Ω)	Voltage Drop @ 50% Load Factor (V)	Voltage Drop @ 100% Load Factor (V)
1	1.38	0.690	1.380
2	0.371	0.371	0.742
5	0.055	0.138	0.275
10	0.017	0.085	0.017
20	0.006	0.060	0.120
30	0.003	0.045	0.090
50	0.0019	0.048	0.095
100	0.000375	0.019	0.038
150	0.000375	0.028	0.056
200	0.000225	0.023	0.045
225	0.000225	0.025	0.051
250	0.000225	0.028	0.056
400	0.000125	0.025	0.050
600	0.000083	0.025	0.050
800	0.000063	0.025	0.050
1000	0.000050	0.025	0.050
1200	0.000042	0.025	0.050

[a] DC resistances generally have a ±50% tolerance.

Fig. 3.47 Trip control (red push-button on lower left is shown for illustration only as a trip control serves no useful purpose located so close to the disconnect switch or circuit breaker). (Photo courtesy of Electric Equipment & Engineering Company).



LED Indicates Breaker Off

LED Indicates Breaker On

LED Indicates Breaker On/Off

Remote Disconnect with LED to Indicate Breaker Off

Fig. 3.48 Switch and circuit breaker position indication and remote trip. The circuit breaker and switch contacts are shown with the circuit breaker off or tripped.

Table 3.14 Switch and Circuit Breaker State Indicators (Typical)

Configuration	Red	Green	Yellow
No indication			
Disconnected	Off		
Connected—Green		On	
Off–On	Off	On	
Electrically tripped			Tripped
Full status	Off	On	Tripped
Connected—Red	On		
On–Off	On	Off	

- Provide voltage stability
- Compensate for voltage drop
- Relocate power equipment to reduce floor space requirements in the power room
- Optimize voltage

The dc–dc converters in telecommunications applications are similar to switch-mode rectifiers and operate on the same basic principles except that the input rectification stage is not needed (Fig. 3.49). The DC–DC converters use a transformer to isolate the input section from the output section (the input dc is converted to ac, which is coupled through the transformer, and then converted back to dc at the output). This allows a load with one type of grounding system to be isolated from the power system that has another type of grounding system. It also helps to prevent disturbances and electromagnetic interference (EMI) on one side of the converter from being coupled to the other side.

Although the conceptual schematic shows field-effect transistors in the inverter section, other types of semiconductors may be used. One type of dc–dc converter uses a 20-kHz switching rate and power transistors in the inverter section (Fig. 3.50). The trigger circuits control transistors Q1 through Q4. Q1 and Q3 operate as a pair and are turned on simultaneously. When Q1 and Q3 are on, Q2 and Q4, which operate as another pair, are turned off. In the next half-cycle of the switching frequency, Q1 and Q3 are turned off and Q2 and Q4 are turned on. The alternating switching action develops a chopped dc voltage in the primary of transformers T1 and T2, which is coupled to the transformer secondary circuits as a square wave where it is rectified by diodes D1 and D2. Subsequent filter circuits smooth the output and remove ripple and switching noise.

Converters provide a well-regulated output voltage over a wide range of input voltages. For example, a typical 48-V converter used for polarity conversion will hold the output voltage within ±1% (+47.5 to +48.5 V) with a 30% change in input voltage (–42 to –60 V). Some converters operate over an input voltage range of 18 to 72 V.

A converter plant has better voltage regulation than a battery plant during discharge conditions. With a battery plant, the load voltage steadily decreases as the battery discharges, but converters provide fairly good regulation throughout the battery discharge period.

Voltage drop between the battery plant and the load may be reduced by using larger conductors or by using converters to provide voltage compensation. In this situation, the converter regulates the output voltage at the desired value when the voltage drop from the

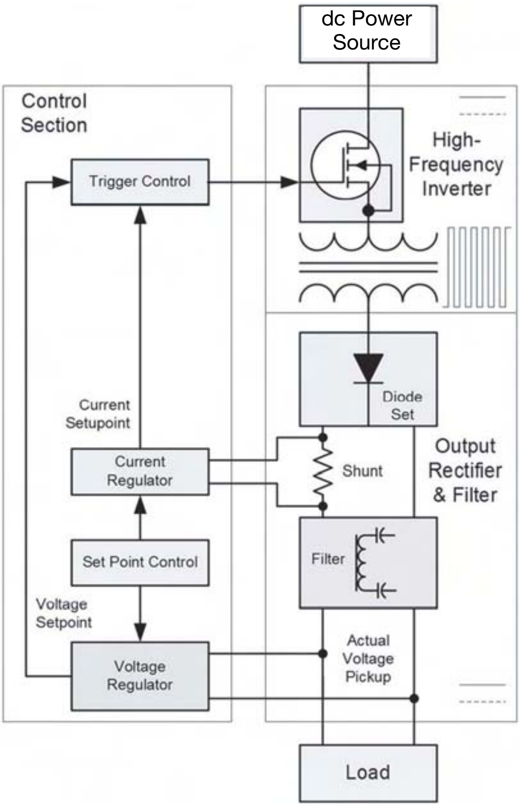


Fig. 3.49 The DC–DC converter conceptual schematic.

battery to the load would otherwise be unacceptable. The converters may be located closer to the load, effectively reducing equipment floor space requirements in the power room and also reducing the conductor size from the converters to the load equipment (assuming that voltage drop and not ampacity is the limiting factor in conductor sizing).

With voltage optimization, the converter output voltage is set to the most desirable operating point of the equipment served. Certain equipment may operate more efficiently at a certain set point voltage or may have increased life or reliability when operated at reduced voltage. Converters with nominal output of 48 V are usually set at 48-V output, whereas 48-V equipment connected to a battery plant normally operates at 52.1 or 54.5 V depending on the battery technology.

Where the load current exceeds some threshold value, usually around 100 to 200 A, the costs of a new converter plant generally will be higher than the costs of a dedicated powerboard and battery plant. Within and above this range, it usually is cheaper to install a dedicated battery plant. The decision to use a battery plant or a converter plant must take into account not only capital recovery costs but also operating costs, including disposal, over the life of the plant. There are many other variables to consider including the availability of floor space, structural requirements for battery plants, and availability and costs of ac distribution for rectifiers.

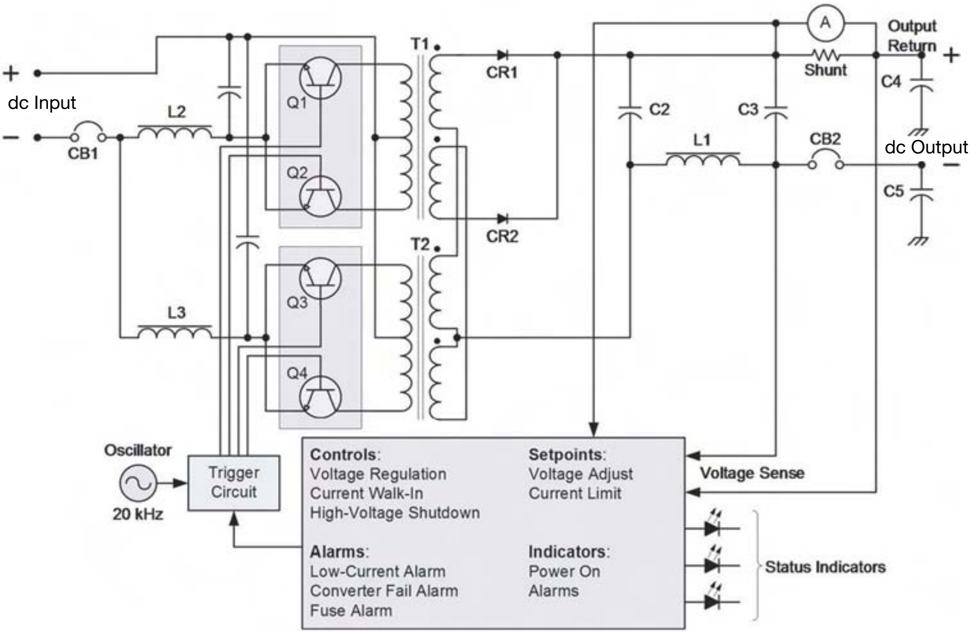


Fig. 3.50 The DC–DC converter schematic showing basic circuit components.

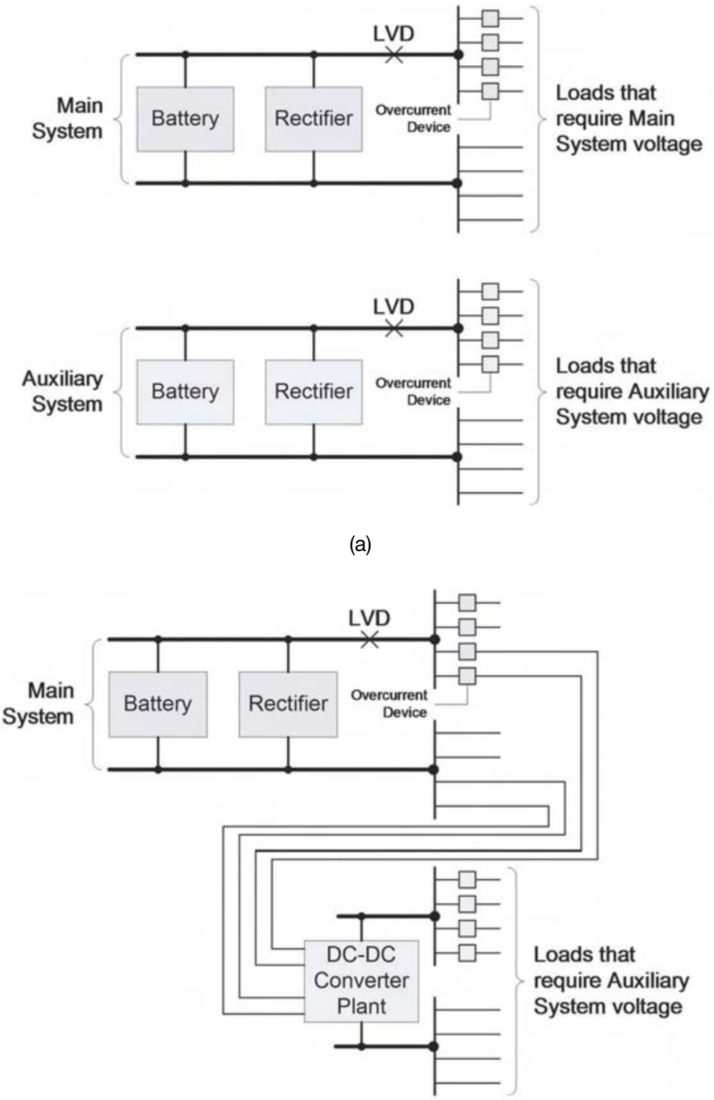
It may be worthwhile to replace an existing battery plant with a converter plant. In this case, the converter plant is connected directly to the existing distribution buses (Fig. 3.51). The charge bus, rectifiers, and battery are eliminated.

The DC–DC converters typically are used in a converter plant assembly with distribution equipment, meters, controls, and alarms dedicated to the converter plant. The standalone application, where a single converter is used that has built-in metering, alarms, and overcurrent protection, is the limiting case of the converter plant. However, single converters seldom are used; instead, converter plants are arranged in a common-bus or split-bus configuration.

With the common-bus configuration the converters and overcurrent device distribution panels are connected to a single common bus (Fig. 3.52). Since the output of converters is limited to 100% of rating, they may not provide enough fault current to open overcurrent devices in the converter distribution bus if those devices are too large. Therefore, a fault in a converter, circuit, or load can disrupt other equipment on the same bus.

The split-bus configuration consists of two common-bus configurations (Fig. 3.53). It reduces the problem with the common bus in that a fault on one of the buses normally will not affect the other bus. The split-bus converter plant lends itself to modern applications in which the load equipment has dual-bus power inputs (A and B). The split-bus configuration is slightly more expensive than the common bus because of the extra bus work, overcurrent protection, and converters. Each bus is shown with *N* converters, which effectively provides 2*N* redundancy. In an alternate configuration, each bus could be equipped with *N* + 1 converters.

The two configurations can be varied according to existing system configuration or re-



(a)

(b)

Fig. 3.51 Replacing a battery plant power system with a DC–DC converter system: (a) before and (b) after.

liability requirements. For example, the converters with their output connected in a split-bus configuration could be powered by a common-bus configuration on their input. Similarly, the common-bus output configuration could be powered by a split bus on their input.

Modern converters use switch-mode power supply technology and have followed the same evolutionary path as rectifiers. Modern converters are modular and have relatively small output ratings (amperes to tens of amperes ranges) compared to older products. A

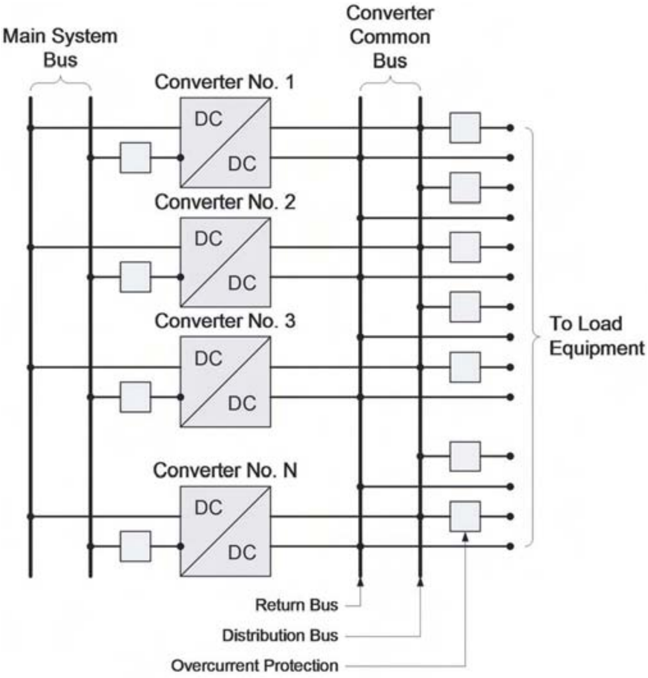


Fig. 3.52 The DC–DC converter common-bus configuration.

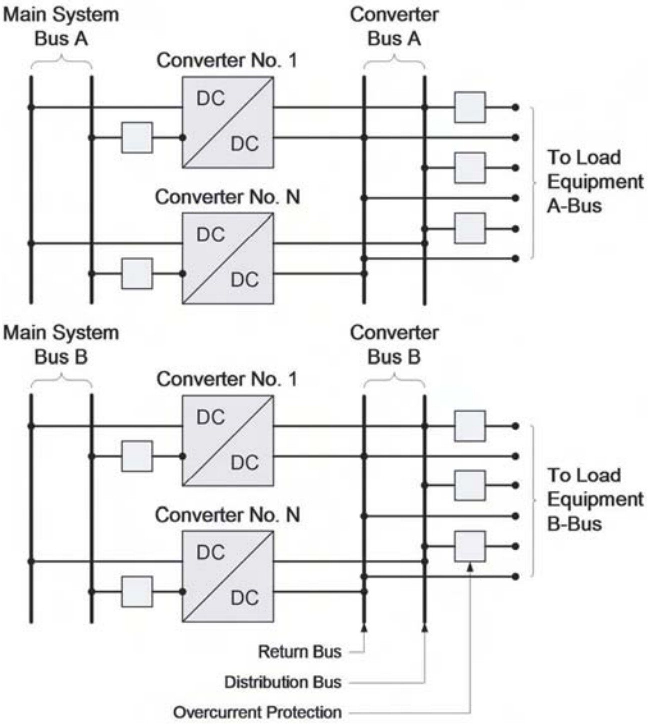


Fig. 3.53 The DC–DC converter split-bus configuration.

large converter plant requires numerous converters, and a dedicated battery plant with rectifiers may be a better alternative.

The DC–DC converters limit their output current, usually to 100% of output rating, by reducing their output voltage when an overcurrent occurs. This also limits their ability to open an overcurrent protective device when a fault occurs. To ensure that overcurrent devices trip under fault conditions, the individual overcurrent devices on the output bus or buses normally are rated no more than one third the total converter output current capacity. For example, if the total converter plant has a 100-A rating, the largest individual overcurrent device would be rated no more than 30 A. The exception is where a single overcurrent device feeds the load, in which case this kind of coordination is not possible.

As with the main dc power system, the output from DC–DC converters and associated systems are referenced to earth ground either through isolated bonding networks or common bonding networks.

3.7.2 Inverters

Some equipment deployed in telecommunications networks operates only on alternating current. If this equipment must operate without any interruption whatsoever or cannot withstand an interruption longer than approximately 50 ms when the primary power source fails, it may be connected to an inverter. Inverters are powered by the main system voltage such as 24 and 48 Vdc. The most common output ac voltage is 120 Vac, one-phase, 60 Hz, although larger loads may require 208 or 240 Vac, one-phase or three-phase, 60 Hz.

The inverter must regulate the ac output voltage within specified tolerances, typically ±5%, over a relatively large range of input voltage. A typical 48-V inverter will meet output specifications from 42- to 56-Vdc input, while 24-V inverters typically meet output specifications from 21- to 28-Vdc input. Another important requirement of inverters used in the telecommunications environment, one that differentiates them from inexpensive consumer inverters, is the requirement that they provide a relatively distortion-free sine wave output voltage waveform.

Inverters add load to the main dc power system and may affect battery reserve times and rectifier system rating. Bus rating also may be affected. It may be more economical to install an uninterruptible power system (UPS) for ac loads (UPS design is beyond the scope of this book).

Three basic inverter configurations have been used (Fig. 3.54):

- Commercial ac primary with inverter standby—also called *passive standby*
- Inverter primary with commercial ac standby—also called *active standby*
- Inverter primary with no standby—also called *continuous operation*

In addition to the basic configurations just described, inverters can be provided in redundant arrangements to guard against individual unit failure (Fig. 3.55). When redundancy is required, the inverters can be configured for parallel or standby operation. With parallel operation, the inverters must have compatible phase synchronization controls so that all units operate in synchronization and in parallel. There is no break or interruption on the ac bus when a unit fails. With standby operation, the redundant inverter is powered but disconnected from the ac output bus by a switch or relay. There typically is a short in-

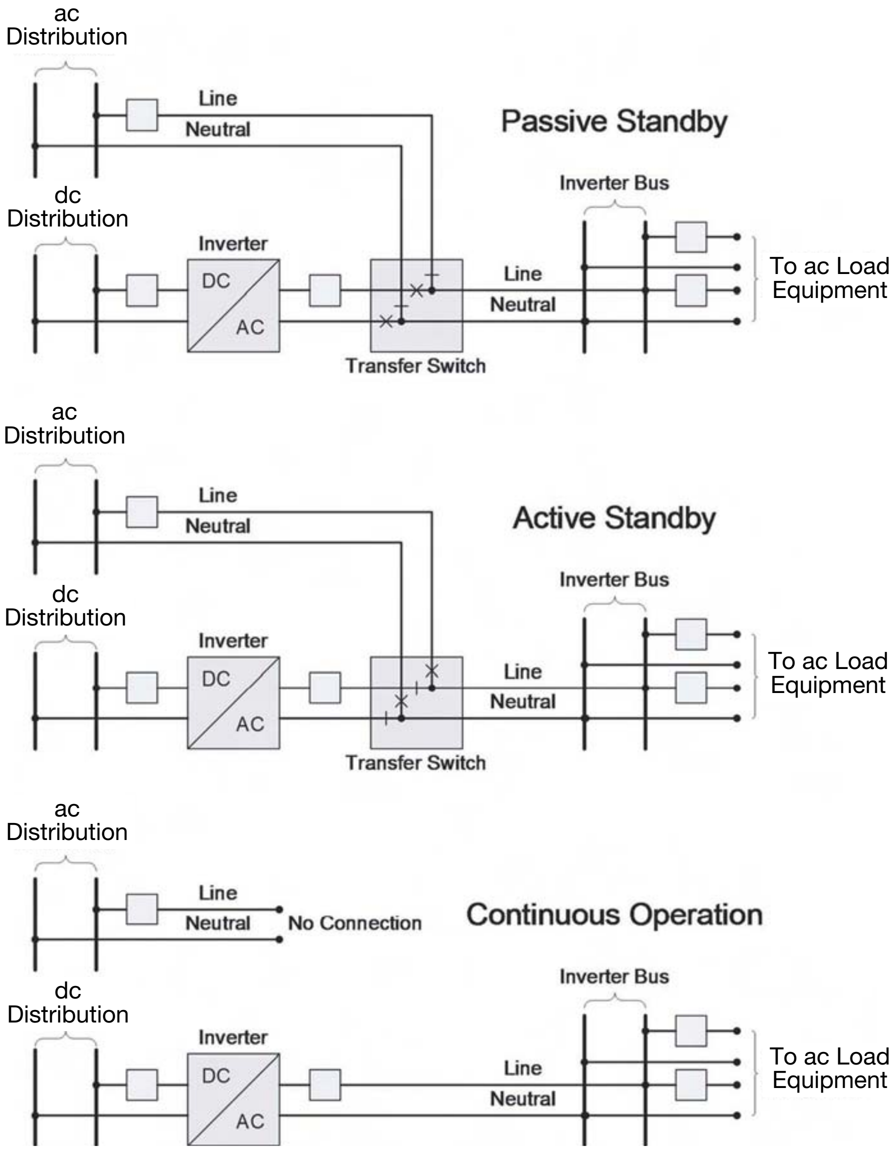


Fig. 3.54 Inverter configurations.

terruption (5 to 50 ms) between the time the failed inverter goes offline and the standby inverter is switched into the circuit.

Figure 3.56 shows a conceptual schematic of an inverter. Several methods are used for inverter output voltage control, including phase angle control, pulse-width control and pulse-frequency control. In the phase-angle switching control method, the outputs of two independent inverter circuits are connected together in one package so that their output voltages add. One of the inverters is controlled by varying the phase of the thyristor trigger pulses so that its output voltage is shifted in phase relative to the output voltage of the

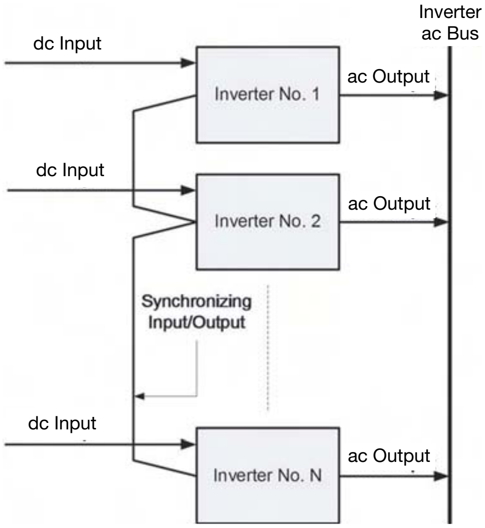


Fig. 3.55 Redundant inverter configuration.

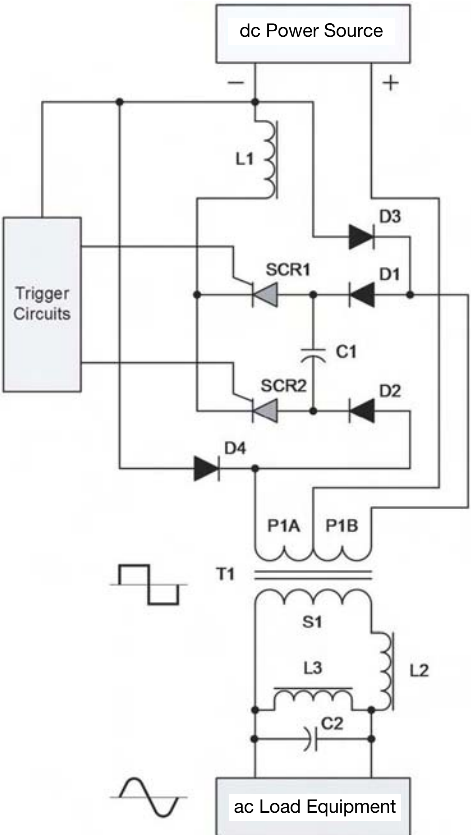


Fig. 3.56 Simplified inverter schematic to illustrate operation.

other inverter. The larger the phase difference between the two inverters, the smaller is the sum of the two voltages. With this type of voltage regulation, the output voltage can be held constant regardless of input voltage or load current variations.

The pulse-width control methods trigger and then turn off the SCRs repeatedly during each cycle of the ac output voltage. In this way, the individual half-waveforms of the output voltage are formed from a number of pulses. By varying the pulse width or pulse repetition frequency, it is possible to regulate the output voltage.

A center-tap circuit is used to achieve the inversion, or periodic reversal, of the direct voltage input. The trigger control alternately triggers the two thyristors SCR1 and SCR2 into conduction, which allows the input current to flow alternately through the transformers two primary windings P1A and P1B. The alternating current in the primary is coupled to the secondary winding S1 and appears as a square wave voltage at the required fundamental frequency (60 Hz). The output is filtered by L2, L3, and C2 so that the inverter output is a relatively clean (undistorted) sine wave. One of the advantages of having a transformer separating the input and output is the isolation it provides, and the output circuit may be referenced to a different grounding system than the input if desired.

When SCRs are used in ac circuits, they turn off when the alternating voltage across them goes through a zero crossing. In dc circuits, however, a quenching capacitor must be used in the circuit to turn off the thyristors (C1).

Pulse-width and pulse-frequency control are used in the inverter shown conceptually in Figure 3.57.

Circuit Description The dc input is supplied through circuit breaker CB1 to the inverter circuits. Capacitor C1 filters the input to prevent coupling of inverter noise back to the input circuit. The trigger circuit generates pulses to turn on thyristors SCR1 and SCR2. Two separate pulse trains are generated at a basic frequency of 60 Hz and 180° out of phase with each other. When SCR1 is triggered and starts to conduct, full input voltage

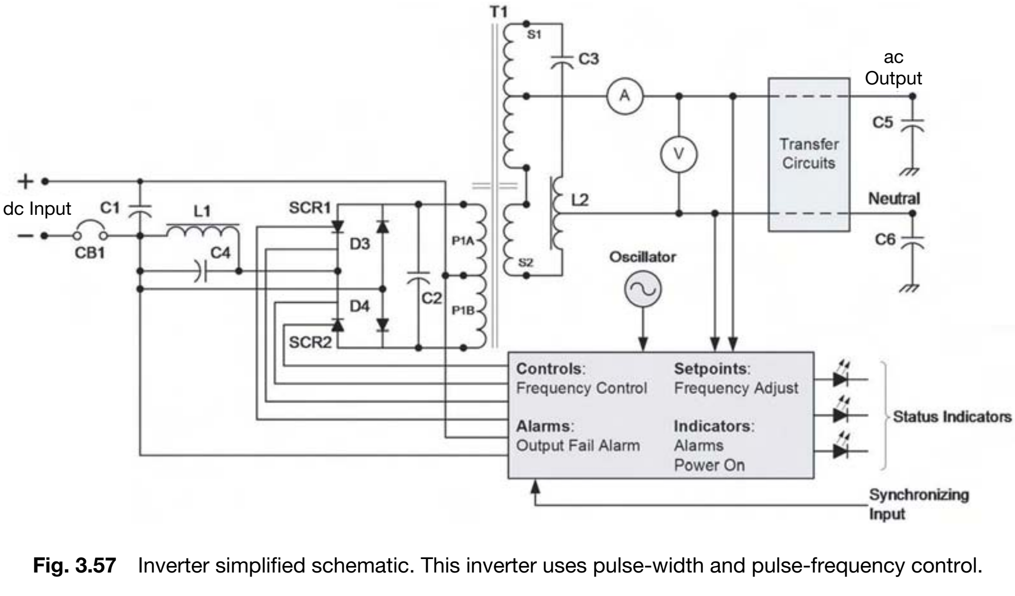


Fig. 3.57 Inverter simplified schematic. This inverter uses pulse-width and pulse-frequency control.

is applied across ferroresonant transformer T1 primary windings P1A. Primary windings P1A and P1B act as a step-up autotransformer and apply twice the input voltage across capacitor C2.

At the proper time, the trigger circuit applies pulses of opposite phase to SCR2 causing it to conduct. At this time, both thyristors are turned on and C2 is shorted out. C2 discharges through SCR2 and current attempts to flow in reverse through SCR1 causing it to turn off. Since SCR2 still is conducting, full input voltage is applied across primary winding P1B. Through autotransformer action, twice the input voltage is applied across C2 but the voltage has opposite polarity to the previous cycle. At the proper time, the trigger circuits turn on SCR1 causing it to conduct and discharge C2. When C2 discharges, the reverse current turns off SCR2. This cycle repeats itself at the frequency determined by the control circuits (60 Hz). The changing voltage polarity appears as a square wave across the primary windings of T1.

Inductor L1 and capacitor C2 form a resonant circuit that provides a commutating pulse to turn off the conducting thyristor. Capacitor C4 prevents high-frequency oscillation, while diodes D3 and D4 prevent the voltage across T1 primary from exceeding the input voltage. These diodes also compensate for leading and lagging power factor in the inverter load circuits by providing a return path to the dc input circuit for reactive currents.

The square wave input to the transformer is coupled to the secondary windings S1 and S2 and filtered by the transformer's inherent inductance giving a distorted sine wave at the output. The transformer secondary windings inductances and capacitor C3 form a secondary resonant circuit that helps to maintain transformer core saturation and output voltage regulation even though the load or input voltage may change.

If there is an output overload or short circuit, the field in the core will collapse because the energy drained from the ferroresonant circuit exceeds what is required to maintain core saturation. The transformer output voltage decreases and limits the output current to a safe value.

Inductor L2 limits harmonic currents at the output of the transformer and thus limits output voltage waveform distortion. Capacitors C5 and C6 reduce electromagnetic interference by suppressing high-frequency currents at the inverter output.

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CHAPTER 4

TELECOMMUNICATIONS BATTERIES

This chapter provides a detailed description of the components that make up a battery and what may be expected from them in telecommunications applications. Battery sizing and design are covered in Chapter 5 and battery maintenance and installation considerations are covered in Chapter 6.

4.1 BATTERIES AND CELLS

4.1.1 Types

Batteries are the energy storage component in a telecommunications power system. The basic battery technology most often used is lead–acid.[1] Two types are used: *vented* lead–acid (VLA) and *valve-regulated* lead–acid (VRLA). These terms indicate the method used to handle the gases that are produced during operation. The VLA cell (also called *flooded* or *wet* cell) allows the gases to freely escape from the cell container while the VRLA limits the amount of gases that escape except under abnormal conditions. Both types are categorized as *secondary* batteries, which indicates they are rechargeable (as opposed to *primary* batteries, which are not rechargeable and are not used in telecommunications applications) and *stationary* by nature of their fixed, nonvehicular installation.

A battery stores electric energy and delivers it to the load on demand. Rectifiers (chargers) recharge the battery after a discharge and provide energy to loads during normal operation. Also, during normal operation, the rectifiers provide float current to the battery to make up for losses due to the self-discharge of the cells in the battery. A telecommunications battery spends most of its life in the fully charged state. Depending on the length of time that rectifiers are not available due to ac power source failure, the discharge portion of the cycle could last from a few minutes to 12 h or more. The battery discharges at a rate determined by the reserve time and discharge current. Upon restoration of the rectifier's ac power source, a fully discharged battery recharges in (typically) 8 to 24 h and then floats at a constant voltage until the next power source failure.

[1] Lithium–metal polymer (LMP) and nickel–cadmium (NiCd) batteries are used in some small-capacity applications.

4.1.2 Cell Configurations

A cell is the basic electrochemical unit in a battery. At a minimum a cell consists of two electrodes immersed in an electrolyte, in a container (or jar). The cell converts chemical energy into electric energy by an electrochemical reduction–oxidation (*redox*) or decomposition–recomposition process, which is more fully described in later paragraphs. Reversing the *redox* process recharges the cell.

Batteries used in telecommunications usually consist of 12 cells (24 V nominal system voltage) or 24 cells (48 V) connected in series.[2] Each lead–acid cell has a nominal voltage of 2 V. The series cell combination is called a *battery string* (Fig. 4.1). Battery strings are connected in parallel to provide higher capacity (Fig. 4.2). In smaller cells sizes, more than one cell may be combined in a package called a monobloc (also called monoblock). The cells in a monobloc may be connected in parallel to increase capacity or in series to increase voltage. A typical monobloc has three cells in series and a nominal voltage of 6 V, although six cells in series for a nominal voltage of 12 V also are common. A *battery system* consists of one or more battery strings in parallel and associated mounting frames or racks.

Battery capacity is measured in units of ampere-hours (Ah), which sometimes is denoted as “C” in manufacturer’s literature. Ampere-hours indicate the load current measured in amperes that may be drawn from the battery over a time period measured in hours.[3] For example, if a 12-cell battery is discharged to an end voltage of 21.0 V (1.75 V/cell) by a load of 12 A in 8 h, the battery capacity supplied to the load *under those conditions* is 12 A × 8 h = 96 Ah. The stated capacity has to be qualified with a particular end voltage, battery temperature, nominal full-charge electrolyte specific gravity, and discharge rate because battery capacity varies with each of these factors (this relationship is described in more detail later).

Vented lead–acid cells range in capacity from about 50 to 8000 Ah. Figure 4.3 shows line drawings of two sizes: 200 and 8000 Ah. VRLA cells range in capacity from much less than 50 Ah to around 2000 Ah. Examples of two VRLA cells are shown in Figure 4.4. VLA cells always are mounted with the vent and terminal posts at the top while most VRLA cells may be mounted in any position but usually vertically with posts at the top or horizontally with posts at the side. Some larger VRLA absorbed glass mat (AGM) cells must be mounted horizontally for proper operation.

4.1.3 Active Components

Cells have three active components (Fig. 4.5)—negative electrode (or plate, which is the terminology used in this book) of almost pure sponge lead (Pb), positive plate of pasted lead dioxide (PbO_2, also called lead peroxide), and electrolyte of water-diluted sulfuric acid (H_2SO_4). The plates are built from lead alloy in the form of a grid frame, which not only conducts the electrical current but also holds the active materials. The active materials are made from lead oxide mixed into a paste with electrolyte and water, pasted into the grids, and allowed to dry. Cells for telecommunications batteries generally are assembled and placed in the container or jar and filled with electrolyte. Current is then forced

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[2] Some 48-V installations may use 23 cells because of load or power equipment limitations, and other cell counts may be found in older installations. Also, higher voltages, such as 130 V, exist in older telecommunication systems. These systems consist of 60 to 65 cells in series, although other cell counts have been used.

[3] A charge of 1 Ah is equivalent to 3600 coulombs (C).

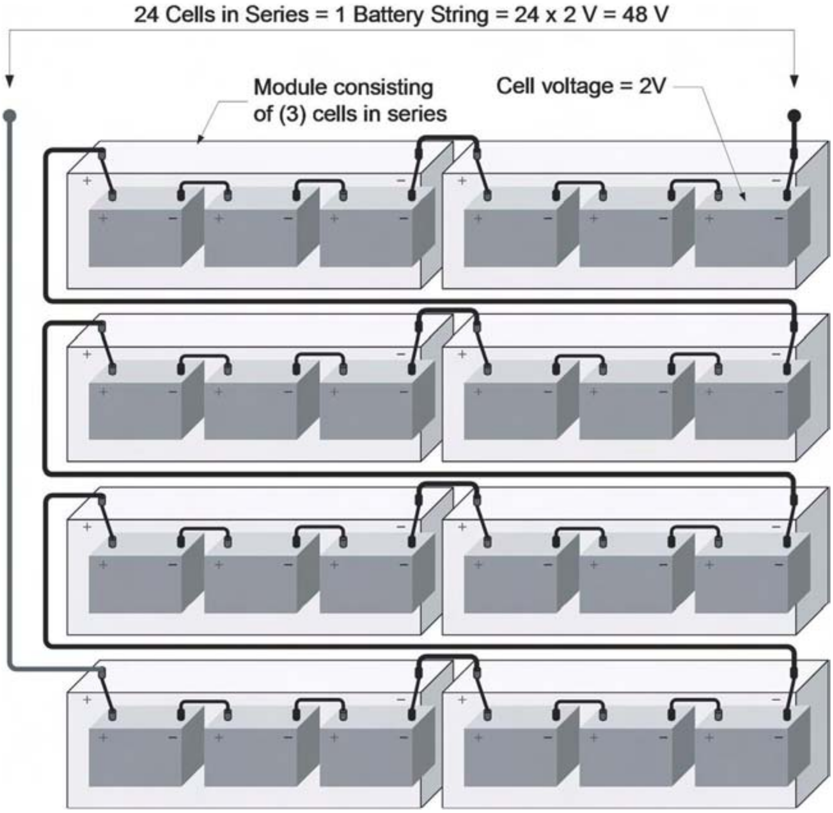

Fig. 4.1 Series connection of 24 cells to form a 48-V battery string. If the capacity of each cell is 100 Ah, the capacity of the series string is 100 Ah. In this illustration, there are eight modules consisting of three cells each.

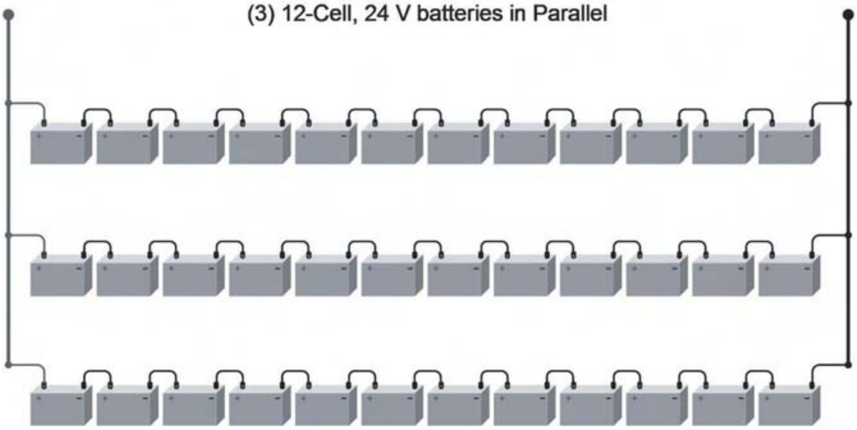

Fig. 4.2 Parallel connection of three 24-V battery strings to increase capacity. If each string is rated 100 Ah, the capacity of the parallel combination is 300 Ah.

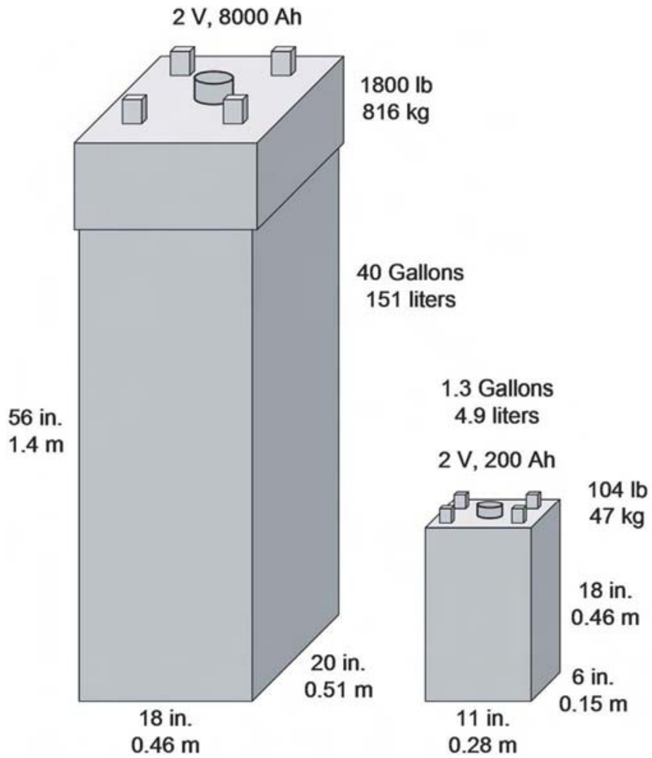

Fig. 4.3 Examples of VLA cells. The flame arrester vent is in the top-middle of the cells and each cell has four terminal posts.

through the plates to form them electrochemically into the negative and positive plates. The final step is to test the cells prior to shipment and service. The negative plate is a gray metallic lead color while the lead dioxide positive plate is a chocolate-brown color.

In some situations, it is desirable to assemble, ship, and then store VLA cells in a dry condition (no electrolyte) for some time prior to service. Manufacturers refer to this as a “dry-charged” battery. In this case, the cells are built as already described except that the plates are formed in tanks and then dried before being assembled. Once assembled the plates are placed in the container (jar) without any electrolyte. The cells are sealed to keep out air and moisture and shipped to the storage site. The cells then may be stored in a cool, dry location for as long as 2 years. Some manufacturers also supply moist-charged cells. Just prior to being placed in service, the cells are filled with electrolyte and fully charged using elevated (activation) voltage. Although the manufacturer will provide the correct specific gravity electrolyte, it can be mixed on-site if desired. If mixed on-site, the specific gravity normally is mixed to about 10 points (0.010) lower than the fully charged specific gravity. For example, if the final specific gravity should be 1.215, the electrolyte would be mixed to 1.205 before it is added to the cells.

Cells have more than one positive plate and more than one negative plate. The plates of a given polarity are connected in parallel (Fig. 4.6). There may be an even number of plates, giving an equal number of positive and negative plates or, as is most often the

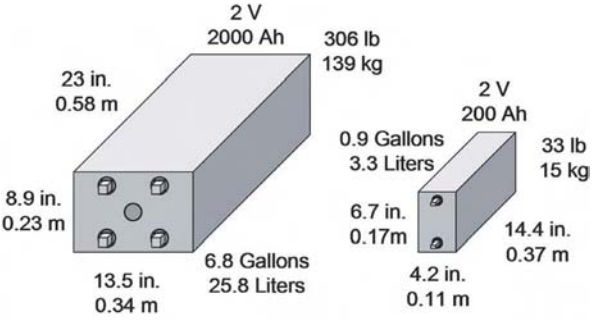

Fig. 4.4 Examples of VRLA cells. Depending on the cell dimensions, one to six cells may be mounted in a steel frame to form a module. Compare the size and weight of the VRLA cells to the VLA cells in the previous figure.

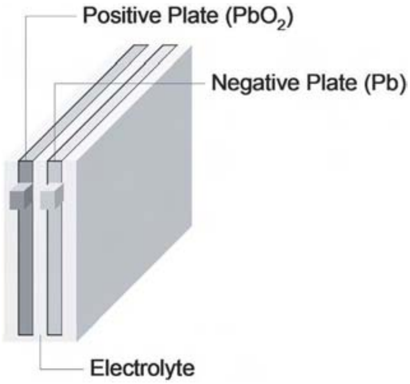

Fig. 4.5 Cell active components.

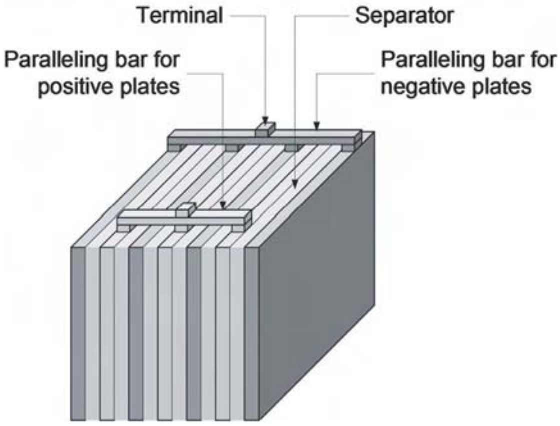

Fig. 4.6 Multiplate cell.

case, odd number, giving one more negative plate than positive. If odd, the number of positive plates can be calculated from

$$\text{Positives} = \frac{\text{Total} - 1}{2} \tag{4.1}$$

Example 4.1 An 8000-Ah cell has a total of 41 plates. Determine the number of positive plates.

Solution The number of positive plates is (41 – 1)/2 = 20.

4.1.4 Electrochemistry

The overall chemical reaction from the charged state to discharged state and from the discharged state to the charged state is shown in (4.2). These reactions apply to both VLA and VRLA cells.

$$\mathrm{Pb} + \mathrm{PbO_2} + 2\mathrm{H_2SO_4} \;\underset{\leftarrow\,\text{Charge}}{\overset{\text{Discharge}\,\rightarrow}{\overline{\hspace{5em}}}}\; 2\mathrm{PbSO_4} + 2\mathrm{H_2O} \tag{4.2}$$

where H_2O = water
H_2SO_4 = sulfuric acid
Pb = lead (negative plate)
PbO_2 = lead dioxide (positive plate)
$PbSO_4$ = lead sulfate

During discharge, the lead in the negative plate partially dissolves in the sulfuric acid and goes into a solution state. When load current flows through the battery on discharge, ionization occurs in which each lead atom loses two electrons as shown in (4.3):[4]

$$\mathrm{Pb} \rightarrow \mathrm{Pb}^{2+} + 2e^- \tag{4.3}$$

where Pb^{2+} indicates ionized lead and e^- indicates a free electron.

The electrons flow through the external load circuit from the negative plate to the positive plate (Fig. 4.7). The positive plate accepts the electrons from the load during discharge as the plate is reduced. The electrolyte completes the internal battery circuit by furnishing ions and, thus, a conductive path between the negative and positive plates. A microporous plate separator prevents the positive and negative plates from shorting out while allowing ions to flow from plate to plate through the electrolyte.

The lead atom in the positive plate absorbs the two electrons as shown in (4.4):

$$\mathrm{Pb}^{4+} + 2e^- \rightarrow \mathrm{Pb}^{2+} \tag{4.4}$$

where Pb^{4+} indicates ionized lead (short four electrons) in the lead dioxide positive plate and e^- indicates a free electron flowing from the negative plate through the load.

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[4] An ion is an atom or group of atoms in which the number of electrons is different from the number of protons and thus having a net positive or negative charge.

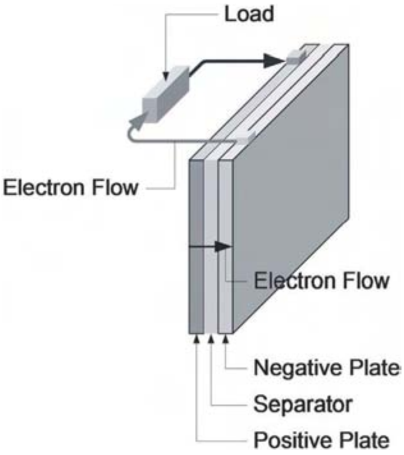

Fig. 4.7 Cell discharge circuit.

The reduction (decomposition) at the positive plate breaks the lead dioxide molecule into Pb^{2+} and O_2. While these reactions are taking place, the sulfuric acid molecule (H_2SO_4) breaks into hydrogen ions (H^+) and sulfate ions (SO_4^{2-}). The H^+ ions from the sulfuric acid and the O_2 from the lead dioxide unite and form water (H_2O) as shown in (4.5):

$$4H^+ + PbO_2 + 2e^- \rightarrow Pb^{2+} + 2H_2O \tag{4.5}$$

The lead ions at the negative and positive plates from (4.3) and (4.4) unite with the sulfate ions to form lead sulfate as shown in (4.6)

$$Pb^{2+} + SO_4^{2-} \rightarrow PbSO_4 \tag{4.6}$$

The chemical reactions (4.3) and (4.6) at the negative plate combine as shown in (4.7):

$$Pb + SO_4^{2-} \rightarrow 2e^- + PbSO_4 \tag{4.7}$$

Similarly, the reactions (4.5) and (4.6) at the positive plate combine as shown in (4.8):

$$PbO_2 + 2e^- \rightarrow PbSO_4 + 2H_2O \tag{4.8}$$

As a final check, (4.7) and (4.8) may be combined to give the discharge direction shown in (4.2). The electrolyte acid concentration is reduced as the battery discharges. The electrolyte in a fully discharged lead–acid battery has a specific gravity of about 1.065 to 1.100.

When the cell is recharged, the chemical processes just described are reversed. Rectifiers force a current into the cell in the opposite direction by providing a voltage source greater than the cell. At the positive plate, the water and lead sulfate break into lead dioxide, hydrogen ions, sulfate ions, and two free electrons as shown in (4.9):

$$2H_2O + PbSO_4 \rightarrow PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \tag{4.9}$$

The hydrogen ions and sulfate ions combine (the action of recomposition) to form sulfuric acid, and the negative plate gains the two electrons lost by the positive plate. Therefore, the lead atoms in the lead sulfate at the negative plate get back their two electrons and change back into plain lead as shown in (4.10):

$$PbSO_4 + 2e^- \rightarrow Pb + SO_4^{2-} \tag{4.10}$$

Reactions (4.9) and (4.10) combine as shown in (4.11), which is identical to the charge direction shown in (4.2):

$$2H_2O + 2PbSO_4 \rightarrow Pb + PbO_2 + 2H_2SO_4 \tag{4.11}$$

As a cell approaches full charge, it cannot absorb all the energy from the charging current, and the excess energy dissociates water by electrolysis into its components hydrogen and oxygen. The water ionizes slightly into hydrogen ions (H^+) and hydroxyl ions (OH^-). The positive hydrogen ions are attracted to the negative plate, where they receive an electron and become a hydrogen atom. Each hydrogen atom unites with another hydrogen atom to form a molecule of hydrogen gas as shown in (4.12):

$$2H^+ + 2e^- \rightarrow H_2 \tag{4.12}$$

The hydroxyl ions at the positive plate lose four electrons and break into water molecules and oxygen gas molecules as shown in (4.13):

$$4OH^- - 4e^- \rightarrow 2H_2O + O_2 \tag{4.13}$$

Reactions (4.12) and (4.13) combine to provide water electrolysis as shown in (4.14):

$$2H_2O \rightarrow 2H_2 + O_2 \tag{4.14}$$

Once the cell reaches full charge, the charge voltage remains constant. The charge voltage is the recommended float voltage for the battery, and the current decreases to a float value. The energy from the float current is consumed by continued electrolysis and by internal resistance losses.

The gassing reactions above indicate the evolution of hydrogen (H) and oxygen (O) in a ratio of 2 : 1. For every 1 Ah of overcharge, about 0.73 liters (0.026 ft^3) of gas are produced of which 0.49 liters (0.017 ft^3) are hydrogen and 0.24 liters (0.0085 ft^3) are oxygen. The open vent on a VLA cell allows the gases to escape. The electrolysis reduces the amount of water in the electrolyte, which effectively raises the specific gravity and drops the electrolyte level. The water loss must be replaced regularly to prevent the electrolyte level in the cells from dropping to the point that the plates will become exposed to air and damaged. Gas bubbles may be seen clinging to the plates and bubbling to the surface in cells with transparent plastic containers. The negative plates will have twice as many (hydrogen) bubbles as the (oxygen) bubbles at the positive plates.[5]

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[5] It is the incorrect and poor practice of some technicians to rap the cell containers with their knuckles to break the bubbles loose. However, the bubbles are part of the natural chemical reactions and should be left to break loose on their own.

A VRLA cell operates on the same electrochemical basis as the VLA cell but depends on the recombination of oxygen and hydrogen during overcharge. In a recombinant cell the same electrolysis takes place as shown in (4.14). The oxygen that is evolved at the positive plate diffuses through the plate separators and reacts with the negative plate to produce lead oxide (4.15). This causes a slight depolarization (reduction in the overvoltage required to drive the electrochemical process) and inhibits the further release of hydrogen, (4.16) and (4.17). The lead oxide reduces to lead sulfate (4.18), which on further charge goes to lead and sulfuric acid (4.19). The result is no net loss of oxygen or hydrogen (or water), although some loss does occur since the recombination reactions are not 100% efficient:

$$2Pb + O_2 \xrightarrow{\text{Overcharge}} 2PbO \qquad \text{(initial reaction)} \qquad (4.15)$$

$$4H^+ + 4e^- \xrightarrow{\text{Overcharge}} 2H_2 \qquad \text{(hydrogen evolution at negative plate)} \qquad (4.16)$$

$$O_2 + 4H^+ + 4e^- \xrightarrow{\text{Overcharge}} 2H_2O \qquad \text{[oxygen reduction (water recapture)]} \qquad (4.17)$$

$$2PbO + 2H_2SO_4 \xrightarrow{\text{Overcharge}} 2PbSO_4 + 2H_2O \qquad \text{(intermediate reaction)} \qquad (4.18)$$

$$2PbSO_4 + 4H^+ + 4e^- \xrightarrow{\text{Overcharge}} 2Pb + 2H_2SO_4 \qquad \text{(final reaction)} \qquad (4.19)$$

Under conditions of gross overcharge, such as when a battery string has one or more shorted cells or if rectifiers are misadjusted, more than normal float current flows into the cell. In this case, not all oxygen and hydrogen is recombined and the gas pressure within the cell builds up. To prevent an explosion due to overpressure, all VRLA cells are equipped with a self-resealing pressure relief valve to vent the gases and reduce the internal pressure. While the risk of dry-out of a properly installed and operated VRLA cell is small, electrolyte still can be lost through a failed vent, post seal, cover seal, or a crack in the container or by slow migration of water vapor through the cell container itself.

Figure 4.8 is a more detailed illustration of a battery throughout a full cycle—fully charged (floating), discharging, fully discharged, and charging. When in the fully charged state, the cells contain maximum lead in the negative plate, maximum lead dioxide in the positive plate, and minimum lead sulfate (upper left). The acid concentration in the electrolyte is at its maximum level (maximum sulfuric acid and minimum water). During discharge, electron current flows from the negative plate through the load to the positive plate. As the battery discharges, the amount of metallic lead in the positive and negative plates decreases and lead sulfate increases (upper right). At the same time, the electrolyte acid concentration decreases (amount of sulfuric acid decreases and the amount of water increases). When the battery is fully discharged, the lead sulfate is maximum and lead in the plates in minimum (lower right). The acid concentration is at its minimum level (minimum sulfuric acid and maximum water). When the battery recharges, current flows from the rectifiers into the negative plate, through the battery, and out the positive plate. The lead sulfate is converted to lead at the negative plate and lead dioxide at the positive plate (lower left). During recharge the acid concentration increases (amount of water decreases and amount of sulfuric acid increases).

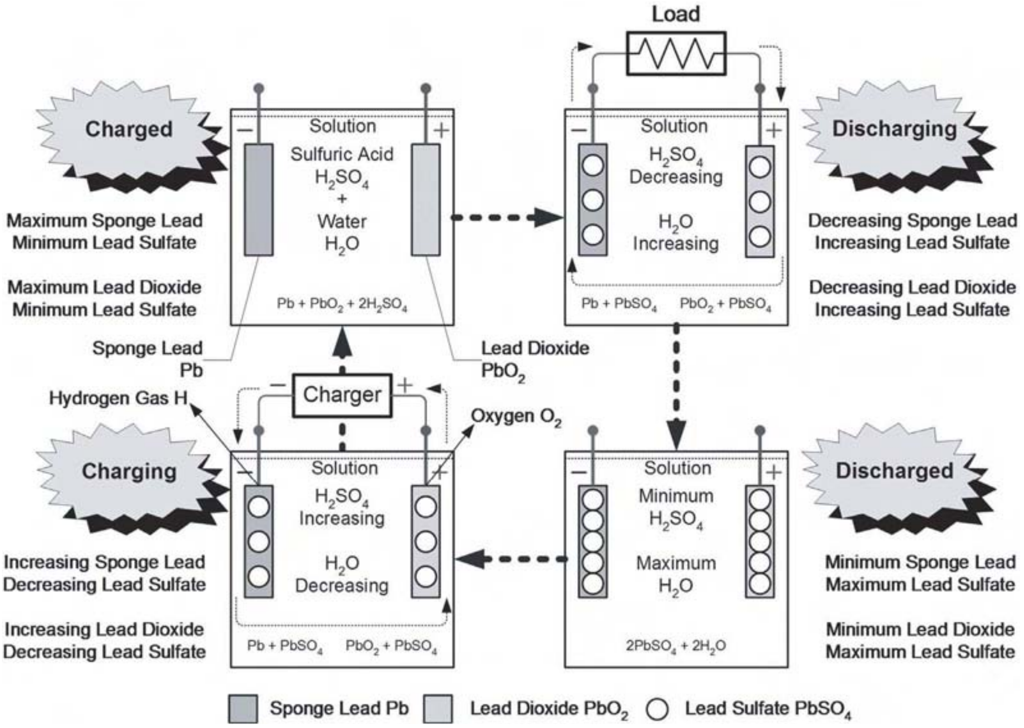

Fig. 4.8 Battery cycle.

Cells also consist of a separator and container (including lid or cover) and other packaging components. The separator physically separates and electrically insulates the positive and negative plates from each other but allows transport of ions between plates during charge and discharge. Separator failure is one cell failure mechanism—in this case, the two plates short out and discharge the cell. In lead–acid batteries, the separator is a microporous rubber or fiber material (older cells used glass or even wood). The separator is not required for electrochemical operation, but it absorbs part or the entire electrolyte, keeping it close to the plate and increasing cell efficiency. The separator used in VRLA cells is a highly porous, absorbent, microfiberglass mat and plays a doubly important role by soaking up the electrolyte and immobilizing it. Electrolyte normally cannot leak out of the VRLA cell unless it is forced out or oozes out under pressure during abnormal operation.

Regularly discharging and charging a cell works active material loose from the positive plates. This material settles to the bottom of the cell (Fig. 4.9), so containers must have extra space at the bottom for collection; otherwise, too much sediment will pile up and short the plates. Separators have a smooth side next to the negative plate and a grooved side (backweb) next to the positive plate. The grooved side is next to the positive plate to allow gas that is formed to escape and any loosened active material to fall to the bottom of the container. Most VLA cells used in telecommunications applications have a fiberglass mat attached to the separator backweb to prevent active material from shedding from the positive plate. The mat also keeps a ready supply of electrolyte near the positive plates.

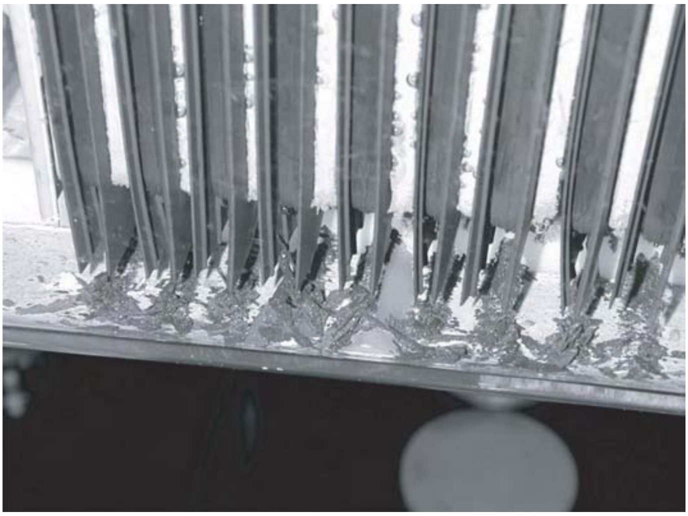

Fig. 4.9 Sediment at the bottom of a cell. (Photo courtesy of M.W. Migliaro.)

Unlike VLA cells and gelled electrolyte VRLA cells, which have excess electrolyte to compensate for water loss during operation, absorbed electrolyte VRLA cells contain only a minimum amount of electrolyte. For example, a typical 1400-Ah VLA cell has approximately 13 gal of electrolyte, but a typical 1400-Ah VRLA cell has only 4.1 gal. Absorbed electrolyte VRLA cells often are referred to as “electrolyte starved.” As a result, the container for absorbed electrolyte VRLA cells is much more compact than VLA for a given ampere-hour capacity, and they can be mounted in any position. VLA cells and gelled electrolyte VRLA cells are mounted with their vent at the top to prevent spilling.

4.1.5 Cell Containers

Various materials are used in the cell containers. Most of the original lead–antimony telecommunications batteries used a hard rubber and were flexible enough that plate growth or mishandling seldom cracked the container and allowed it to leak; glass jars were used in some smaller batteries. Except in the largest sizes, lead–calcium and modern lead–antimony cells generally use a transparent plastic container made from styrene, polycarbonate, or flame-retardant polyvinyl chloride (PVC). Early lead–calcium cell containers were sensitive to stress caused by excessive plate growth and subsequently cracked and leaked, leading to a large number of battery fires. These packaging problems largely were solved by controlling the calcium to better control plate growth.

The limiting oxygen index, or LOI, is used to measure the relative flame retardant characteristic of a material. LOI is the minimum concentration of oxygen in an oxygen–nitrogen mixture that will support continued combustion of a particular material once the flame source is removed. Air is 21% oxygen so any material with an LOI of 21% or less will burn readily in air. A higher value indicates less flammability. Typically, a polycarbonate or flame-retardant PVC material with an LOI > 28% is used in cells where flame-retardant properties are required, such as in all central office applications. It should be noted that many standard catalog cells are not flame-retardant (e.g., styrene containers do not have LOI > 28%) and, if a flame-retardant container is needed, it must be specified in the battery purchase specification and costs extra.

Large hard rubber cells (4000 Ah and larger) sit directly on the battery room floor and have a steel angle frame built around them in seismic applications. Small to medium cells with plastic cases (above 100 to 3900 Ah) are mounted on battery racks, usually two tiers high (Fig. 4.10), while the smallest cells (100 Ah and smaller) may be rack mounted or installed on shelves in a frame or relay rack or cabinet (Fig. 4.11).

Except in some very small installations, the frames, racks, and shelves are conductive steel and, for safety purposes, are bonded to ground. Also, concrete floors on which the racks or cells sit are conductive. Any electrolyte leakage usually leads to an electrical path to ground and possibly arcing, which can ignite the cell containers. Therefore, much effort has gone into perfecting container and cover materials and posts and seals to prevent leakage. The potential for acid leaks is one of the reasons VLA batteries seldom are installed in network equipment rooms and, instead, almost always are installed in separate rooms.

Vented lead–acid batteries have been used in their present form for about 100 years. VRLA batteries did not find widespread use in telecommunications until the mid-1980s. The majority of installations today use VRLA technology, and almost all outside plant equipment and remote telecommunications enclosures such as access nodes and digital loop carrier remote terminals use VRLA technology (NiCd batteries and a limited amount of alternate technologies, such as lithium–metal polymer, are used in some applications). VRLA batteries have been given a number of different names, mainly by manufacturers eager to differentiate their products. Some names are "maintenance free" (a definite misnomer), SLA (sealed lead–acid), AGM (absorbent glass mat), "gel-cell," suspended or absorbed electrolyte, and others.

Fig. 4.10 Medium VLA clear plastic 24-cell battery in seismic zone 4 rack.

Fig. 4.11 Small 6-cell VRLA monoblocs on a frame-mounted tray (four monoblocs visible in front and four in back in middle-bottom of picture). (Photo courtesy of M.W. Migliaro.)

Roughly 60% of the cell weight is lead plates and lead components. Although pure lead is the ideal plate material, it is too soft except in certain battery types such as the round cell designed by the AT&T Bell System (Fig. 4.12).[6] For modern stationary battery applications, adding antimony (approximately 4% by weight, chemical element Sb) hardens the lead. Other variations also have been used, including 1 to 2% antimony with some selenium to act as a grain refiner. These are called "lead–selenium" or "low-antimony" cells. Another lead-hardening method uses calcium (approximately 0.03 to 0.05% by weight, chemical element Ca). Tin also is used (approximately 0.8% by weight, chemical element Sn). Most modern VLA installations use what are called lead–calcium cells, although these cells actually use a tertiary alloy consisting of lead, calcium, and tin. The tin provides additional corrosion resistance for the plate grid. Also, some manufacturers add aluminum to the lead–calcium–tin alloys to better control calcium content. Very little of the aluminum winds up in the final grid, but it is used to provide a layer on top of the molten alloy during casting to minimize oxidation and subsequent loss of calcium. VRLA cells use lead–calcium or lead–tin, although at least one manufacturer uses a patented alloy with antimony.

The first lead–calcium cells were deployed in the telecommunications network around 1950, but it took about 20 years to solve all the problems associated with them. Lead–calcium is viewed as a superior material combination mainly because the water consumed by the lead–calcium VLA battery is much smaller (by a factor or 1/10 to 1/20), as is the float current when compared to lead–antimony. The reduction in water consumption leads di-

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[6] The round cell uses pure lead plates, which minimize plate corrosion and growth, and a positive plate paste that provides additional mechanical stability. The round shape minimizes the stress effects of plate growth that does occur. The plates are supported in a unique structure that relies less on the plates themselves. The original design life of the round cell was 30 years, although current marketing materials claim 70-year life. Because the round cell uses different manufacturing processes and materials than conventional stationary cells, the costs are much higher (approximately 2 to 2.5 times for a given ampere-hour capacity).

Fig. 4.12 Battery consisting of round cells and seismic zone 4 rack installed in southeastern Alaska. Round cells are not very space efficient, but they have a relatively long life when properly operated and maintained.

rectly to reduced maintenance costs because the electrolyte level in the battery does not need to be checked and water replenished as often. There is very little water loss from a VRLA cell because of the recombination reactions that take place in the cell while it is under positive pressure (i.e., regulated by its valve).

4.1.6 VLA and VRLA Comparison

VLA Advantages

- Container usually is transparent so visual examination is possible.
- Longer life.
- Not subject to thermal runaway.

VLA Disadvantages

- :Requires regular electrolyte maintenance (water addition).
- Releases hydrogen gas during charging.
- Can be installed only in one position (vent at top).
- Racks must be specially designed for seismic applications.
- Requires flame arrester vent.
- Requires spill containment system (except in small sizes).

VRLA Advantages

- Normally low hydrogen gas venting (except during overcharge).
- Higher energy density.

- Can be installed in any position (absorbed electrolyte cells).
- Smaller footprint (can be stacked vertically).
- Acid containment system normally not required (unless by local codes).
- Most battery racks inherently seismic rated.
- Built-in flame arrester vent (if specified).

VRLA Disadvantages

- Opaque container or steel frame around modules so visual examination is impossible.
- Shorter life.
- Failure mechanisms not seen in VLA cells.
- Subject to thermal runaway.
- Very heavy floor loading in stacked installations.

4.2 BATTERY VOLTAGE AND DISCHARGE CURVES

4.2.1 Cell Voltages and Specific Gravity

The open-circuit voltage of a fully charged lead–acid cell depends directly on the electrolyte specific gravity. Specific gravity is the ratio of the electrolyte density to water density at the same temperature. Pure water has a specific gravity of 1.000 and pure sulfuric acid has a specific gravity of 1.835.[7] The specific gravity used in telecommunications VLA cells usually is 1.215, for absorbed electrolyte VRLA cells is 1.300, and for gelled electrolyte VRLA cells is 1.260 to 1.280 (however, variations exist among different manufacturers of VRLA cells) at 25°C (77°F). The approximate relationship between cell voltage and specific gravity is

$$\text{OCV} \approx 0.845 + \text{SG} \tag{4.20}$$

where OCV = cell open circuit voltage (V)
SG = electrolyte full-charge specific gravity at 25°C (77°F)

For the typical specific gravities previously mentioned, the open-circuit voltage of a VLA cell is 2.06 V and of an absorbed electrolyte VRLA cell is 2.15 V. The open-circuit voltage and specific gravity depend on temperature. The temperature coefficient for open-circuit voltage is variously reported as 0.2 to 5.5 mV/°C (0.33 to 9.1 mV/°F) at 25°C (77°F) [1–3], and the temperature coefficient for specific gravity is 0.0006 to 0.00075/°C (0.001 per 3°F) at 25°C (77°F) for SG in the range of 1.215 to 1.300 [1]:

$$\text{VPC}(T) = \text{VPC}(25^\circ\text{C}) + \alpha_V(25 - T) \tag{4.21}$$

where $\text{VPC}(T)$ = cell voltage at temperature T (V)
VPC(25°C) = cell voltage at 25°C (V)
T = temperature (°C)
α_V = temperature coefficient for open-circuit voltage (0.2 to 5.5 mV/°C)

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[7] One cubic centimeter of water at +4°C weighs 1 g and the same amount of sulfuric acid at the same temperature weighs 1.835 g.

$$\mathrm{SG}(T) = \mathrm{SG}(25°\mathrm{C}) + \alpha_{\mathrm{SG}}(25 - T) \qquad (4.22)$$

where SG(T) = specific gravity at temperature T
SG(25°C) = specific gravity at 25°C
T = temperature (°C)
α_{SG} = temperature coefficient for specific gravity (0.0006 to 0.00075/°C)

Example 4.2 The measured cell voltage is 2.170 V at 33°C (91°F). Determine the voltage corrected to 25°C (77°F).

Solution First, rearrange Eq. (4.21) to solve for VPC (25°C):

$$\mathrm{VPC}(25°\mathrm{C}) = \mathrm{VPC}(T) - \alpha_V(25 - T)$$

The difference between the base temperature and the actual temperature is 25 – 33 = –8°C. Assuming α_V = 5.5 mV/°C, the correction is –8°C × 0.0055 mV/°C = –0.044 V so the cell voltage corrected to the base temperature is 2.170 V – (–0.044 V) = 2.214 V.

Example 4.3 The measured cell voltage is 2.200 V at 15°C (59°F). What is the voltage corrected to 25°C (77°F)?

Solution The difference between the actual temperature and the base temperature is 25 – 15 = 10°C. Assuming α_V = 5.5 mV/°C, the correction is 10°C × 0.0055 mV/°C = 0.055 V giving a cell voltage corrected to the base temperature is 2.200 V – (+0.055 V) = 2.145 V. Note: This indicates that, although the measured voltage appears proper, the cell really is being undercharged based on the operating temperature.

Example 4.4 The measured specific gravity in a VLA cell is 1.204 at 33°C (91°F). Determine the specific gravity corrected to 25°C (77°F).

Solution The difference between the base temperature and the actual temperature is 25 – 33 = –8°C, and, assuming α_{SG} = 0.0006/°C, the correction is –8°C × 0.0006 = –0.005 giving a corrected specific gravity at 25°C of 1.204 – (–0.005) = 1.209 SG.

Example 4.5 The measured specific gravity in a VLA cell is 1.215 at 15°C (59°F). Determine the specific gravity corrected to 25°C (77°F).

Solution The difference between the base temperature and the actual temperature is 25 – 15 = +10°C, and, assuming α_{SG} = 0.0006/°C, the correction is +10°C × 0.00006 = +0.006 giving a specific gravity corrected to the base temperature of 1.215 – (+0.006) = 1.209 SG.

4.2.2 Float and Equalize Charge Voltages

Battery design life will not be achieved unless the float voltage is well regulated. The regulation normally is ±0.5%, which for most 48-V systems is ±0.260 to 0.273 V and for most 24-V systems is ±0.130 to 0.136 V (depending on whether VLA or VRLA batteries are used). The rectifiers largely determine the regulation, although poor design of the rectifier dc circuits can affect it. Rectifier dc circuit design is covered in Chapter 5, System Design.

In addition to the overall battery float voltage regulation, the individual cell voltages and corresponding specific gravities must be maintained within certain limits, typically ±0.02 V and ±0.04 V of the average cell voltage for VLA lead–antimony and VLA lead–calcium cells, respectively, and within 10 points of the specific gravity (for VLA, specific gravity is 1.215 ±0.010). The voltage tolerance for VRLA cells typically is greater, and some manufacturers specify three different tolerances depending on cell age; for example, ±0.13 V for < 6 months, ±0.08 V for 6 to 12 months, and ±0.06 V for > 12 months.

Since the specific gravity of VRLA cells cannot be measured, only cell voltage has operational relevance. For example, say a 24-cell VRLA battery is floated at 54.48 V, which is equivalent to 2.27 V/cell. If, in this example, the cell voltage tolerance is ±0.06 V, the acceptable voltage measured at any individual cell could range from 2.21 to 2.33 V. Cells that operate at a higher than normal voltage are in a relative overcharge condition and cells that operate lower than normal are in an undercharge condition. VLA and VRLA batteries require different float voltages (and have different voltage tolerances).

Another difference worth noting is the need for equalizing in VLA batteries. The voltage across individual VLA cells or specific gravity in float operation will drift apart over time, particularly if subject to cycling, and exceed the tolerance mentioned above. Raising the battery charging voltage for some length of time (typically 24 to as much as 200 h) until all cells meet the voltage tolerance is known as *equalize charging or equalizing*.[8] During the equalize period, the cell voltage for higher than normal cells will decrease and for lower than normal cells will increase. Equalizing too often or for too long will cause excess gassing, excess loss of water from the electrolyte, and shorter battery life. Lead–calcium VLA batteries usually do not need equalizing as often as lead–antimony if operated at higher float voltages (e.g., 2.20 to 2.25 V/cell for a nominal 1.215 specific gravity).

Equalizing normally is not used with VRLA batteries because their design and higher float voltages prevent cell voltage drift, although, if the VRLA cells do drift due to inappropriate float operation, the manufacturer may recommend an equalize charge.

The actual float and equalize voltages vary with the cell type and, particularly, with electrolyte specific gravity. Table 4.1 shows typical values that apply to most battery types. Manufacturer's instructions always should be consulted to confirm the values to be used in an operating system. Typical equalize time periods for VLA batteries are shown in Table 4.2. Generally, a battery is equalized until successive measurements of specific gravity or cell voltage show no change over a period of several hours. Load equipment may limit the equalization voltages used. For example, some older equipment has a maximum operating voltage of 56.0 V so the maximum equalize voltage would be 2.33 V/cell, assuming no voltage drop between the battery and the load equipment.

4.2.3 Battery Discharge

The discharge curve for lead–acid cells is fairly flat (Fig. 4.13). The discharge period is the time required for the cell voltage to reach its final value (final cell voltage or end-of-discharge voltage). When the cell transitions from float to discharge, there is an immedi-

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[8] Other terms sometimes used in place of equalize charge are *freshening charge* and *check charge.*

Table 4.1 Float and Equalize Voltages

Type	Cell Voltage (V/cell)	12-Cell System (V/cell)	24-Cell System (V/cell)
Float			
VLA (lead–antimony)—1.215 SG	2.15–2.17	25.80–26.04	51.60–52.08
VLA (lead–calcium)—1.215 SG	2.17–2.25	26.04–27.00	52.08–54.00
VRLA—1.300 SG	2.25–2.27	27.00–27.24	54.00–54.48
Equalize			
VLA (lead–antimony)—1.215 SG	2.24–2.39	26.88–28.68	53.76–57.36
VLA (lead–calcium)—1.215 SG	2.24–2.39	26.88–28.68	53.76–57.36
VRLA[a]—1.300 SG	2.30–2.35	27.60–28.20	55.20–56.40

[a] VRLA batteries should not be equalized or operated at elevated voltages unless recommended by the manufacturer.

ate voltage drop due mostly to the cell internal resistance. As the cell discharges, the voltage continues to decrease due mostly to polarization. Hydrogen bubbles that form on the positive plate cause polarization. This has two effects—the bubbles cause a substantial increase in the resistance at the contact surface between the plate and the electrolyte, and the hydrogen reacts chemically with the plate in such a way that it sets up a voltage that opposes the cell voltage.

The cell voltage on discharge (under load) is lower than the open circuit voltage at the same charge levels. Similarly, the voltage required to charge a cell is higher than the open-circuit voltage. Figure 4.14 shows how cell voltage and specific gravity varies over typical discharge–charge cycle.

Five parameters describe the discharge characteristics of stationary batteries: (1) capacity in ampere-hours at (2) a specified discharge rate in hours to (3) a final cell voltage in volts/cell (also called *end-of-discharge voltage* or *cut-off voltage*), (4) battery temperature, and (5) the nominal full-charge electrolyte specific gravity. For telecommunications batteries in North America, the nameplate discharge characteristics are specified at the 8-h rate

Table 4.2 Equalizing Voltages and Time Periods

Type	Cell Voltage (V/cell)	Time (h)
VLA (lead–antimony)—1.215 SG	2.24	80
	2.27	60
	2.30	48
	2.33	36
	2.36	30
	2.39	24
VLA (lead–calcium)—1.215 SG	2.24	222
	2.27	166
	2.30	105
	2.33	74
	2.36	50
	2.39	^34

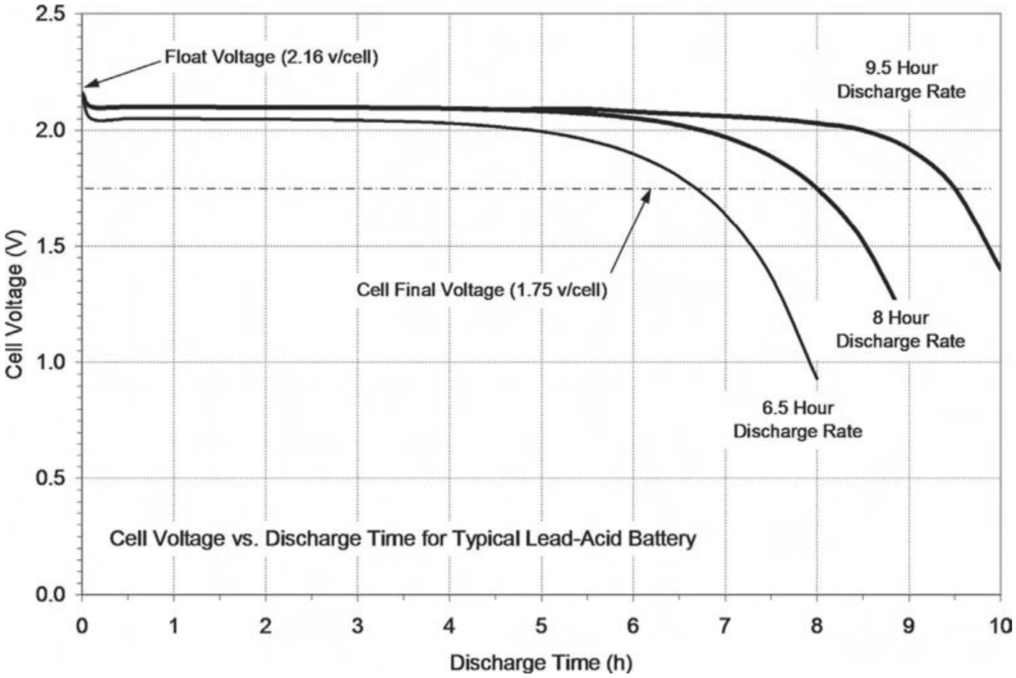


Fig. 4.13 Lead–acid cell discharge curve.

to 1.75 V/cell [some VRLA battery manufacturers use a 10-h rate and some small-capacity (< 100 Ah) VRLA batteries are specified at a 20-h rate]. A fully charged cell with C_8 Ah capacity will discharge to 1.75 V/cell in 8 h at 25°C (77°F) if the discharge current *I* in amperes is C/8. Looked at another way, if a battery is discharged to 1.75 V/cell in 8 h and the current required to do that is *I* amperes, the cell capacity, C_8, in Ah is *I* A × 8 h.

Manufacturers typically produce a basic cell design and then vary the number of plates to provide different capacities in a product series. One set of discharge characteristic curves applies to the series and the curves are then scaled according to the number of positive plates. Table 4.3 shows the ampere-hour capacity and number of plates for a series of VLA cells, and Figure 4.15 shows the corresponding discharge curves.

Example 4.6 The nameplate capacity of a battery is 680 Ah. Determine the current required to discharge this battery to 1.75 V/cell in 8 h at 25°C.

Solution The current is 680 Ah ÷ 8 h = 85 A.

Example 4.7 Determine the capacity of a battery that is discharged in 8 h to 1.75 V/cell at 25°C when the discharge current is 150 A.

Solution The ampere-hour capacity (at the 8-h rate) is 150 A × 8 h = 1200 Ah.

As shown above, if the cell is discharged at its nameplate rate at 25°C, it will reach 1.75 V in 8 h (middle curve in Fig. 4.13). The depth of discharge is 100%, which corresponds to

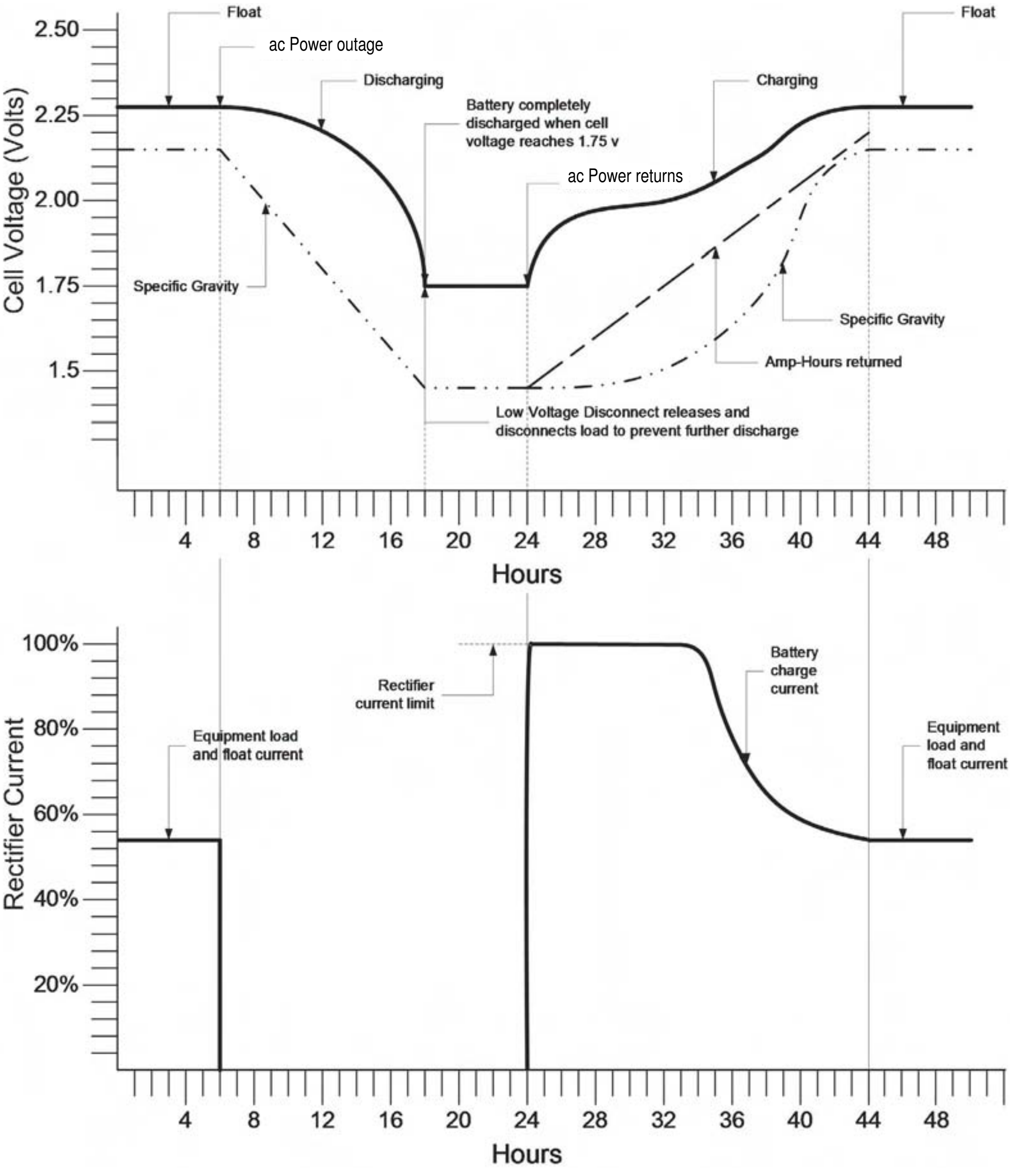


Fig. 4.14 Typical cell voltage and specific gravity variations over discharge–charge cycle. In this illustration, a low-voltage disconnect (LVD) relay automatically disconnects the load at 1.75 V/cell. Also shown (lower graph) is the rectifier current that powers the equipment and recharges the battery. Not obvious from the upper graph is a slight increase in cell voltage when the load is disconnected.

42.0 V for a 24-cell battery and 21.0 V for a 12-cell battery. If the cell is discharged at a higher current, it will discharge in less than 8 h to 1.75 V (lower curve in Fig. 4.13) and if discharged at a lower current, it will discharge in more than 8 h (upper curve in Fig. 4.13). Under these conditions, the cell actually has less-than-nameplate capacity at the higher discharge current and more-than-nameplate capacity at the lower discharge current. This is illustrated in Figure 4.16, which shows the percentage of nameplate capacity for typical

Table 4.3 Example VLA Battery Series—Capacity and Ah/Positive Plate are at 25°C to 1.75 V/cell and 8-h Discharge Rate

Capacity (Ah)	Number Positive Plates	Number Negative Plates	Total Plates	Ah/Positive Plate
840	5	6	11	168
1008	6	7	13	168
1176	7	8	15	168
1344	8	9	17	168
1680	10	11	21	168
1848	11	12	23	168
2016	12	13	25	168

lead–acid batteries (at 8 h rate to 1.75 V/cell) versus actual discharge rate. Note that the 8-h discharge rate yields 100% nameplate capacity and that faster discharge rates (< 8 h) yield less than 100% nameplate capacity.

The actual discharge capacity of a stationary battery also depends on the final cell voltage. If the final cell voltage is higher than nameplate (> 1.75 V/cell), the battery is discharged to less than nameplate capacity. In other words, if the battery is not fully discharged to 1.75 V/cell, it still has some unused capacity, and it has not reached 100% depth of discharge. Similarly, if the final cell voltage is lower than nameplate voltage

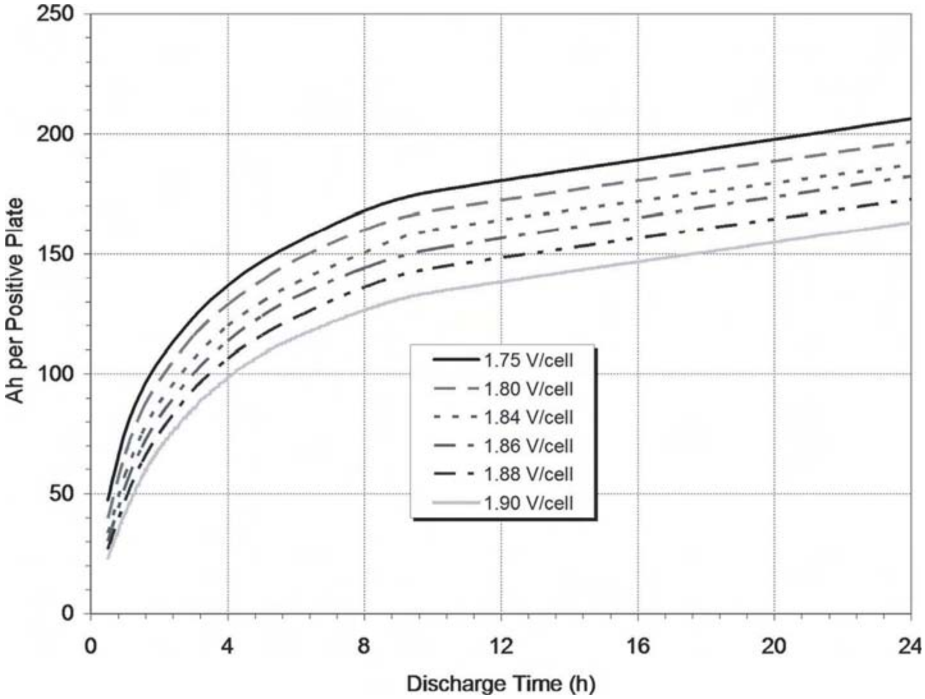


Fig. 4.15 Discharge curves corresponding to the example battery series with different end-of-discharge voltages.

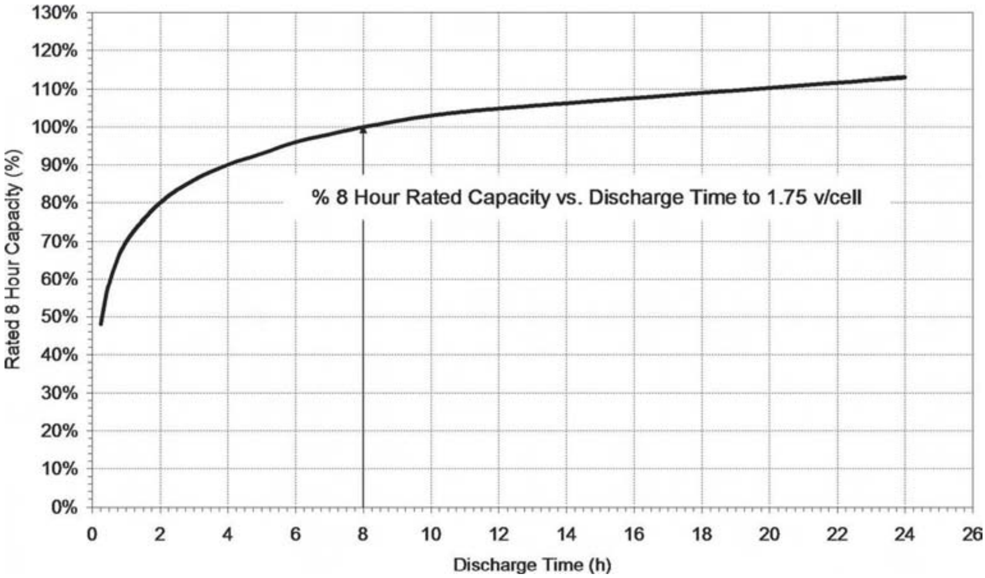


Fig. 4.16 Percentage nameplate capacity vs. actual discharge rate for typical VLA cells.

(< 1.75 V/cell), the battery will have more than nameplate ampere-hour capacity. However, to prevent damage from overdischarge, telecommunications batteries should not be discharged to less than 1.75 V/cell unless allowed by the manufacturer.

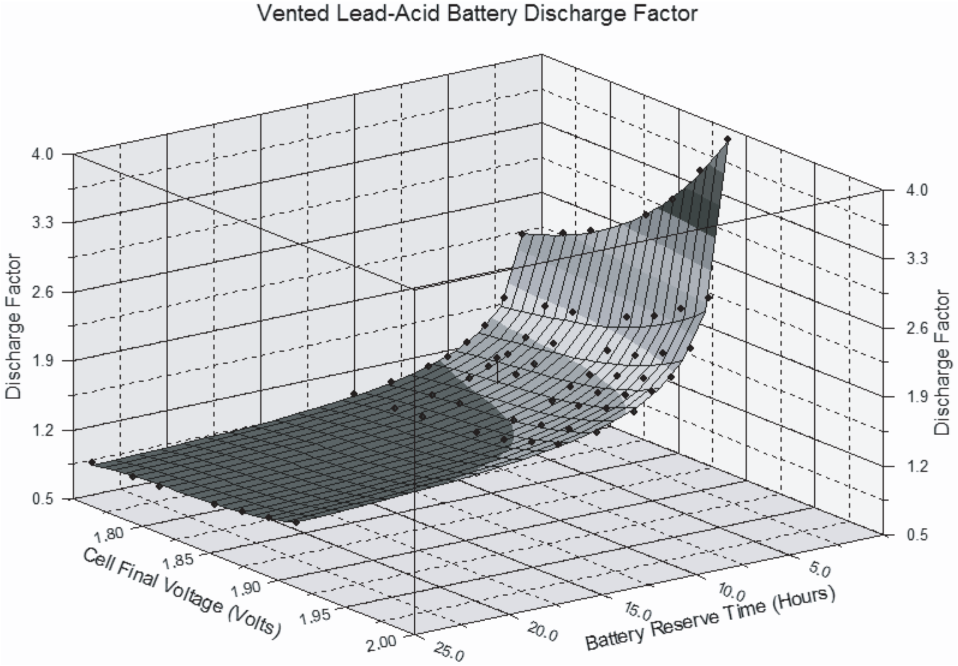
Discharging a battery to 1.75 V/cell releases the most capacity, but the battery system may power equipment that is unable to operate at such a low final voltage. For example, several end office and transit switching systems used in the current network do not operate below 44.0 or 44.5 V. Also, there can be an up to 2.0-V drop from the battery terminals to load equipment. To support 44.0 V at the load with a 2.0-V distribution drop, the final battery voltage must be 46.0 V. This corresponds to 1.92 V/cell. There is no practical reason to discharge a battery below this voltage if the equipment it powers will not work. Therefore, for design purposes, the battery final voltage would be 46.0 V and the average cell final voltage would be 1.92 V.

4.2.4 Discharge Factor

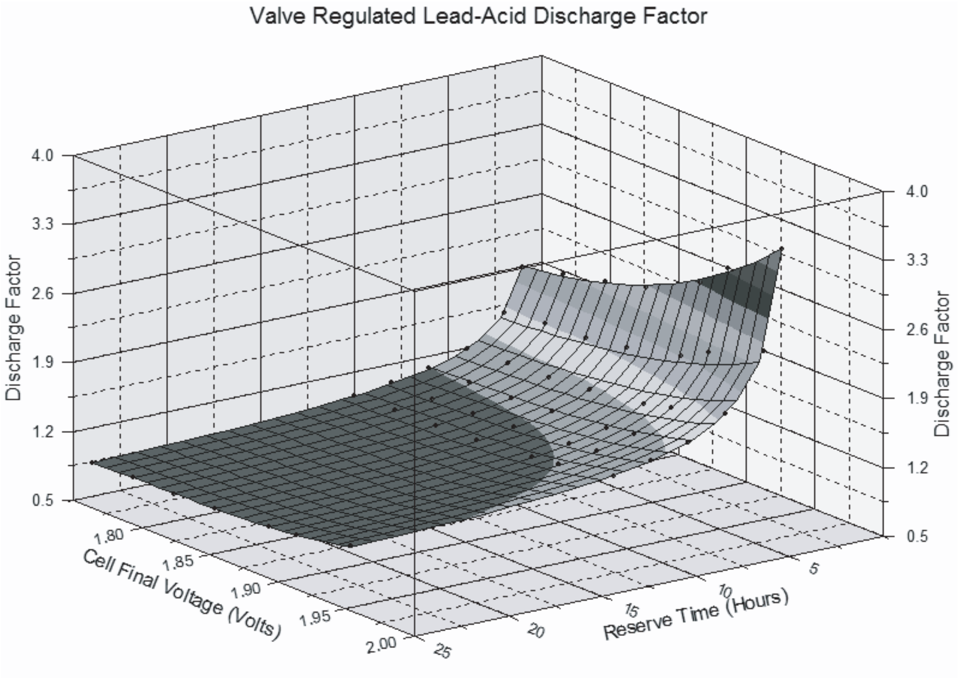
A discharge factor (DF), also called capacity factor, is used to summarize the variations in cell capacity with varying discharge rate and final cell voltage. Figure 4.17(a) and 4.17(b) show three-dimensional (3D) plots of the discharge factor versus battery reserve time and cell final voltage for VLA and VRLA cells. The 3D plot shows that as discharge rate, or reserve time, decreases below nameplate (8 h), the discharge factor increases above 1.0. Also, as the final cell voltage increases above nameplate (1.75 V/cell), the discharge factor increases above 1.0. While the 3D plot shows the overall effects, two-dimensional plots are easier to use in battery sizing calculations (see Chapter 5, System Design).

4.2.5 Self-Discharge

A cell will discharge even if it is not connected to a load. Self-discharge, also known as *local action,* takes place continuously whether the cell is charging, discharging, or stand-



(a)



(b)

Fig. 4.17 (a) VLA discharge factor showing overall effects of reserve time and cell final voltage. (b) VRLA discharge factor showing overall effects of reserve time and cell final voltage.

ing in an open-circuit condition. Floating the battery at a constant voltage overcomes the effects of self-discharge. The plate materials, lead and lead dioxide, are thermodynamically unstable in electrolyte and react with it. Oxygen evolves from the reaction of the electrolyte with the positive plate (lead dioxide), and hydrogen evolves from the reaction of electrolyte with the negative plate (lead). Self-discharge increases rapidly with increase in temperature and specific gravity.

If one part of a battery runs warmer than the rest, the warmer cells will have a higher rate of self-discharge, and their capacity gradually falls below the others. Therefore, batteries must be located so that sunshine or space heaters and air conditioners do not affect a portion of the battery by introducing differential temperatures between cells in the same string. Differential temperature is limited to 3°C (5°F).

The rate of self-discharge when on open circuit is quite high for VLA and comparatively low for VRLA cells. Self-discharge rate increases with temperature and age and can be minimized by storing batteries at cooler temperatures between 5 and 15°C (40 and 59°F). All lead–acid batteries in storage require periodic recharging. Typical self-discharge values at 25°C (77°F) are

- 6 to 7% per month for lead–antimony VLA
- 3% per month for lead–calcium VLA
- 1 to 2% per month for VRLA

4.2.6 Overdischarge

A cell will become overdischarged if it drops below its rated final cell voltage. During battery discharge, weak cells will be exhausted well ahead of normal cells and then will become overdischarged or oversulfated. The latter may cause the plates to buckle and the grids to crack. Continued overdischarge may reverse the polarity, making positive plates out of the negatives and negative plates out of positives. Reversal usually destroys the cells.

4.3 TEMPERATURE PERFORMANCE

Telecommunications batteries are optimized for operation at 25°C (77°F). Operation above 27°C (80°F) is not normally recommended except in special designs because of greatly shortened life. Operation at lower temperatures generally will increase battery life but it lowers battery capacity (Fig. 4.18). The temperature factor (TF) in Figure 4.18 is indicative of lead–acid batteries, but there may be considerable variation among manufacturers and cell types. It may be used as a first-order estimate to adjust battery nameplate capacity for operation at lower than optimum temperatures. The temperature factor equals 1.0 for operation at 25°C (77°F). Since batteries should not be operated at higher than normal temperatures, the temperature factor used in battery sizing calculations never will be less than 1.0.

Low temperatures may freeze the electrolyte and the resulting expansion may rupture the battery container or warp the plates. This danger applies not only to operating batteries but batteries in storage. As batteries self-discharge in storage, their specific gravity decreases, thus changing the freezing point. Lead–acid batteries in storage require periodic recharging. The freezing point of electrolyte versus its specific gravity is shown in Figure 4.19.

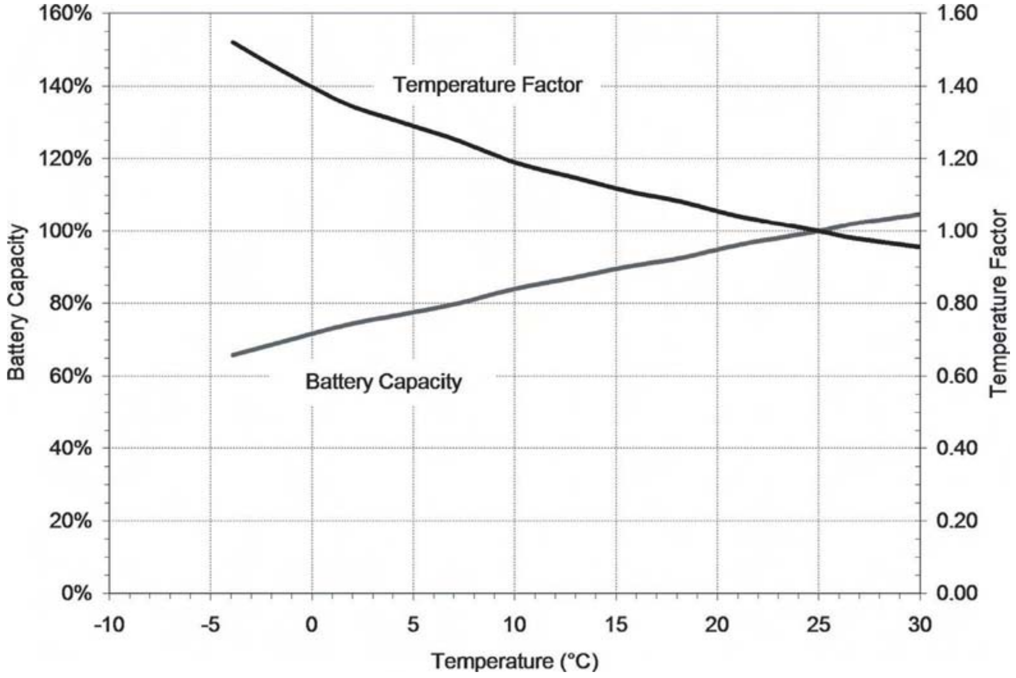


Fig. 4.18 Percentage battery capacity (temperature factor) vs. temperature. This curve is meant to show the general relationship; there may be significant differences among manufacturers and cell types.

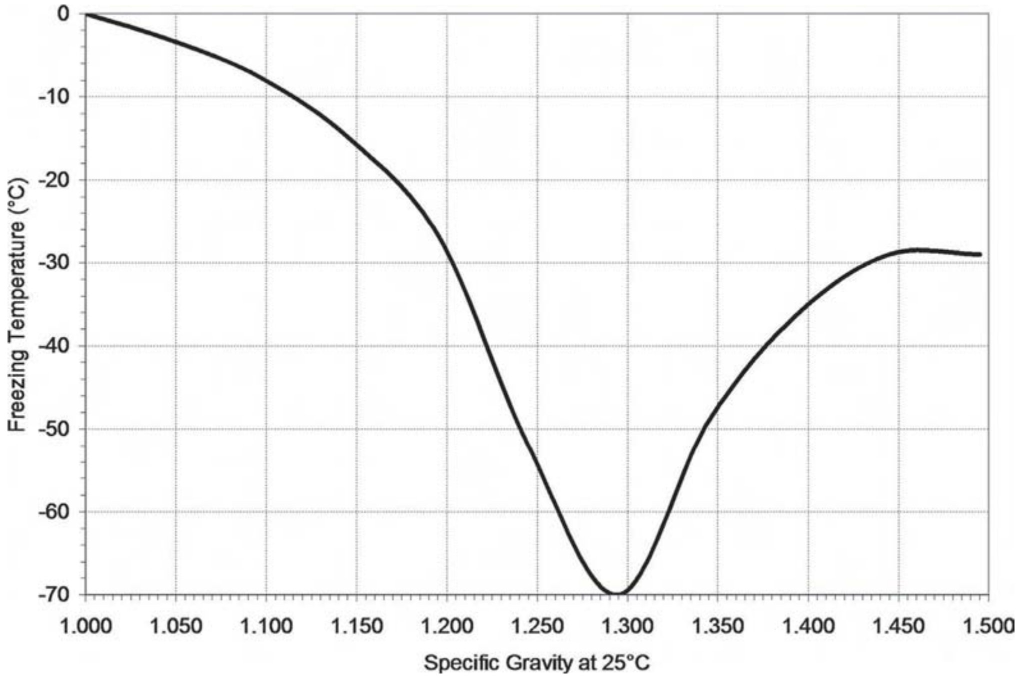


Fig. 4.19 Electrolyte freezing point vs. temperature.

4.4 BATTERY LIFE

4.4.1 End-of-Life Definition

The positive plates generally are the life-limiting components in modern stationary lead–acid cells used in telecommunications—as a battery operates, the positive plates corrode.

Telecommunications batteries are considered at the end of their useful life when their capacity decreases to 80% of nameplate. For example, when the capacity of a 1000-Ah battery decreases to 800 Ah, the battery is, by definition, at end of life. Conversely, if 800 Ah are required at the end of life, a 1000-Ah battery must be installed initially.[9] The 80% factor is taken into account in battery sizing calculations by the end-of-life (EL) factor, which is 1.25. Other end-of-life factors may be used if justified.

The initial capacity of new cells may be slightly lower than the nameplate capacity. The capacity will increase to 100% in a short time after the battery is connected to the power system and charged and under ideal conditions will stabilize at 100% for most of the battery's life. As the battery approaches end of life, the capacity will decrease. Tests made on a large number of operational VRLA battery systems show that a large number of cells start to lose significant capacity within a few years of installation.

Cycling (discharging and charging) will decrease the battery life, as determined by the cycling regimen. The aging mechanisms primarily are changes in the performance of the positive plate active material and positive plate grid oxidation. As a battery is discharged and then recharged, the lead dioxide active material changes from a highly active crystalline form to a less active amorphous structure. Also, the lead metal used in the positive plate grid oxidizes to lead dioxide, which has lower electrical conductivity. As the grid conductivity decreases, the cell internal resistance increases and diminishes the current delivery on discharge and charge acceptance on recharge. Another consequence of grid oxidation is plate growth due to intergranular corrosion of the positive plate grid. Lead dioxide has about 20% greater volume than lead metal. An obvious sign of plate growth in VRLA cells is bloating and bulging and in VLA cells is plate warping.

A battery that is seldom or lightly cycled will last longer than a battery that is continuously and deeply cycled. Most telecommunications applications are subject to long float periods with occasional cycling. The amount and depth of cycling depends on several factors:

- Length and depth of discharge—the lower a battery is discharged (greater depth of discharge), the shorter its life.
- Amount of recharge before the next discharge cycle—if a battery is not fully recharged before the next outage that causes a discharge, the shorter its life.
- Length of time in the discharged state—the longer a battery remains in the discharged state before it is recharged, the shorter its life.

The life of a modern lead–calcium VLA cell in a central office environment can be 20 years under noncycling float service. A daily discharge of 10% reduces the life by a

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[9] Over the years, the definition of end of life has changed from 50% to 75% and presently is 80% according to [4, 5].

factor of $\frac{1}{2}$. A depth of discharge higher than 10% on a daily basis is not recommended for lead–calcium VLA cells. The life of a lead–antimony VLA cell is about the same as lead–calcium; however, lead–antimony cells may be discharged to 50% on a daily basis with some life reduction. VRLA cells generally have a shorter useful life than VLA, typically 5 to 10 years in a controlled environment and 2 to 5 years in an uncontrolled environment such as outside plant access nodes where high temperatures are common. In a cycling environment, VRLA cells have better performance than VLA cells (Fig. 4.20). Tests on the cycle performance of AGM batteries show that there is a long time period where the capacity is relatively stable before the capacity sharply decreases (Fig. 4.21).

An interesting difference exists between manufacturer's claims and warranty coverage. Marketing materials typically claim the batteries have a 20-year life, but the warranty will provide full replacement value within only 1 or 2 years after new and a linear decrease in value over time.

4.4.2 Life-Limiting and Failure Mechanisms

In addition to thermal runaway, which is unique to VRLA batteries, there are many failure mechanisms in both VLA and VRLA lead–acid batteries (Fig. 4.22).

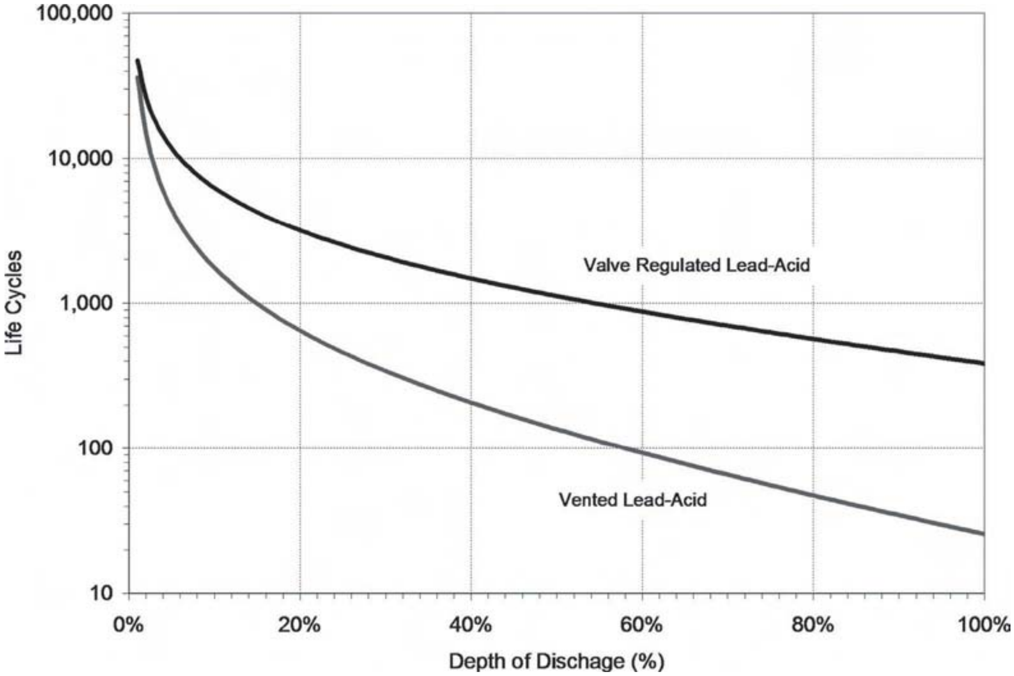


Fig. 4.20 Cycle-life dependence on depth-depth of discharge for VLA and VRLA batteries. This chart is based on batteries used in automotive and electric vehicle applications (data from Chapter 11 of [6]), but tests on stationary VRLA AGM batteries show results similar to the VRLA curve shown (Chapter 13 of [6]).

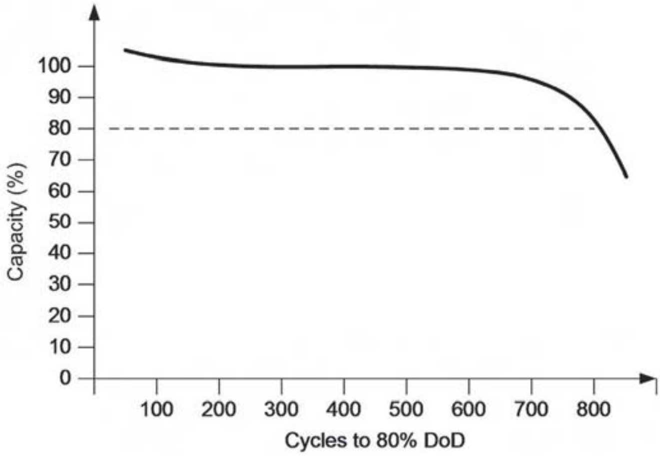


Fig. 4.21 Capacity loss vs. discharge cycles to 80% depth of discharge for typical VRLA batteries. Capacity is relatively constant before steadily decreasing.

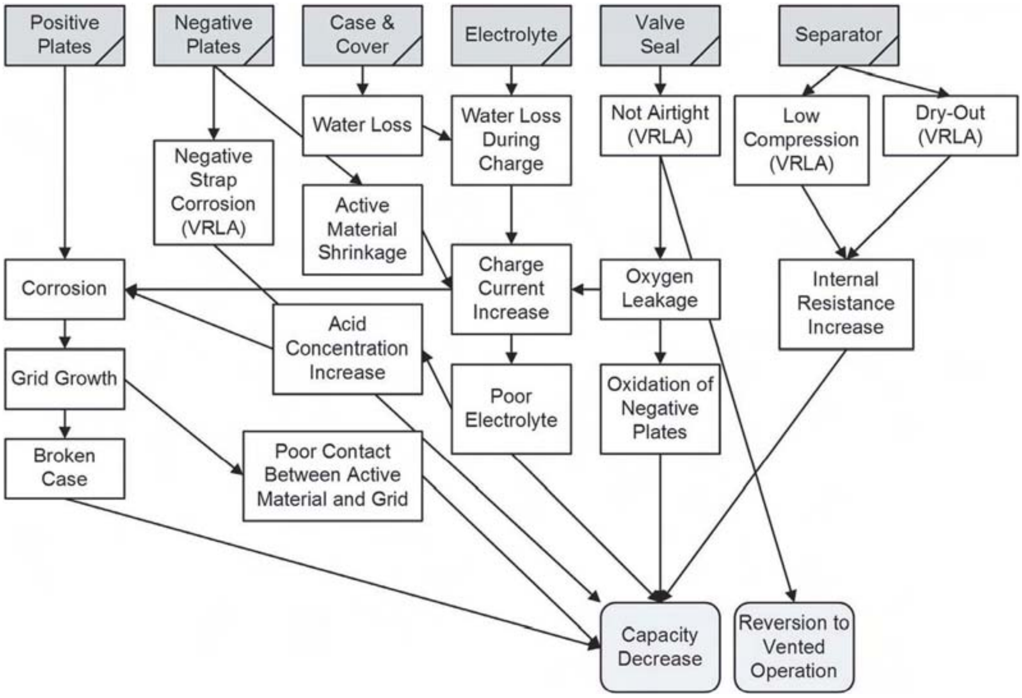


Fig. 4.22 Cell failure mechanisms.

All failure mechanisms lead to capacity decrease, which is manifested as reduced life. Some failure mechanisms in VRLA batteries may lead to catastrophic failures. The most common VRLA failures are:

- Grid corrosion leading to capacity loss
- Plate shorting
- Plate growth leading to bulged or bloated cell, damaged post seals, and leaky seals
- Dry-out due to water loss through vent, water vapor transmission through container walls, and consumption of water by the positive grid corrosion reactions

The causes of failure in any battery usually are:

- Excessive cycling
- Post seal leakage (mainly a problem with VRLA but can also cause problems with VLA)
- Loose intercell connections
- High or low float voltage
- High or low temperature (freezing)
- Discharge without recharge
- Overdischarge
- Cracked and leaking cell container (Fig. 4.23)

4.5 CHARGE ACCEPTANCE AND THERMAL RUNAWAY

Batteries are not 100% efficient and not all of the energy put into a battery by charging is available during discharging. The charge acceptance, or efficiency, is around 85 to 90%; for every 100 Ah removed from a battery during discharge, 110 to 115 Ah have to be returned to it during recharge. This efficiency must be taken into account when calculating the recharge time (see Chapter 5, System Design).

The charge acceptance of a completely discharged battery is initially low, but the battery accepts current more readily after it is slightly charged. The charge acceptance stays at a high level until the battery is about 80% recharged. As the battery becomes fully charged, some of the charge energy is used to generate hydrogen and oxygen and some is used to make up for internal losses that otherwise would be manifested as self-discharge.

Batteries accept more charge current at higher temperatures than at lower temperatures. This can lead to thermal runaway in VRLA batteries because their compact packaging limits their ability to dissipate the generated internal heat. Figure 4.24 shows that some cells in a typical VRLA module stacking scheme are surrounded on four sides by other cells. These “internal” cells generally will run hotter than other cells. As the cells are charged, internal losses heat the cells increasing their charge current, and the heat produced by the reaction exceeds the heat removed. Higher charge current leads to higher temperatures until the cells are damaged, possibly catastrophically (Fig. 4.25). Polypropylene containers used for VRLA cells start to soften at 95°C (203°F) and melt at 155°C (311°F).

While VRLA cells are more susceptible to thermal runaway when being charged after a discharge, similar conditions can be brought on by the simple failure of one or more

(a) (b)

Fig. 4.23 Leaking cell at customer premises—the cell cracked due to shipping or installation handling, allowing electrolyte to leak onto the grounded metal battery enclosure. Since electrolyte allows current flow, the resulting short circuit generated enough heat to burn a hole through the battery jar (a) about 1 in. across and enclosure (b) about $\frac{3}{8}$ in. across like a blowtorch.

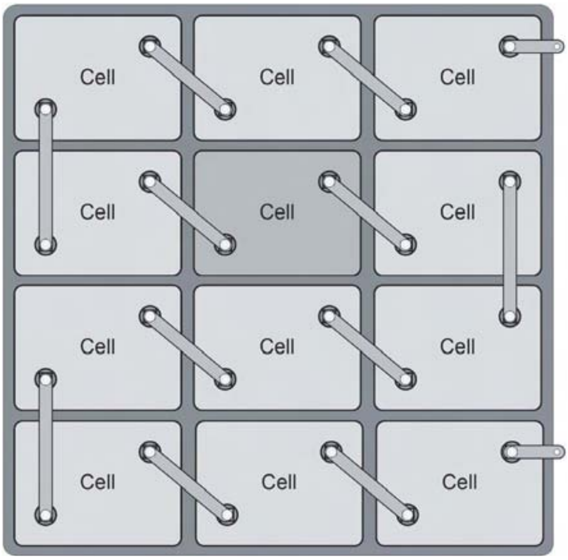


Fig. 4.24 Typical VRLA modular stacking scheme. The upper-middle cell cannot dissipate heat as readily as cells on the edges.

Fig. 4.25 Heat damage to a 2-cell VRLA monobloc from thermal runaway—note discoloration in the area of the letters "Lib." (Photo courtesy of M.W. Migliaro.)

cells during normal float operation. For example, if 1 cell of a 12-cell string shorts out while under float, the voltage in the remaining 11 cells must rise to the float voltage. If the float voltage is 27.0 V (2.25 V/cell for 12 cells), the voltage across the remaining cells is 2.45 V, which clearly is an overcharge condition. If 2 cells fail shorted, the voltage across the remaining 10 cells is 2.70 V.

The production of hydrogen sulfide (H_2S) has been observed during VRLA thermal runaway. Hydrogen sulfide is a poisonous, colorless gas with an offensive smell similar to rotten eggs. It can be very damaging to equipment and a serious health hazard to people because it can paralyze the respiratory system, leading to serious injury or death. Thermal runaway is not observed in VLA batteries because they are better able to dissipate internal heat.

Using temperature-compensated charging can reduce the chances of thermal runaway in VRLA batteries. The compensation is based on a negative temperature coefficient (NTC) in the range of –2.5 to –4.5 mV/°C/cell (–1 to –3 mV/°F/cell); that is, the battery voltage is reduced as the temperature increases. If the temperature falls, the battery voltage is then increased; however, it is not increased indefinitely as it would eventually damage the battery. Figure 4.26 shows a typical compensation curve. Note the plateau at 10°C (50°F) in this example where further decreases in battery temperature do not affect the voltage. Figure 4.27 shows the susceptibility for thermal runaway under float and charging conditions.

Ideally, temperature probes for temperature-compensated charging would be mounted inside each cell. However, practical installations use external temperature sensors mounted on cell terminal posts. This provides satisfactory results since lead plate grids are good thermal conductors (Fig. 4.28). In older installations, a standalone temperature compensation module may be used, which is mounted on the battery frame. Although the standalone module does not sense post temperature, it still senses battery temperature rise (or, more accurately, the temperature of the battery frame or module structure). Further details on temperature-compensated charging, including application information, can be found in Chapter 5, System Design.

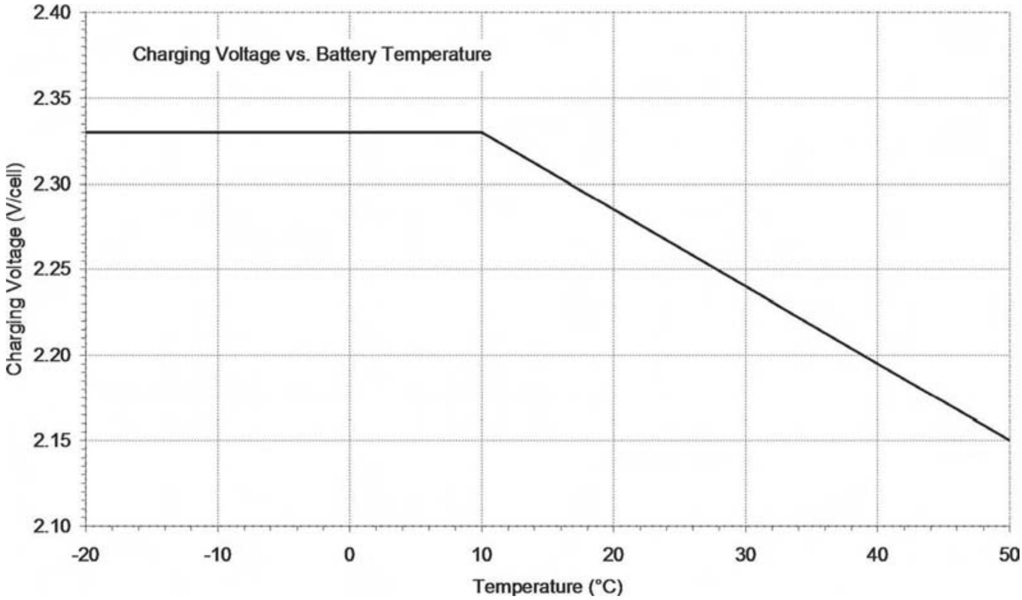


Fig. 4.26 Typical voltage vs. battery temperature for temperature-compensated charging.

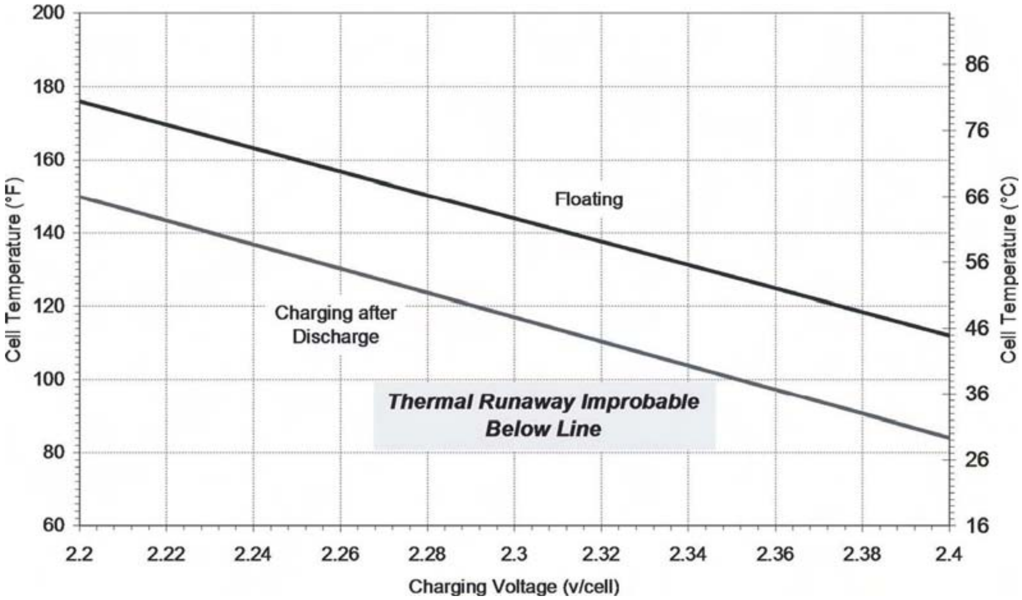


Fig. 4.27 Susceptibility to thermal runaway. VRLA batteries are more susceptible to thermal runaway during charging after a discharge because more heat is generated than during float operation, as shown. Thermal runaway is unlikely when the battery is operated below the respective line for each condition.

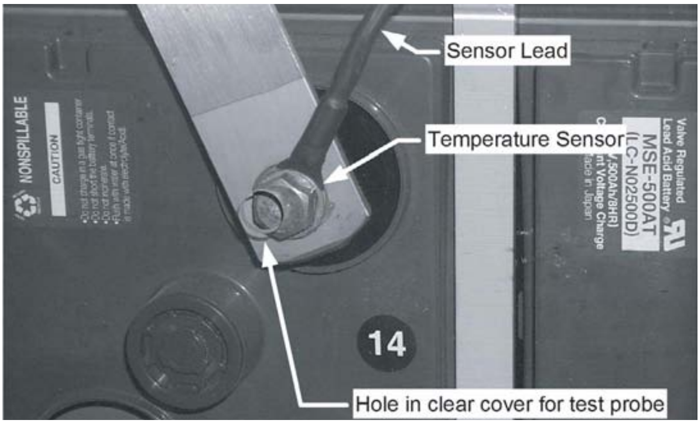


Fig. 4.28 Temperature compensation probe mounted on cell terminal post.

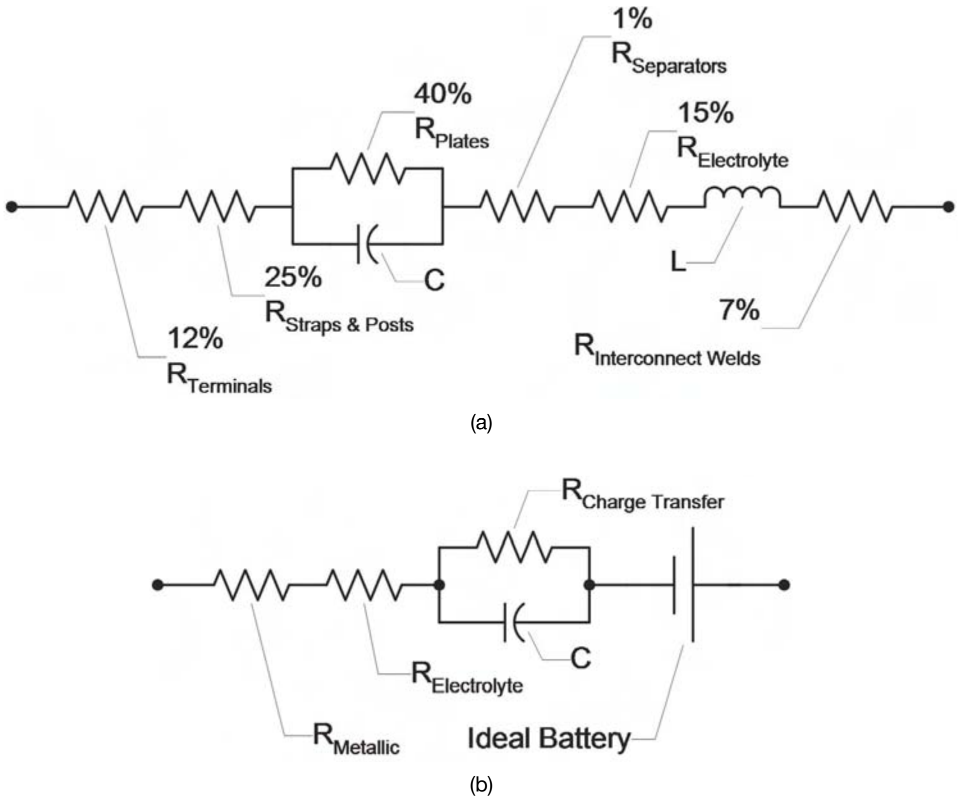
The float current required by a fully charged VLA battery is related to its capacity. A rule of thumb for lead–calcium is 4 and 10 mA per 100 Ah of capacity at 25°C when floated at 2.17 V/cell and 2.25 V/cell, respectively. For example, the float current for a 2000-Ah VLA lead–calcium battery at 25°C that is floated at 2.25 V/cell will be approximately 20 × 10 mA = 0.2 ±0.1 A. The float current for lead–antimony cells is about 5 times greater than that for a VLA lead–calcium cell when the cells are new and 20 times greater when the cells are at end of life. Float current increases with temperature and float voltage.

4.6 CELL IMPEDANCE AND CONDUCTANCE

The equivalent circuit of a cell is shown in Figure 4.29(a). This circuit is useful when considering the various failure mechanisms and to show how the components affect the cell resistance. For example, the terminals, plate straps (paralleling bars), and internal interconnecting welds account for 44% of the total resistance. A somewhat simplified and more common representation of a cell is shown in Figure 4.29(b). This circuit is useful in battery and cell testing.

Battery and cell testing generally has two objectives: (1) determining capacity and (2) predicting cell failure. Much effort has gone into determining capacity from internal resistance, impedance, or conductance measurements but the technology to do so does not yet exist. The only reliable and accurate capacity measurement is based on discharging the battery. However, to be done accurately, the battery must be disconnected from the dc power system and discharged into a load bank. This is difficult and risky in any system because during testing, which can require 5 to 12 h or more (or 2 to 3 h with current technology), the power system reserve is compromised. The risk is higher especially in systems with only one battery string, in which no reserve would be available during the test period. Capacity testing is not done too often (usually at 5-year intervals, if ever) because the tests can be very costly and difficult, if not impossible, especially in remote areas.

Internal resistance, impedance, or conductance measurements can be used to predict cell failure. Also, cell voltage trends and specific gravity measurements (the latter is applicable only to VLA cells, although there is a movement in the industry away from spe-



(a)

(b)

Fig. 4.29 (a) Cell equivalent circuit showing the resistance breakdown. (b) Simplified cell equivalent circuit.

cific gravity measurements) may be used to predict cell failure. For example, a cell may be headed for failure if its voltage or specific gravity decreases over time or drops quickly and does not recover by proper charging.

A cell with an internal short usually will float at its open-circuit voltage rather than the float voltage. For example, the open-circuit voltage for a typical VRLA cell is 2.15 V. If the system float voltage is 2.27 V/cell (54.48-V system voltage), a cell measurement of 2.15 V probably indicates an internal short. Cell voltage generally, but not always, is a reliable indicator for VRLA batteries.

True impedance measurements include both a resistive and reactive component, whereas conductance is the real part of the admittance (reciprocal of impedance). However, both types of measurements give the same indication. Additional information on battery maintenance and testing is provided in Chapter 6, System Installation and Maintenance.

4.7 SHORT-CIRCUIT CURRENTS

Batteries can supply a large amount of energy to a fault but not indefinitely. The length of time depends on the discharge rate. For bolted faults close to the battery, the battery will discharge quickly, but the short-circuit currents may last long enough to damage conductors and components or start fires. Telecommunication batteries are designed to not rupture when shorted. It is necessary to consider fault current in battery circuit design, which is covered in more detail in Chapter 5, System Design.

There are several ways to calculate battery fault current depending on what information is available. The fault currents should be obtained directly from the manufacturer if possible. Alternately, the fault currents can be calculated from the cell open-circuit voltage and cell resistance using Ohm's law:

$$I_{\mathrm{SCC}} = \frac{V_{\mathrm{OC}}}{R_{\mathrm{Cell}}} \tag{4.23}$$

where I_{SCC} = short-circuit (fault) current at cell post
V_{OC} = open-circuit voltage, from Eq. (4.20)
R_{Cell} = cell resistance including post and plate connection resistances

If the manufacturer provides detailed discharge curves for individual cells or for a general design covering various cell capacities, the cell internal resistance may be determined graphically. The internal cell resistance is the slope of the "initial volts" line in the discharge curve (this is not the same resistance that would be measured with an impedance tester):

$$R_{\mathrm{Cell}} = \frac{\Delta V}{\Delta I} \tag{4.24}$$

where R_{Cell} = cell internal resistance (Ω)
ΔV = voltage change ($V_1 - V_2$) corresponding to ΔI on initial volts curve (V)
ΔI = current change ($I_2 - I_1$) corresponding to ΔV on initial volts curve (A)

If the current scale on the initial volts curve is based on amperes, then the values may be used directly in Eq. (4.24). However, if the current scale is based on amperes per positive plate, then the curve ampere values first must be multiplied by the number of positive plates in the cell. Figure 4.30 shows initial volts versus amperes per positive plate for an example cell design (this figure should not be assumed to represent all cells).

The total number of positive and negative plates may be even or odd. If even, the number of positive plates, N_P, is exactly one-half the total. For example, if the cell has a total of 16 plates, as determined from the data sheet, then $N_P = 8$. If the total is odd, the number of positive plates is determined by first subtracting 1 from the total number of plates and then dividing by 2 per Eq. (4.1). For example, if the total number of plates is 19, then $N_P = 9$.

Example 4.8 Determine the fault current available from a 17-plate cell represented by Figure 4.30.

Solution The number of positive plates in this cell are (17 – 1) ÷ 2 = 8 positive plates. First, find the slope of the initial volts curve. Choose convenient points on the curve such as 40 and 80 A per positive. The corresponding initial voltages are 1.90 and 1.78 V, giving a cell internal resistance per Eq. (4.24) of (1.90 – 1.78 V) ÷ [(80 – 40 A/positive) × 8 positive plates] = 0.000375 Ω. Next, assume the cell has a specific gravity of 1.215 and calculate the cell open-circuit voltage. From Eq. (4.20) the cell open-circuit voltage =

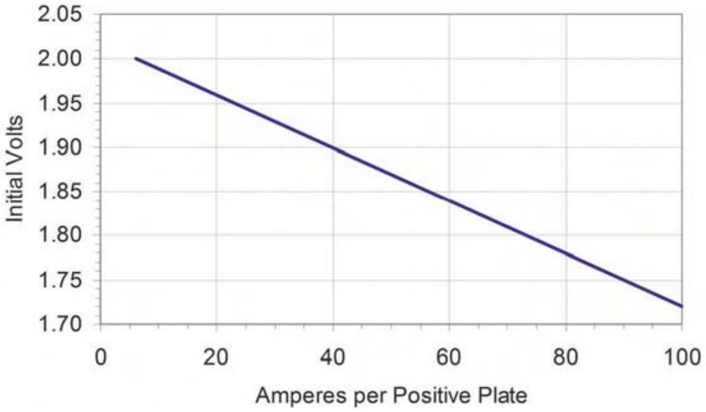


Fig. 4.30 Example initial volts vs. amperes per positive plate.

2.060 V. Finally, determine the short-circuit current. From Eq. (4.23), the short-circuit current is (2.060 V/cell) ÷ 0.000375 Ω = 5493 A.

The foregoing calculations considered an individual cell. The data provided by manufacturers generally include the resistance effects of one cell interconnect strap. If not, the fault current available from a battery string could be less than from an individual cell due the resistance of the cell interconnection straps. The total series resistance of a battery is

$$R_B = R_C N_C + R_I \tag{4.25}$$

where R_B = total battery equivalent resistance including cell interconnection resistance (Ω)
R_C = cell internal resistance (Ω)
N_C = number of cells in battery (24 cells for 48-V battery and 12 cells for 24-V battery)
R_I = total resistance of interconnection straps (Ω) if not included in the battery manufacturer's discharge data for the cell

The short-circuit current available from a battery is

$$I_{\text{SCB}} = \frac{V_B}{R_B} \tag{4.26}$$

where I_{SCB} = short-circuit current at battery terminals (A)
V_B = battery open-circuit voltage ($V_{\text{OC}} \times N_c$) (V)
R_B = total battery equivalence resistance including cell interconnection resistances (Ω)

Figure 4.31 shows typical short-circuit current magnitudes available at the terminals of telecommunications batteries. Variations can be expected for different brands and for models within a brand.

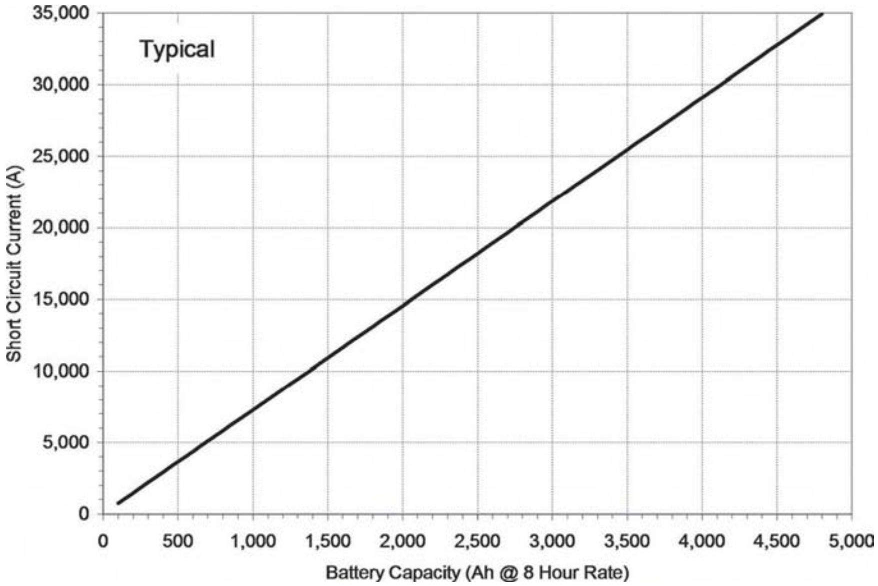


Fig. 4.31 Battery short-circuit current vs. battery capacity.

4.8 CELL GASSING AND VENTILATION

As previously mentioned, VLA cells emit hydrogen during normal operation as well as during abnormal operation. Flame arrestor vents are available and should be used on all VLA cells to prevent a spark outside the cell from igniting the hydrogen in the cell. Battery manufacturers do not always provide flame arrestor vents unless they are specified with the battery order. VRLA cells can emit hydrogen during normal and abnormal operation. When a valve in a VRLA cell fails open, the cell turns into a VLA cell.

Hydrogen concentration in air above 4% by volume is the lower explosive limit. To prevent such a concentration, battery rooms for both VLA and VRLA batteries always should be ventilated. Ventilation does not always mean forced-air ventilation, as convective or natural air movement through inlet and outlet air vents may be sufficient in many situations, particularly with small batteries. Hydrogen diffuses easily through vents and door cracks without the help of fans.

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CHAPTER 5

SYSTEM DESIGN

PART I DIRECT CURRENT POWER SYSTEMS COMPONENT DESIGN

This part describes guidelines for collecting and preparing the necessary information and the procedures for systematically designing each of the basic components in the dc power system. Although some of the guidelines are very specific, the problem of dc power system design is like any other.

- There is no single correct method.
- All practices and procedures and rules of thumb have exceptions and equally valid alternatives.
- There are no substitutes for common sense and good engineering judgment.

5.1 SYSTEM DESIGN CONSIDERATIONS

A telecommunications dc power system must provide the specified voltage range at the load equipment and battery when the prime power source is available and for the specified reserve time when the prime power source or rectifier system fails. The design of a dc power system to meet this and other requirements includes, among other things, considerations of battery capacity, component and wire current ratings, voltage drops, as well as the need to simultaneously recharge the battery and operate the load equipment.

The design process involves preparation and execution. Preparation includes planning, gathering data, and developing system requirements. Execution includes developing designs based on those requirements.

New systems are the easiest to design because there are no constraints caused by existing and many times inadequate infrastructure. The new infrastructure is built to accommodate the new systems, and the designer can choose from a wide variety of new

dc Power System Design for Telecommunications. By Whitham D. Reeve

equipment. Expansion or retrofit of existing systems, particularly older systems, usually is more difficult because of the physical and electrical limitations inherent to the equipment already in place. Major parts of dc power systems used in telecommunications, particularly main buses, are difficult to expand because they cannot be taken out of service.

5.1.1 Basic Design Steps and Guidelines

The design of dc power system components follows the basic sequence shown in Figure 5.1.

5.1.2 Planning Interval

Direct current power systems have very long life—many systems are still in service that are 50 years old or older. Designing systems to last this long requires planning to not only meet initial requirements but to allow flexibility and expansion over time. Some components such as main buses are very difficult to expand while in service and therefore are designed to meet ultimate load requirements. The planning interval to be used depends on the application.

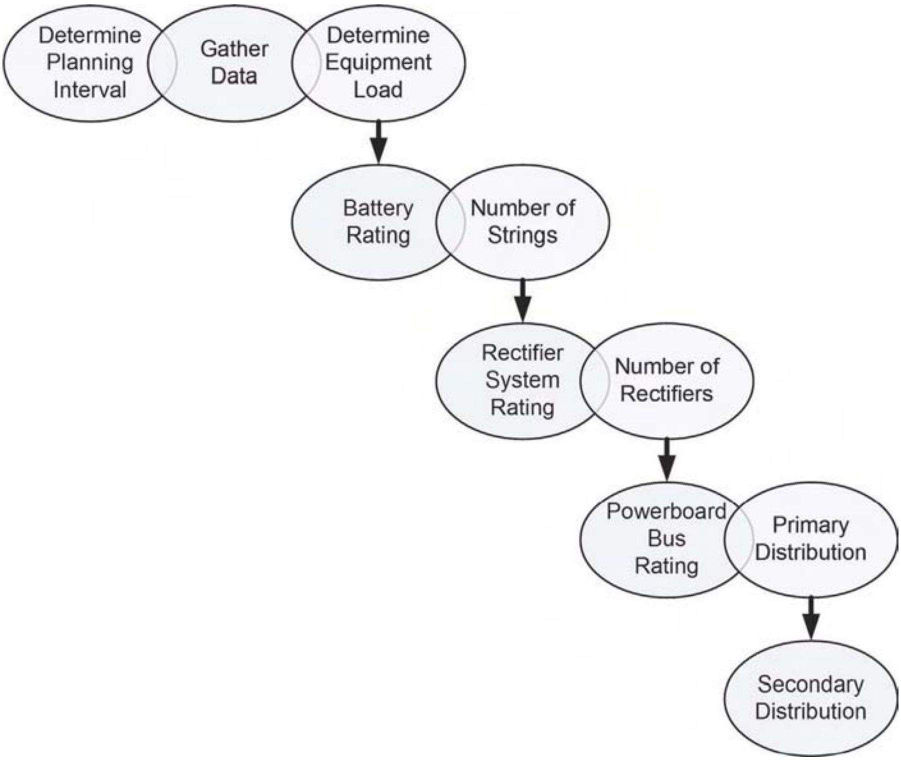

Fig. 5.1 Basic design sequence.

There is little question that long-term planning has never been more difficult than in the telecommunications industry since 1996.[1] This is particularly true of incumbent local exchange carriers (ILEC)[2] subject to competition, which up to that time enjoyed a monopoly that allowed them to control and plan the use of spaces in their central offices. While these ILECs may still control and plan their own technology deployment, they are obligated under certain conditions to provide space in their central offices for equipment belonging to competitive local exchange carriers (CLEC). In doing so, ILECs may not generally reserve unused central office space for their own exclusive use, making it very difficult to determine what, if any, space is available for either ILEC or CLEC equipment on even a short-term basis. The equipment placed in central offices directly affects dc power systems and, if it is impossible to forecast equipment placement and load growth, it is equally impossible to forecast dc power system requirements over the long term. However, there are indirect methods that may be used to estimate the equipment load and these are described later.

When planning the dc power system, it is necessary to determine the initial and ultimate planning intervals. In a central office environment, the initial interval generally is the present capacity requirements plus 2 or 3 years' growth. The ultimate interval normally accounts for 10 to 20 years' growth, although certain components, such as the powerboard main bus, may require a prediction well beyond 20 years.

The guideline for central office powerboard planning is to deploy new or additional units or increased bus capacity when the actual load on the existing powerboard has reached 50 to 80% of its bus rating. For example, an 800-A powerboard would be expanded when the load exceeds 400 A (50%) but before it reaches 640 A (80%). As a matter of good practice a powerboard is not loaded more than 80% of its rated capacity.

Direct current power system components for small telecommunications enclosures, such as access node remote terminals (less than approximately 700 access lines), usually are designed and equipped for ultimate capacity. The dc power components in larger remote terminals and equipment enclosures can be designed and equipped on an incremental growth basis. For example, rectifiers and battery strings may be initially equipped to handle 2 or 3 years' incremental growth and then expanded as the load grows beyond the initial capacities.

Data gathering can be time consuming and tedious, but the activity nevertheless is necessary (Fig. 5.2). Many larger companies have technical groups dedicated to compiling and processing planning data. From a power system perspective, the results of such efforts are an estimate of the initial load, information on the growth rates throughout the planning intervals, and an estimate of the ultimate load. Different power system components may have different initial and ultimate requirements and planning intervals.

Floor Space Requirements and Availability The floor space required by a dc power system depends on the types of battery and rectifier technologies, charge/discharge bus current ratings and physical configurations, primary distribution requirements, and

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[1] The Telecommunications Act of 1996 (TA96), enacted by the U.S. Congress and signed into law in February 1996, fundamentally affected the way telecommunications systems are planned, operated, and built.

[2] ILEC is a contemporary name defined by the Federal Communications Commission (FCC) as a network operator that provided telecommunications exchange services on February 8, 1996, the day TA96 was signed into law.

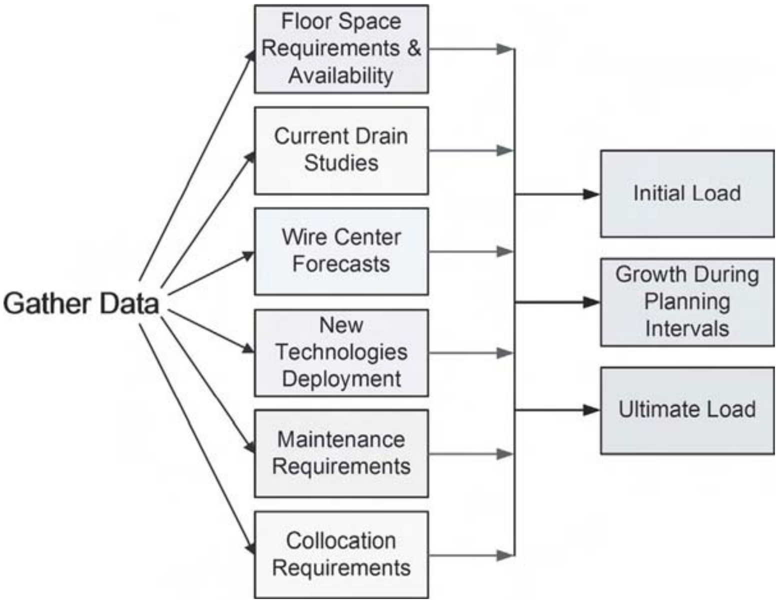

Fig. 5.2 Information planning for dc power systems.

growth requirements. Power system components must have adequate space around them for safe and efficient operation and maintenance. Some considerations are

- Complete batteries or individual cells or modules will require eventual replacement and there must be space for lifting devices to remove the components and place the new ones.
- Electrical codes (where applicable) and safety practices require a safe amount of workspace around energized equipment so the planner must take into account maintenance and installation aisle space.
- Existing building spaces may be inadequate in terms of structural strength or availability and remodeling may be required.
- Ventilation and air conditioning systems may be inadequate for batteries and additional power system and network equipment and may require modification or expansion.

Current Drain Studies Historical load growth is very useful in predicting future load growth in many situations. Modern power systems include monitors that log many parameters associated with operation, and external data loggers can be permanently or temporarily installed in power systems that have accessible current shunts or data logging interfaces. Most modern dc power system controllers have integrated data loggers, which are accessible through a craft interface.

Wire Center Forecasts A typical wire center provides regular services such as POTS (plain old telephone service) and DSL.[3] Historic growth data normally is readily

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[3] DSL, or digital subscriber line, is a generic name for transmission technologies that provide digital services over metallic twisted cable pairs or optical fibers.

available in company records. Forecasts are developed by projecting past growth and comparing it with estimates of future requirements.

New Technologies Deployment New technology equipment generally is more compact than the equipment it replaces, but the power it consumes per unit volume is higher. Examples of new technologies are fiber-to-the-home (FTTH) and fiber-to-the-curb (FTTC) and the associated infrastructures for television and broadband services delivery.

Maintenance Requirements At some point in their lives, old systems and equipment become obsolete because they do not meet current requirements, replacement parts may no longer be available, or software systems are no longer supported and kept up to date. Examples are rectifiers, voltage conversion devices, and power system controllers that no longer meet system needs.

Collocation Requirements Most ILECs view collocation as a major impediment to their financial success; other ILECs and network operators view collocation as a source of revenue and business collaboration. Collocated equipment requires power, but the question of how much power can be very difficult to answer without detailed knowledge of future requirements or at least some method to estimate them.

Particular types and brands of equipment will be used in most central offices. For example, the major load in central offices owned by local telephone service network operators will be an end office switching system. Equipment in the access network will be remote switching terminals (RST) or access nodes (digital loop carrier and optical fiber nodes) served by the end office switch. If the node is for transmission purposes, the major load may consist of terrestrial microwave radio terminals or fiber-optic terminals. Many sites will consist of a combination of switching and transmission equipment. In any case, the loads may be determined from the manufacturer's installation and engineering guidelines.

5.1.3 System Operating Voltages and Ranges

The operating voltages described in this section are specified by industry [1]. The specified ranges are determined by assuming that in a typical facility some loads may be close to the power system (low voltage drop in the distribution loop) and some far away (high voltage drop in the distribution loop). Equipment exists in the network and will be available in the future that safely operates outside of the ranges given here; however, the dc power system must be designed to accommodate all equipment in a given facility. The equipment with the highest minimum voltage and lowest maximum voltage generally will set the operating range of the power system in a given facility.

The operating range for nominal 24-V systems is specified as 20.0 to 28.3 Vdc. Most 24-V systems have a negative ground (positive operating voltage with respect to ground). The minimum voltage, 20.0 V, corresponds to an end-of-discharge condition where the final cell voltage is 1.75 V/cell (21.0 V final battery voltage) and a maximum of 1.0 V drop in the distribution loop (from the battery terminals to the load equipment terminals). The maximum voltage, 28.3 V, corresponds to a 12-cell battery being equalized at 2.35 V/cell (28.2 V battery voltage), a minimum of 0.0 V drop in the distribution loop, and rectifiers operating at the high side of +0.5% regulation (0.14 V).

Two operating ranges are specified for nominal 48-V systems:

- Range 1: 42.75 to 56.7 V
- Range 2: 40.0 to 56.7 V

The 48-V systems used in telecommunications have a positive ground (negative operating voltage with respect to ground).[4] The minimum voltage in range 1—42.75 V—is based on design limitations in some existing end office switching systems that use dc signaling on network-to-user interfaces such as loop-start line circuits (POTS) and ground-start analog line circuits, loop-reverse battery (LRB), analog trunk circuits, and E&M analog trunk circuits. This includes Lucent 5ESS and Nortel DMS-10 and DMS-100, and others. To accommodate 42.75-V minimum equipment voltage and 2.0-V maximum distribution loop voltage drop, the final battery voltage must be 44.75 V (1.86 V/cell).

The minimum voltage in range 2—40.0 V—is based on the same thinking as for 24-V systems but with a maximum distribution loop voltage drop of 2.0 V. Therefore, the minimum voltage corresponds to an end-of-discharge condition where the final cell voltage is 1.75 V/cell (42.0 V final battery voltage) and a maximum of 2.0-V drop in the distribution loop (from the battery terminals to the load equipment terminals). This range does not consider any limitations, if applicable, in the end office switching system.

The maximum voltage in both ranges 1 and 2 is 56.7 V, and this corresponds to a 24-cell battery being equalized at 2.35 V/cell (56.4-V battery voltage), a minimum of 0.0-V drop in the distribution loop, and rectifiers operating at the high side of +0.5% regulation (0.28 V).

Equipment and systems that operate satisfactorily at lower voltages of 40.0 to 42.0 V are available, but for any group of interdependent network equipment, the system minimum voltage is determined by the loads requiring the highest minimum voltage. A large amount of equipment in use today requires 44.0 V minimum. Therefore, if network equipment that operates down to 42.0 V is interdependent on equipment that operates down to 44.0 V, the minimum operating voltage for the group is 44.0 V.

Similar considerations are required at the high end of the range. For example, if equipment is used in a facility that cannot withstand prolonged operation at a voltage higher than 56.0 V, then the high limit for the power system must be set to 56.0 V even though there may be equipment in the same facility that operates satisfactorily at, say, 60.0 V. It should be noted that prolonged operation at higher voltages almost always reduces equipment reliability even when the equipment is rated for the higher voltage. It also should be noted that a considerable amount of equipment used in the network today is designed to operate at voltages outside of the ranges just discussed, either higher or lower or both.

5.1.4 Load Characteristics

One consideration in dc power system design is how the load current changes as the voltage decreases on battery discharge. The load characteristics of individual network components depend on their technology. There are three basic types of load characteristics:

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[4] See Chapter 1, Introduction, for a brief discussion of why this polarity is bonded to earth ground.

- Resistive—current (and power) decreases as voltage decreases [Fig. 5.3(a)]
- Constant current—current stays constant (and power decreases) as voltage decreases [Fig. 5.3(b)]
- Constant power—current increases (and power stays constant) as voltage decreases [Fig. 5.3(c)]

Most modern network equipment can be classified as constant power, in which case the current increases as the battery voltage decreases.

5.1.4.1 Estimating Equipment Loads

All telecommunications facilities will have one or more of the equipment types shown in Table 5.1. This table can serve as a checklist for new facilities to ensure that the power system design takes into account all equipment that may be used initially or in the future.

Network equipment load characteristics depend on its basic function and technology. Digital end office circuit switches have a large fixed load component plus a relatively small variable component that depends on traffic levels. If the central office facility has a significant amount of pair gain equipment, such as digital added main line (DAML) and universal digital loop carrier (UDLC), the load is boosted by the pair gain equipment, which also is traffic dependent on a one-for-one basis with circuit-switch load (each off-hook or ringing DAML line corresponds to an off-hook or ringing circuit-switch line).[5]

Some rules of thumb are

- Each on-hook (idle) line circuit draws ~ 0.8 W.
- Each off-hook (busy) line circuit draws ~ 2.5 W.
- Each ringing line circuit draws ~ 1 to 2 W.
- Each off-hook DAML line draws a few watts.

Most central offices include transmission and multiplex equipment and packet switching and routing equipment. The dc load caused by this type of equipment is constant regardless of traffic. The load currents in two typical central offices that consist of digital end office switching systems are shown in Figures 5.4(a), 5.4(b), and 5.5.

The load characteristics of wireless radio frequency (RF) equipment are quite different from switching systems. With trunked channelized RF equipment, there is a relatively small fixed (static) load component and a large variable load component. The variable component depends on traffic (each active channel contributes to the load), and daily variations are fairly predictable—midmorning, midafternoon, and evening (Figs. 5.6 and 5.7).

For example, a typical 30-channel AMPS/TDMA cellular site has ~70 A fixed load, and the load per active RF channel is ~ 5 to 7 A at 27 Vdc.[6] Since most modern RF equipment uses constant power switch-mode power supplies, the current increases as the voltage decreases when the system battery discharges.

Wireless systems, like all telecommunications systems, experience peak traffic during disasters such as airline crashes, tornados, hurricanes, earthquakes, and floods. The peak

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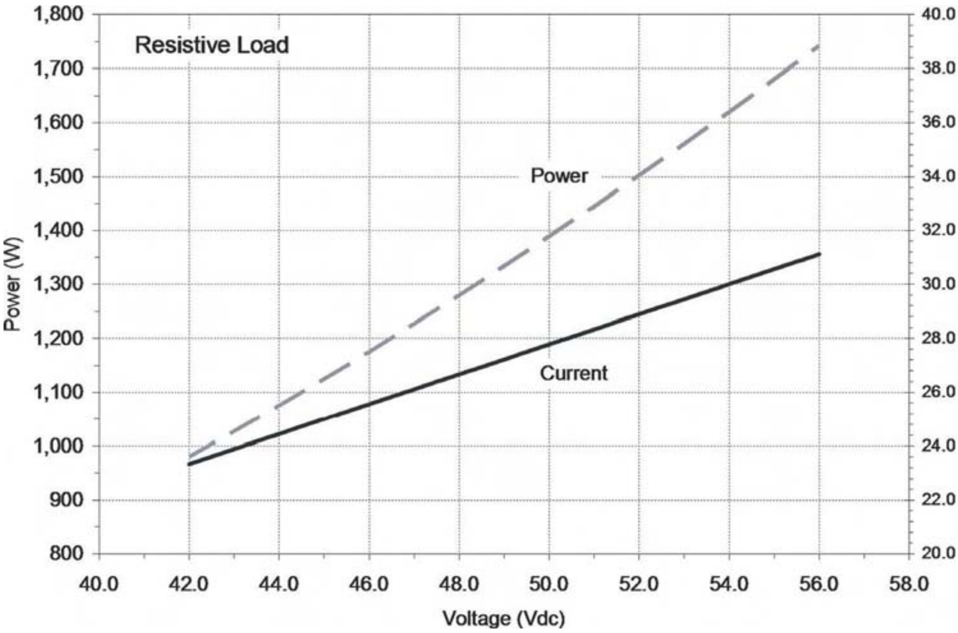
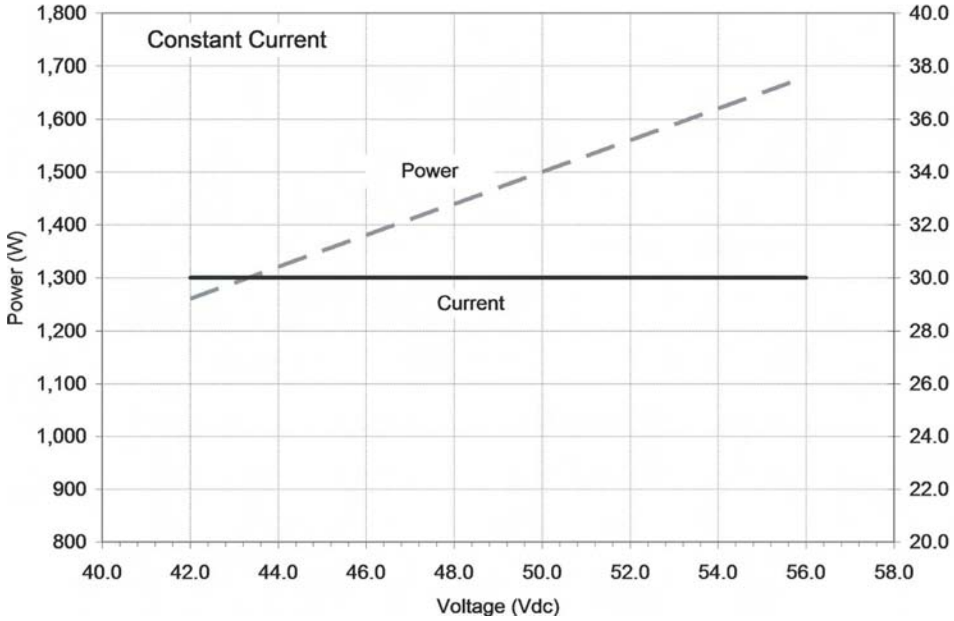
[5] Pair gain equipment is access network equipment that is used to temporarily or permanently provide more than one POTS line on one metallic twisted cable pair.

[6] AMPS stands for Advanced Mobile Phone service and TDMA stands for Time Division Multiple Access. Both are modulation technologies used in mobile wireless telecommunications services.

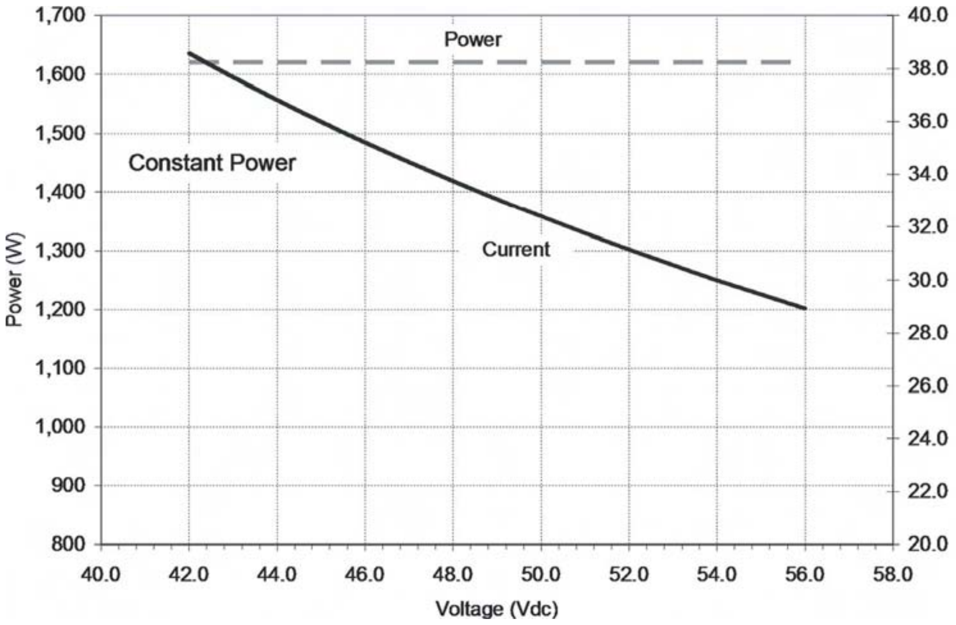


(a)



(b)

Fig. 5.3 (a) Resistive load characteristics. (b) Constant current load characteristics.

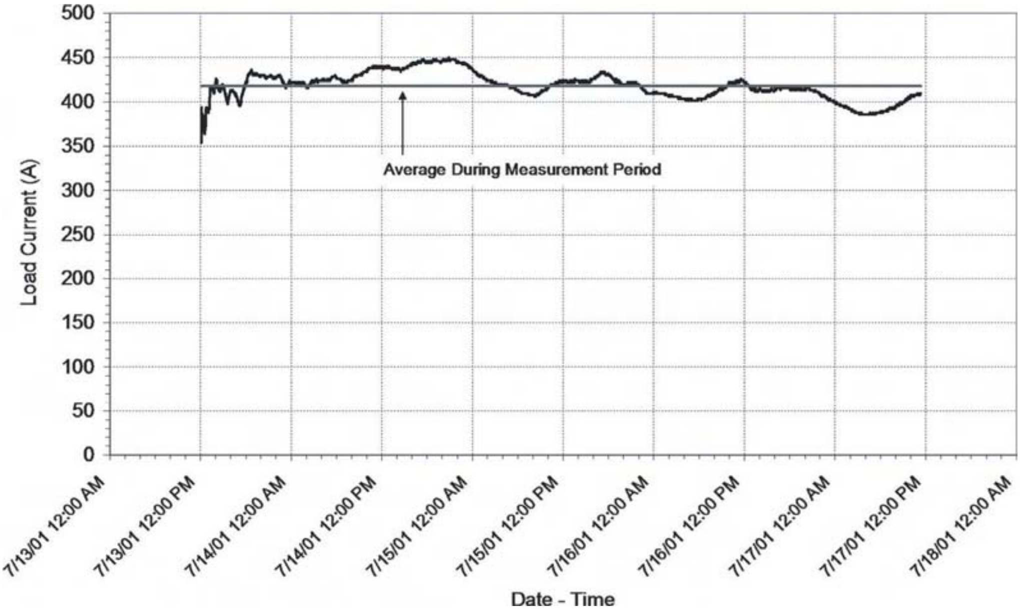


(c)

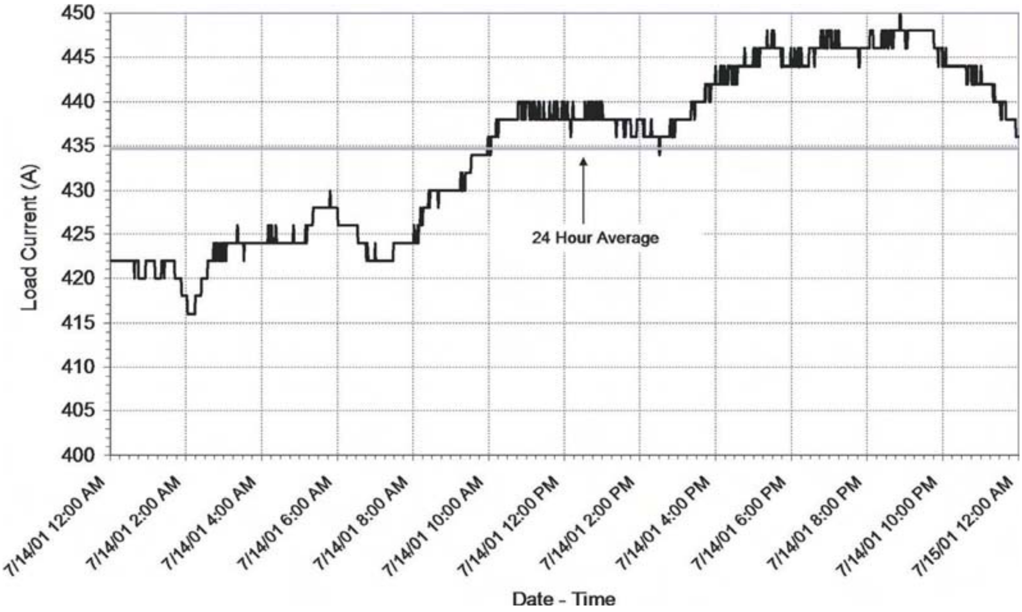
Fig. 5.3 (c) Constant power load characteristics.

Table 5.1 Network Equipment Types Connected to the dc Power System

Analog loop transmission equipment
dc–dc converters
Digital circuit multiplication equipment (DCME)
Digital cross-connect systems (DCS)
Digital subscriber line access multiplexers (DSLAM)
Digital subscriber line (DSL) loop termination equipment
Digital microwave radio terminals
Echo cancellers
End office and transit circuit-switching and packet-switching systems
Fiber-optic terminals
High bit-rate DSL (HDSL) span termination equipment
Host digital terminals (HDT)
Internet and data network equipment such as ATM switches, routers, and related servers
Inverters
Local area network (LAN) routers and related equipment such as hubs, switches, and data controllers
Mobile and fixed wireless radio frequency (RF) equipment
Mobile switching centers (MSC), either circuit or packet switching
Modem servers for dialup Internet service
Primary multiplexers (channel banks) and M13 multiplexers
Operation support systems
Optical line termination (OLT) equipment
Pair gain systems such as digital added main line (DAML) and universal digital loop carrier (UDLC)
Remote office test line equipment and testboards
T1-carrier span termination



(a)



(b)

Fig. 5.4 (a) Central office—local exchange network operator. Measurement of main bus load over a 4-day period (Friday afternoon to Tuesday morning) during July 2001. The primary load is a circuit switch with approximately 12,000 access lines; other loads include digital microwave radio and fiber-optic termination equipment, and almost all other items listed in Table 5.1. The switching system primarily serves residential subscribers. (b) Same location as (a) except the scale has been expanded to show only one day, Saturday. This graph clearly shows that the central office serves mostly residential subscribers—low load during early morning hours and high load during late evening hours. A central office that primarily serves business subscribers will show a midmorning and midafternoon peak.

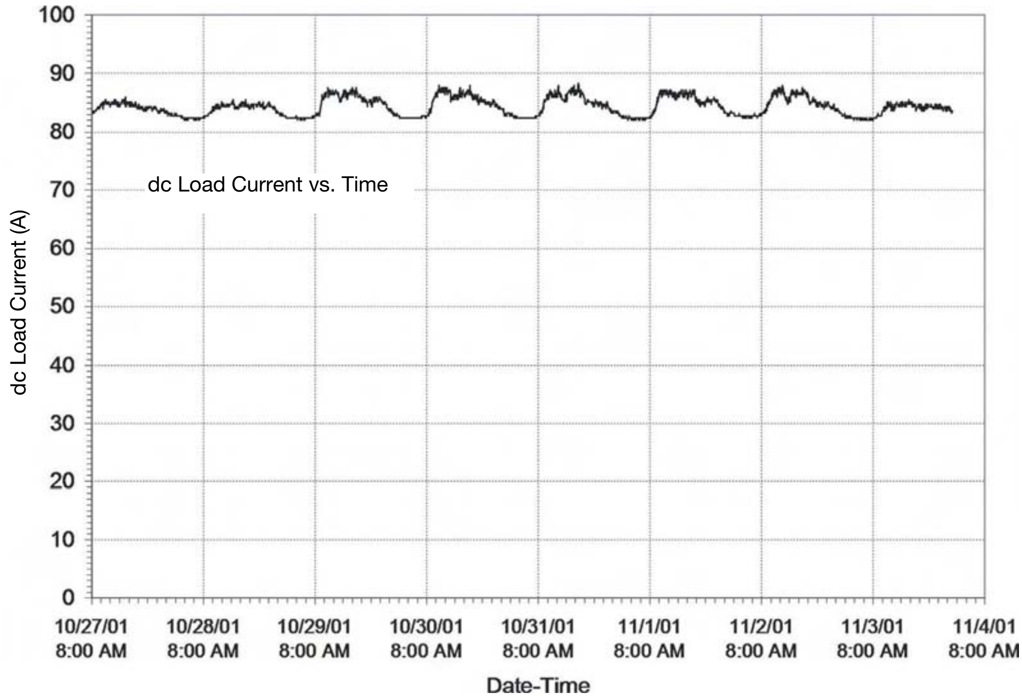
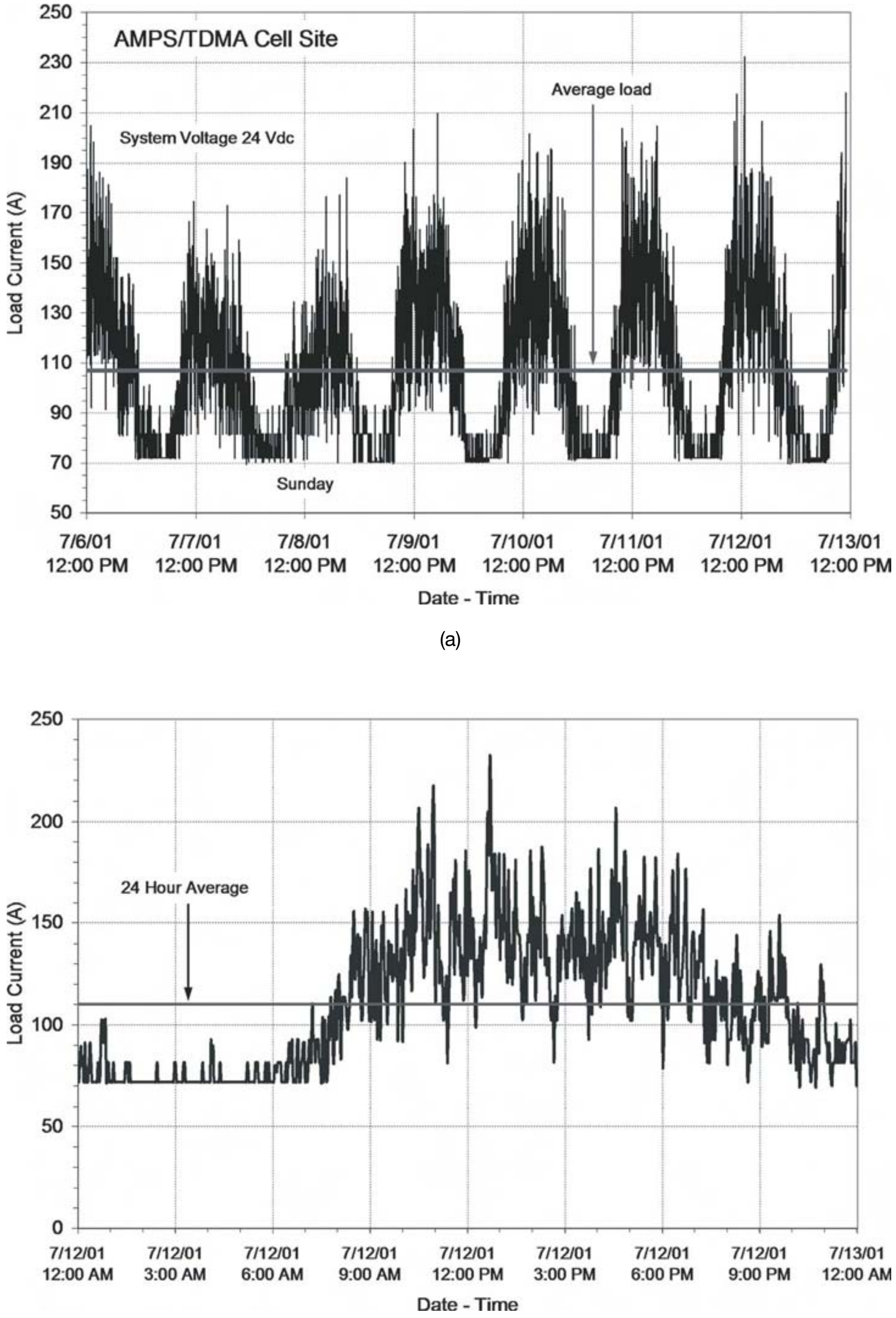


Fig. 5.5 Central office—local exchange network operator. Measurement of main bus load over a 7-day period in October 2001. The primary load in this central office is a circuit switch with 2000 access lines. The switching system serves a mix of business and residential subscribers. Note the daily load variations of about 10% due to line traffic.

traffic effects may be localized to a particular community, commuting corridor, or central office or may be spread over a wide geographic region. The design basis for public telecommunications systems is not peak traffic but instead to achieve acceptable blocking levels during high-average traffic conditions (e.g., the average of the busy hours during the 10 highest traffic days during the busy season, 10HDBSBH—10 high day busy season busy hour). Nevertheless, wireless cell-based base transceiver stations (BTS) and their associated power systems need to be designed to handle simultaneous calling on all channels.

Equipment loads can be estimated from manufacturers' data sheets if they are available. Unfortunately, in many cases accurate and detailed information is difficult to obtain without actually buying the equipment. This makes designing a new facility for a new switching system somewhat difficult unless that same system is used elsewhere by the network operator and detailed engineering information is available. One public source of useful load information for a variety of network equipment that may be found in rural central offices is [2].

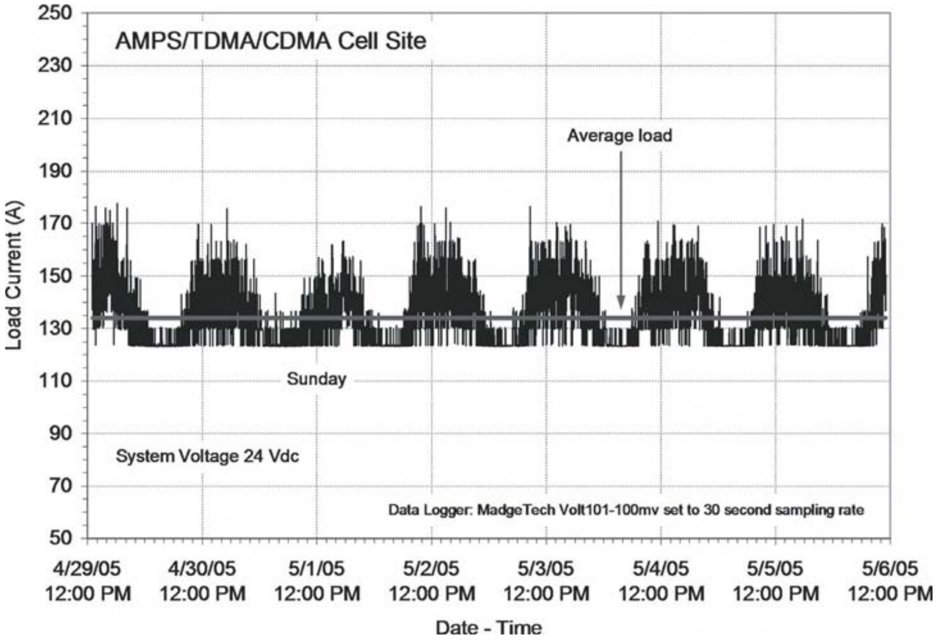
Each generation of network equipment uses less power than its predecessor, which implies that the overall load in a given facility is likely to decrease over time. However, what really happens is the load increases as the amount of equipment increases with system growth (this is true of both end office and transit switching systems, which represent the majority of the load in most central offices). By the time the load equip-



(a)

(b)

Fig. 5.6 (a) RF cell site—wireless network operator. Measurement of main bus load over a 7-day period in July 2001 at a site in southcentral Alaska. At that time the site included 29 AMPS and TDMA RF channels in a ratio of 15 : 6. Note that the fixed load component is around 70 A with a peak around 230 A (at 24 V). Compare with part (c). (b) Same location as (a) except the scale has been expanded to show only one day during midweek, Thursday.



(c)

Fig. 5.6 (c) Same location as (a) except the data were taken about 4 years later in May 2005. At that time the site included three CDMA RF channels and 29 AMPS and TDMA RF channels.[7] Compare with (a) and note that the base load has significantly increased while the peak load has significantly decreased. This probably is due to a larger percentage of users having CDMA handsets than TDMA or AMPS (CDMA RF carriers are online all the time).

ment reaches maximum capacity, it is obsolete and requires either total or partial replacement. This occurs at approximately 8- to 12-year intervals. When the major group of equipment is replaced, the load decreases significantly, and another load growth cycle starts.

One indirect method that may be used to estimate equipment loads in a facility is to assume that all power delivered to network equipment is dissipated as heat in the equipment room. While this is completely true of modern transmission systems, a small fraction of the power delivered to landline end office switching systems is dissipated in the outside plant and customer premises installation and for wireless systems is dissipated in the antenna and through propagation outside the facility. In all cases, this is ignored in the estimates.

Assuming that the network equipment complies with Telcordia's Network Equipment Buildings Systems (NEBS) requirements [3][8], then the heat dissipation can be calculated

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[7] CDMA stands for Code Division Multiple Access and is a modulation technology for mobile wireless services.

[8] NEBS requirements are technical requirements originally prepared by Bell Communications Research (Bellcore) for its Bell Operating Company (BOC) clients. Bellcore is now known as Telcordia. Because the BOCs have large market power, many equipment manufacturers build according to NEBS requirements so they can sell to the BOCs. NEBS requirements are not national standards but are considered de facto standards by a large segment of the telecommunications industry in the United States.

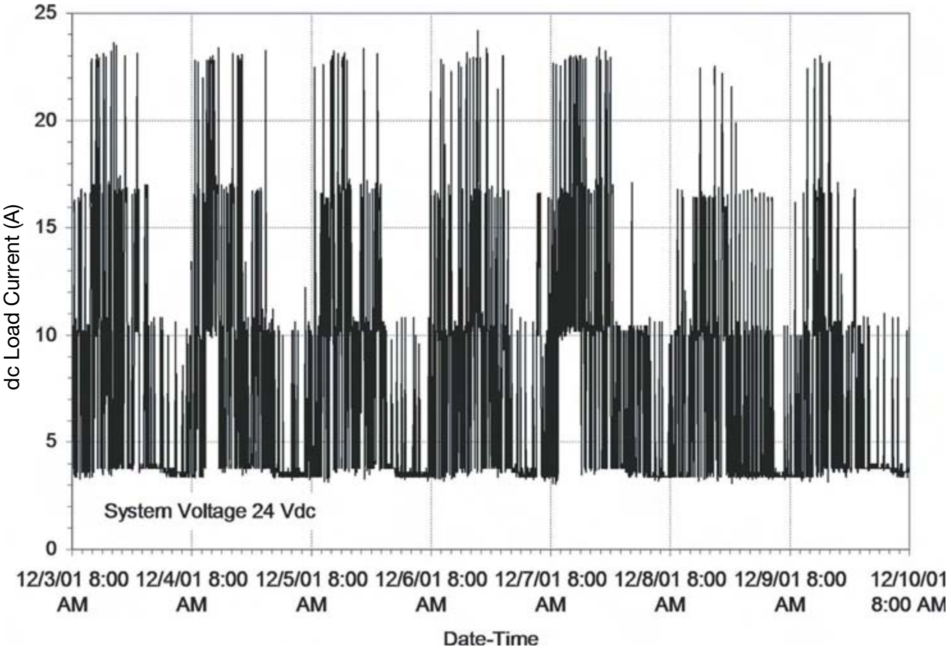

Fig. 5.7 800 MHz trunked radio (specialized mobile radio—SMR) RF site used for fixed wireless local loop service. Measurements show the main bus load over a 7-day period in midwinter 2001. This site consists of 4 analog FM voice channels operating at 24 V and is located in southwest Alaska.

from those requirements. NEBS requirements specify objective maximum heat dissipation in terms of area or volume for three configurations:

- Entire central office equipment space
- Individual equipment frames
- Individual equipment shelf or chassis in a frame

For all usable area in the central office equipment space:

- Objective maximum for usable central office space—79.9 W/ft^2

Example 5.1 The floor plan for a small central office is shown in Figure 5.8. Room 104 is the equipment room. Determine (1) the objective maximum heat dissipation for this space and (2) the estimated current from a 48-Vdc power system to produce this heat.

Solution The dimensions of room 104 are 24 ft 0 in. long by 19 ft 8 in. wide, and the area is 472 ft^2. Using NEBS objectives, the maximum objective heat dissipation is 79.9 W/ft^2 × 472 ft^2 = 37,713 W (37.7 kW). At a nominal load voltage of 48 Vdc, the current required to generate this amount of heat would be approximately 786 A.

It is well known that not all equipment and not all central office spaces are designed to meet NEBS requirements, but this amperage calculation can be used as a starting point for system design.

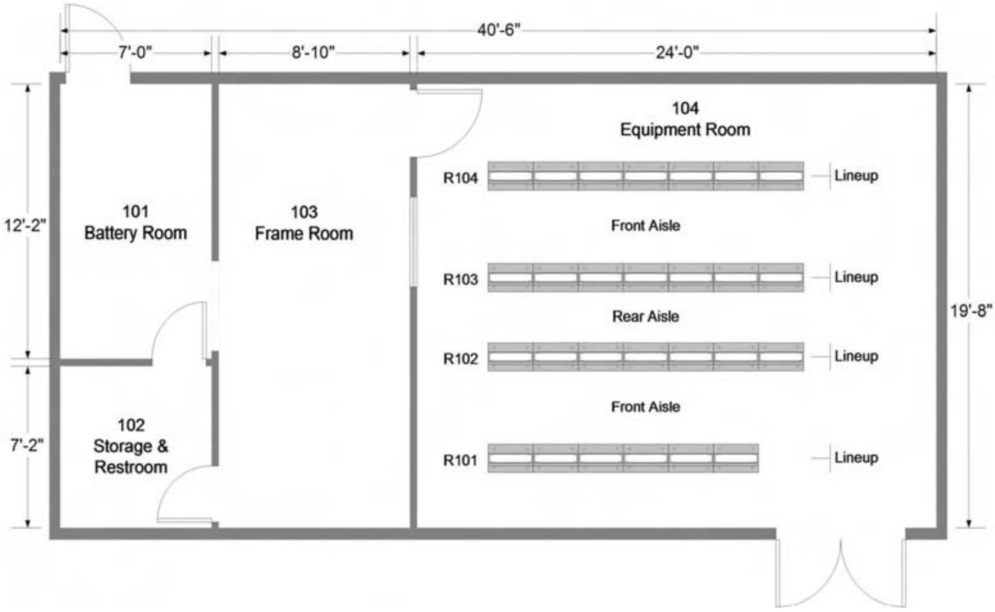

Fig. 5.8 Central office floor plan for Example 5-1.

The NEBS objectives for the maximum heat dissipated by an individual equipment frame are:

- Convection cooled equipment—134.7 W/ft^2 maximum heat dissipation
- Forced-air fan-cooled equipment—181.2 W/ft^2 maximum heat dissipation

Applying these objectives requires knowledge of the effective floor area covered by the frame. The area includes one-half aisle in front and back (Fig. 5.9). Equipment frames with higher heat dissipation, whether or not the equipment is fan cooled, may require wider aisles in order to meet the overall objective of 79.9 W/ft^2 for the entire space.

Equipment frames in a telecommunications facility are aligned in rows, or *lineups* (Fig. 5.8). The spaces between lineups are *aisles.* Various names are given to the aisles depending on whether they are in front or back of the lineup. Since the maintenance on most equipment is done from the front, the front aisle sometimes is called a *maintenance* aisle but more often just *front* aisle. The rear aisle in many types of installations is narrower because routine maintenance access to it is unnecessary and extra space for workers to move around is not critical. This aisle sometimes is called the *installation* aisle but more often just *rear* aisle. If equipment cabinets require access only from their front, they may be mounted back-to-back or close to walls to conserve floor space. In seismic areas, equipment frames and cabinets that are not fastened together usually are separated by 6 to 12 in. In other cases, both front and rear access is required for installation and routine maintenance and front and rear aisle widths are the same. Most central offices have a mixture with different aisle widths.

The overall design requirements for equipment frames, cabinets, and panels are described in [4], and a *Universal Telecom Framework,* which encompasses dimensional pa-

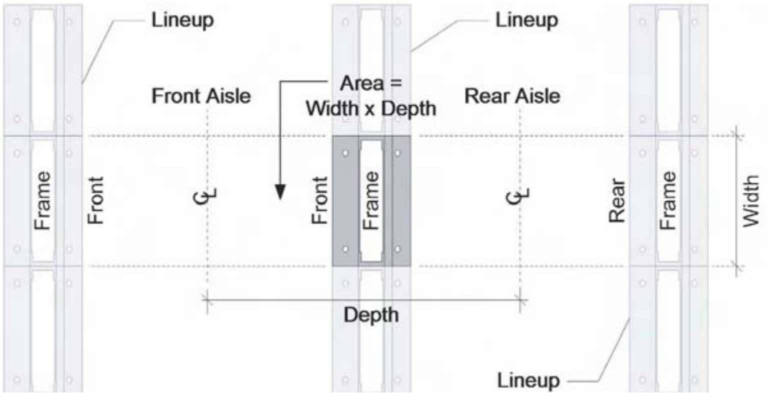

Fig. 5.9 Equipment frame area for NEBS heat dissipation (frame in center of drawing). This illustration shows the plan view of equipment frames and aisle spacing.

rameters, performance (such as loading) and application criteria, is described in [5]. For purposes of this discussion, equipment frames can be open rack structures (*relay racks*) or enclosed cabinets. Network equipment frames usually are 12 to 15 in. deep, although the trend is toward deeper frames. Traditional frame widths are either $20\frac{3}{8}$ in. (19-in. frame) or $24\frac{3}{8}$ in. (23-in. frame), but the trend is toward wider frames. Frame heights of 7, 8, 9, and $11\frac{1}{2}$ ft have been used, but in many installations 7- or 8-ft frames have replaced the 9- and $11\frac{1}{2}$-ft heights.

Transmission and other equipment installed since the late 1980s in many central offices use frames that are 26 in. wide and 7 ft high. Traditional circuit switching system frames usually are much wider (30 to 32 in., or more) and deeper (15 to 18 in.). As a matter of engineering policy, many companies use only 23 in. (nominal) frames and do not use 19 in. frames in new installations, traditional switching systems being the exception. The width of nominal 23 in. frames for heat calculation purposes usually is assumed to be 26 in. (rather than the actual width).

Some of the latest generation switching systems fit in “standard” 19- or 23-in. frames, but the equipment shelves are up to 24 in. deep (30 in. of depth with cabling). Data switching, routing, and server equipment originally designed for enterprise applications has been installed in central offices even though it was never intended for that environment. This equipment usually is 20 to 24 in. deep and overall has unwieldy dimensions and ill-fitting mounting arrangements, which affect how they are mounted and how many can fit in a frame.

The equipment depths used in NEBS objectives are 12, 18, or 24 in. (if the actual depth is between sizes it is rounded up; e.g., if the actual depth is 14.5 in., it is rounded up to 18 in.). Recommended aisle widths in the NEBS objectives for typical frame depths are shown in Table 5.2, but considerable variations exist in practice. The main point is to design aisle widths that meet both heat dissipation and physical maintenance requirements. The total floor area of an equipment frame for calculation purposes is

$$A_{\text{Floor}} = \frac{W_{\text{Frame}}\left(D_{\text{Frame}} + \dfrac{W_{\text{Front}}}{2} + \dfrac{W_{\text{Rear}}}{2}\right)}{144}\ \text{ft}^2 \tag{5.1}$$

Table 5.2 NEBS Objective Aisle Widths [3]

Frame Depth (in.)	Front Aisle (in.)	Rear Aisle (in.)
12	30	24
18	54	30
24	42	30

where A_{Floor} = floor Area (ft^2)
W_{Frame} = frame width (in.)
D_{Frame} = frame depth (in.)
W_{front} = front aisle width (in.)
W_{rear} = rear aisle width (in.)

To convert dimensions in inches to millimeters, multiply by 25.4 and to convert dimensions in square feet to square meters, multiply by 0.0929.

Example 5.2 Determine the footprint including aisles of a 23-in. (nominal) equipment frame that is 18 in. deep where the aisles are 36 in. (front) and 30 in. (rear).

Solution For calculation purposes, the frame width is assumed to be 26 in. Using Eq. (5.1)

$$A_{\text{Floor}} = \frac{26(18 + \frac{36}{2} + \frac{30}{2})}{144} = 9.21 \text{ ft}^2$$

The NEBS objectives for the maximum heat dissipated by an individual equipment shelf or chassis (Fig. 5.10) are based on a volumetric value determined by the shelf footprint (equivalent floor area including one-half aisles) and height.

- Convection cooled—20.9 W/ft^2/ft of vertical frame space
- Forced fan cooled—27.9 W/ft^2/ft of vertical frame space

The height includes any required heat deflectors (air ramps), spacers, and fan cooling trays even if separate from the chassis. For example, if a shelf is 10.5 in. high but requires

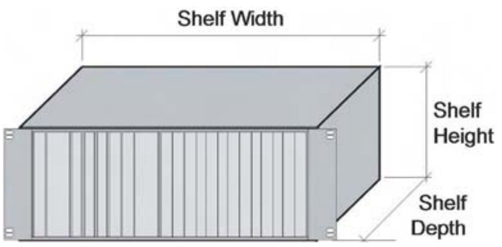

Fig. 5.10 Equipment shelf dimensions; the overall footprint includes shelf depth plus one-half aisle widths (not shown).

an open space or deflector of 1.75 in. above it, then the height dimension used in the calculations is 12.25 in. Most network equipment has a vertical dimension in increments of 1.75 in., which often is referred to as one "rack space unit" (RSU) or "rack mounting unit" (RMU). Therefore, an equipment height of 5.25 in. is equal to 3 rack mounting units. A 7-ft frame can hold at most 42 rack mounting units (42 × 1.75 in. = 73.5 in. = 6.125 ft) because of structural components at the top and bottom.

The dc load current for frames and shelves may be determined by using the same concepts as for the total central office space.

Example 5.3 Determine the objective maximum heat dissipation for a 7-in. high (4 rack space units) by 15-in. deep convection cooled equipment shelf mounted in a 23-in. frame with 36-in. aisle in front and 30-in. aisle in back.

Solution According to general practice, the 15-in. depth is rounded up to 18 in. The total depth is 18 in. (one-half front aisle) + 18 in. (equipment) + 15 in. (one-half back aisle), or 51 in. = 4.3 ft. The area is the frame width, 26 in. = 2.167 ft, times the total depth of 4.3 ft, or 9.318 ft^2. The equipment height is 7/12 = 0.583 ft, and the maximum objective heat dissipation is 20.9 $\text{W/ft}^2\text{/ft} \times 9.318\ \text{ft}^2 \times 0.583\ \text{ft} = 114\ \text{W}$. This wattage corresponds to a load current of approximately 2.4 A at 48 V input voltage.

Example 5.4 A fan-cooled next-generation switching equipment shelf is 14 rack mounting units (24.5 in. = 2.042 ft) high, 12 in. deep and fits in a 23-in. frame. Three of these will fit in a 7-ft frame. Each shelf requires two 50-A power feeds, but the actual load never exceeds 12.5 A (total of both power input buses). (1) Determine if this equipment meets NEBS objectives when the front and rear aisle widths are 30 in. and 24 in., respectively. (2) Determine how many of these equipment shelves may be mounted in a 7-ft equipment frame if NEBS objectives for equipment frames are to be met.

Solution (1) The total depth is 15 in. (one-half front aisle) + 12 in. (equipment frame) + 12 in. (one-half rear aisle) = 39 in. = 3.25 ft, and the width is 26 in. = 2.167 ft. The floor area is $3.25\ \text{ft} \times 2.167\ \text{ft} = 7.042\ \text{ft}^2$. At a nominal input voltage of 48 V, the heat dissipation is 48 V × 12.5 A = 600 W. The heat per volume is $600\ \text{W} \div (7.042\ \text{ft}^2 \times 2.042\ \text{ft}) = 41.7\ \text{W/ft}^2\text{/ft}$. This equipment does not meet NEBS equipment shelf objectives of 27.9 W/ft^2 (by a factor of about 1.5).

(2) The NEBS objective for an equipment frame with fan-cooled equipment is 181.2 W/ft^2. The floor area is 7.042 ft^2. Therefore, the maximum allowable heat dissipation is $181.2\ \text{W/ft}^2 \times 7.042\ \text{ft}^2 = 1276\ \text{W}$. Since one shelf dissipates 600 W and two shelves would dissipate 1200 W, two equipment shelves may be mounted in the frame (even though three physically fit in the frame).

5.1.4.2 Load Conditions

Two load conditions are used to size dc power system components (except the battery system):

Normal Average load current during normal "busy hour" operation. Normal load current is one of the parameters used to size rectifiers.

Peak Peak load current during worst-case conditions (lowest discharge voltage and peak load) and includes prediction of future growth estimates. Peak load currents are used to size the primary distribution circuits and conductors, primary overcurrent protective devices, and system discharge bus capacity. These components are difficult to add or expand once the system is operational.

Where most loads are constant power, neither condition may be suitable for battery size calculations; however, a conservative design may use peak currents for battery system design. This may be too conservative in some applications because it assumes the load current drawn by constant power equipment to be at a maximum level from start to finish of battery discharge, which is not the case. A less conservative but more accurate battery system design uses an average voltage at the load during battery discharge.

The average voltage depends on the battery voltage and the voltage drop between the battery terminals and equipment terminals, which in turn depends on the average load current and circuit and battery internal resistance. It would be a waste of time to try to determine precise values for the variables because of the many required assumptions. Instead, it is sufficient to use typical average values for the load operating voltage: 44 to 48 V for 48-V systems and 22 to 24 V for 24-V systems. The lower values would apply where most loads are on circuits with maximum voltage drop and the higher values would apply where most loads are close to the battery system and connected by circuits with low voltage drop. For example, the average current to a 1300 W load would be 29.6 A for an average load voltage of 44 V and 27.1 A for an average load voltage of 48 V.

5.1.4.3 Collocation Collocation agreements specify the obligations and conditions under which the equipment space owner allows others to occupy and use it. The occupation may be voluntary and desirable as a matter of business or it may be involuntary and (probably) undesirable as a matter of regulation. An example of the former is a space provider for many network operators and an example of the latter is an ILEC subject to competition.

The ILEC collocation agreements normally do not allow batteries in equipment rooms; however, if the ILEC puts its own batteries in its equipment rooms, it normally cannot prevent CLECs from doing the same thing (ILECs cannot hold CLECs to different standards than they themselves use). Equipment installed under a *virtual* collocation agreement normally is powered from the same powerboards and distribution systems as the ILEC's own equipment. Equipment installed under a physical collocation agreement normally is powered from distribution circuit breaker or fuse panels dedicated to collocation equipment.

The amount of power provided to collocated equipment is in amperage increments specified in collocation tariffs or agreements. Typical increments are 40 and 15 A. The feed to collocation equipment normally is redundant. For example, if a collocater requires a 40-A service, a redundant feed consisting of a 40-A feed from the A-bus and a 40-A feed from the B-bus is provided. The collocater may be billed on a bulk basis (e.g., for the 40-A feed just described) or in billing units or increments. If the billing unit or increment is 15 A, then a 40-A service would be billed as three units of 15 A each.

5.2 BATTERY SYSTEM DESIGN

The results of the battery system design are

- Choice of technology—vented lead–acid (VLA) or valve-regulated lead–acid (VRLA)

- Total battery capacity in ampere-hours (at the nameplate 8-h rate at 25°C to 1.75 V/cell)
- Number of battery strings required to provide the total capacity

5.2.1 Choice of Technology

The choice of battery technology includes a number of considerations, such as initial and operational costs, weight, floor space requirements, anticipated growth, battery life, and reliability. The choice between the VLA and VRLA batteries can be made based on the information provided in Chapter 4, Telecommunications Batteries; however, there is one additional important consideration not described there:

- When analyzing the choice between VLA and VRLA, engineering economic analysis should play a part in the decision.

Engineering economic analysis is one of the many analysis tools seldom used anymore in the telecommunications industry, although it is an important engineering process.[9] Numerous books are available that describe engineering economic analysis methods, some targeted toward telecommunications [6–10]. An example will illustrate a specific application to battery technology selection.

Example 5.5 Determine the annual charges, including capital recovery, over a 20-year period for a 24-cell 1000-Ah VLA battery compared to a 1000-Ah VRLA battery. The material cost, including delivery to the site, for the VLA battery is $15,000 and for the VRLA battery is $18,000. Installation costs are estimated to be $4500 for the VLA and $3000 for the VRLA battery. Do the analysis using a 5% annual cost of money and make the following assumptions: Labor cost is $80 per hour (including overhead); there are no operating costs other than maintenance; and there is no inflation. For this example, ignore all costs associated with floor space (the VLA battery generally will require more floor space) or remodeling that may be required.

Solution First consider battery life: A reasonable assumption is that VRLA battery life will be 10 years (i.e., it must be replaced at 10-year intervals) and that one cell will require replacement 5 years and another 7 years after the new installation. Each cell replacement is estimated to cost $2030, which includes 16 labor-hours and replacement cell cost of $750 (this assumes a warranty fight between the manufacturer and the network operator is not worth the trouble; here, it is assumed the costs of an army of lawyers is much greater than the cost of a replacement cell). The replacement cost of the VRLA battery is estimated to be the same as the initial battery. The VLA battery is assumed to last 20 years with no cell replacements before end-of-life. The costs of cell and battery replacements include the costs of disposal.[10]

Now consider maintenance: Routine maintenance costs for the two battery technolo-

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[9] Engineering economic analysis is not particularly difficult; however, to do the analysis correctly and as accurately as possible, numerous assumptions about the future are required and these predictions are difficult to make.

[10] Battery manufacturers generally do not charge for disposal, but shipping from the site to the disposal depot is the user's responsibility.

gies will be different. The VLA battery requires routine inspections, cell resistance, voltage and specific gravity measurements, and water replenishment. The VRLA battery requires routine inspections and cell resistance and voltage measurements. Chapter 6 has a more complete list of maintenance tasks, but for this example it is assumed that, including travel time to the site, annual VLA battery maintenance requires 40 labor-hours ($3200 per year) and annual VRLA battery maintenance requires 20 h ($1600 per year).

The above assumptions are summarized in terms of investments and maintenance expenses for each year of the study period (Table 5.3). This table also shows the present value factor, component present value dollar amount, and total present value for each battery technology at the 5% interest rate. Under the conditions stated and with the assumptions made, the sum of the present values of investments and expenses are essentially equivalent over a 20-year study period and 5% interest rate (a coincidence).

Table 5.3 Capital Investment, Expense, and Present Value (PV) Summary for Example 5-5

Year	VLA Investment and Expense	VLA Present Values	VRLA Investment and Expense	VLA Present Values	P/F
0	$15,000+ installation @ $4,500	$19,500	$18,000+ installation @ $3,000	$21,000	1.000
1	$3,200	$3,046	$1,600	$1,523	0.952
2	$3,200	$2,902	$1,600	$1,451	0.907
3	$3,200	$2,765	$1,600	$1,383	0.864
4	$3,200	$2,634	$1,600	$1,317	0.823
5	$3,200	$2,509	$1,600 + cell replacement @ $2,030	$2,846	0.784
6	$3,200	$2,387	$1,600	$1,194	0.746
7	$3,200	$2,275	$1,600 + cell replacement @ $2,030	$2,581	0.711
8	$3,200	$2,166	$1,600	$1,083	0.677
9	$3,200	$2,064	$1,600	$1,032	0.645
10	$3,200	$1,965	$1,600 + battery replacement @ $18,000 + $3,000	$13,876	0.614
11	$3,200	$1,872	$1,600	$936	0.585
12	$3,200	$1,782	$1,600	$891	0.557
13	$3,200	$1,696	$1,600	$848	0.530
14	$3,200	$1,616	$1,600	$808	0.505
15	$3,200	$1,539	$1,600 + cell replacement @ $2,030	$1,746	0.481
16	$3,200	$1,466	$1,600	$733	0.458
17	$3,200	$1,395	$1,600 + cell replacement @ $2,030	$1,583	0.436
18	$3,200	$1,331	$1,600	$666	0.416
19	$3,200	$1,267	$1,600	$634	0.396
20	$3,200 + battery replacement @ $15,000 + $4,500	$8,558	$1,600 + battery replacement @ $18,000 + $3,000	$8,520	0.377
	Total present value	$66,735		$66,651	

Each cost component is converted to an equivalent present value using the present value factor (also called *single payment–present value*):

$$\frac{\mathrm{P}}{\mathrm{F}} = \frac{1}{\left(1 + \frac{i}{100}\right)^{n}} \tag{5.2}$$

where P/F = present value factor
i = annual interest rate (%)
n = time period (year)

Discussion As expected, future payouts are deemphasized by the time value of money. Even when the time value of money is not taken into account, both scenarios cost about the same. Of course, any change in the assumptions, particularly those associated with maintenance expenses throughout the battery system life, may cause one battery technology to be considerably less expensive than another. For example, at 5% cost of money, a 20% decrease in the expected VLA annual maintenance expenses (from $3200 per year to $2560 per year) over the 20-year period will yield an $8000 (rounded) reduction in the total present value, and a 20% increase in the expected VRLA annual maintenance expenses (from $1600 per year to $1920) will yield a $3700 (rounded) increase in the total present value. The differences are more dramatic at lower costs of money and less dramatic at higher costs of money.

5.2.2 Battery Capacity

The factors used to calculate battery capacity are

- Equipment load current
- Battery reserve time
- Discharge factor (capacity factor)
- Temperature factor
- End-of-life factor (aging factor)
- Design margin (uncertainty factor)

These are summarized in[11]

$$AH_{\text{8hour}} = I_{\text{EQ}} t_{\text{BR}} F_{\text{Discharge}} F_T F_{\text{EL}} F_{\text{Margin}} \tag{5.3}$$

where AH_{8hour} = capacity referred to the nameplate discharge rate of 8 h at 25°C to a final cell voltage of 1.75 V/cell (Ah)
I_{EQ} = equipment load current (A)
t_{BR} = battery reserve time (h)
$F_{\text{Discharge}}$ = discharge factor (no units)
F_T = temperature factor (no units)

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[11] The letters AH are used in this book rather than C, which is found in some literature, to avoid confusion with the C used in capacitance equations.

F_{EL} = end-of-life factor (or aging factor, no units)
F_{Margin} = design margin (or uncertainty factor, no units)

5.2.2.1 Battery Reserve Time There are two general guidelines for battery reserve time depending on whether or not the facility is equipped with a permanent standby generator:[12]

- Standby generator available: 3 to 5 h reserve time
- Standby generator not available: 8 to 12 h reserve time

The telecommunications industry's baseline reserve time requirement for a facility that has a permanent standby generator is 3 h [11]. Operational experience may indicate a longer reserve time is needed. Also, in rural areas or where fuel or repair resources are not readily available, a longer time such as 5 hours is more appropriate for a baseline.

Where a standby generator is not permanently installed, the baseline reserve time is 8 h [11], but a longer reserve time may be needed based on operational experience, the required driving time to the site with a portable generator and other operational conditions. For example, power outages may last for weeks after severe storms. Reserve times measured in weeks are seldom provided at any site; however, a reserve time longer than 12 h may be appropriate if portable generators have to be rotated through an area. The selection of reserve time should be based on economic analysis and operational conditions.

The above guidelines are very general in nature. Whatever the specific situation, the battery system is to be designed to bridge prime power source interruptions. An "order of magnitude" value for electric utility service failures is two per year and for average duration (time per failure) is one to two hours for facilities with a single electrical service entrance. Some telecommunications facilities have two separate service entrances (and separate distribution circuit feeds from the electric utility) to increase overall service reliability. Where multiple circuit supplies have all circuit breakers closed (no manual or automatic switching required on failure of one of the circuits), the failure rate is about 17% and the average duration is about 40% of single circuit services. Interruption rates for multiple utility circuit supplies with manual or automatic switching schemes are comparable to single circuit supplies, but switching schemes provide smaller average duration, on the order of 15 min. Failure rates are highest for utility supplies operated at distribution voltages and lowest for supplies operated at subtransmission and transmission voltages (> 35 kV).[13] Only very large facilities are fed at subtransmission and transmission voltages.

The frequency and duration of commercial and industrial electric supply interruptions depend on numerous factors. For example, electrical services fed by overhead lines in heavily forested areas will experience more and longer faults from trees falling onto the lines—either deadfalls or windfalls or due to snow load. During the 1970s and early 1980s, electric utilities installed a large amount of underground residential distribution (URD) cable that had high failure rates due to premature insulation breakdown. If such a line feeds the telecommunication facility, there will be numerous extended interruptions until the cables are replaced. Some areas of the country have a high incidence of tornados, and some coastal areas are subject to severe seasonal storms. Some parts of the country

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[12] State public service commission regulations may specify reserve times outside of the ranges given.

[13] These values are adapted from [12], Table 40, for electric utility supplies to industrial plants.

may have inadequate electricity grids with a high risk of extended service outages, while other areas may have just the opposite.

Although the average interruption lasts 1 to 2 h, battery system design has to encompass more than an average interruption. If the site has a standby power source, such as an engine–generator set, the battery must supply power only between the time the prime power source is interrupted and the time the standby power system switches online. Standby systems normally are setup to ignore momentary interruptions and to start and switch online after some time delay—typically 2 or 3 min or possibly longer (30 to 60 min, or more). A site with frequent short interruptions, say, < 10 min, would be set to wait, say, 20 min. A typical preheated diesel engine–generator set requires 15 to 45 s to start and switch online, so where there is a functional standby system the battery may have to operate only for time durations of a few minutes to an hour. However, standby power systems do not always start and run reliably and they eventually must be refueled.[14] In some installations, the standby generator set is the least reliable part of the system (usually because it is not maintained to the same high level as the telecommunications equipment).

The following example will illustrate some of the factors to be considered when deciding battery reserve time.

Example 5.6 Recommend the battery reserve time for the following conditions: A telecommunications facility is located in a suburban area approximately a 4-h drive from the network operator's dispatch center. It is the network operator's policy to not dispatch a technician to a site unless a commercial power outage exceeds 2 h (all sites have alarm systems that detect power outages). Power reliability is considered "okay" because "there have not been many outages" over the years. The outages that have occurred lasted between 30 min and 12 h, although one outage about 4 years ago lasted 3 days. The building does not have a standby generator, but it is equipped with a manual transfer switch and an ac receptacle for temporary connection of a portable engine–generator set.

Solution Since this site does not have a standby generator, the minimum battery reserve time is 8 h. However, if an outage exceeds 2 h, it will take at least 4 h for a technician to reach the site from the dispatch center. To that time (a total of 6 h) needs to be added the time it takes to locate the technician on call-out duty and for the technician to get to the dispatch center, find a functioning portable generator, and hitch it to the truck. Once at the site, additional time is required to unhitch the generator, set it up, and put it online. This can easily add 2 h to the time required. In this case, the total elapsed time is 8 h and the entire baseline reserve time is used up. It is possible the generator needs to be fueled because the last time it was used the dispatch center forgot to refuel it. It also is possible the generator has a history of hard starting and difficulty being placed online. Any number of other things could go wrong and they probably will. With these additional considerations, it would be wise to add at least another hour or two, giving a total recommended reserve time of at least 9 or 10 h for this site. Only a fool-hardy engineer assumes everything will go right every time.

5.2.2.2 Discharge Factor The next parameter to be determined is discharge factor, $F_{\text{Discharge}}$. This factor takes into account the actual discharge rate if different than the nameplate rate of 8 h and cell final voltage if different than the nameplate final voltage of

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[14] See [12] for data.

1.75 V/cell. The first part requires determination of the battery final voltage (V_{BF}), which is the minimum voltage to which the battery can discharge and still maintain equipment operation. The battery final voltage must be greater than the minimum equipment operating voltage (V_{ME}) by an amount equal to the voltage drop from the battery terminals to the load equipment terminals and includes all circuit conductors and connections in between (Fig. 5.11). The maximum voltage drop, suggested in [1], is

- 1.0 V for 24-V systems
- 2.0 V for 48-V systems

The circuit from the battery terminals to the load equipment terminals includes the battery circuit, primary distribution circuit (including discharge bus), and one or more secondary distribution circuits. The total voltage drop is

$$V_{\text{Total}} = V_{\text{Battery}} + V_{\text{Primary}} + V_{\text{Secondary}} \tag{5.4}$$

where $V_{\text{Total}} \leq 1.0$ V for 24-V systems and ≤ 2.0 V for 48-V systems
V_{Battery} = voltage drop in battery circuit (V)
V_{Primary} = voltage drop in primary distribution circuit, including discharge bus (V)
$V_{\text{Secondary}}$ = voltage drop in secondary distribution circuits (V)

and the battery final voltage is

$$V_{\text{BF}} = V_{\text{Total}} + V_{\text{ME}} = V_{\text{Battery}} + V_{\text{Primary}} + V_{\text{Secondary}} + V_{\text{ME}} \tag{5.5}$$

where V_{BF} = battery final voltage (V)
V_{ME} = minimum operating voltage of load equipment (V)

The final cell voltage (V_{CF}) equals the battery final voltage (V_{BF}) divided by the number of cells (N_{Cell}) in the battery (12 cells for 24-V systems and 24 cells for 48-V systems), or

$$V_{\text{CF}} = \frac{V_{\text{BF}}}{N_{\text{Cell}}} \tag{5.6}$$

Example 5.7 Determine the battery final voltage and cell final voltage for the circuit shown in Fig. 5.12.

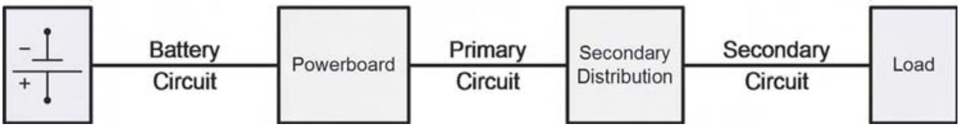


Fig. 5.11 One-line diagram showing the total voltage drop from battery terminals to load equipment terminals.

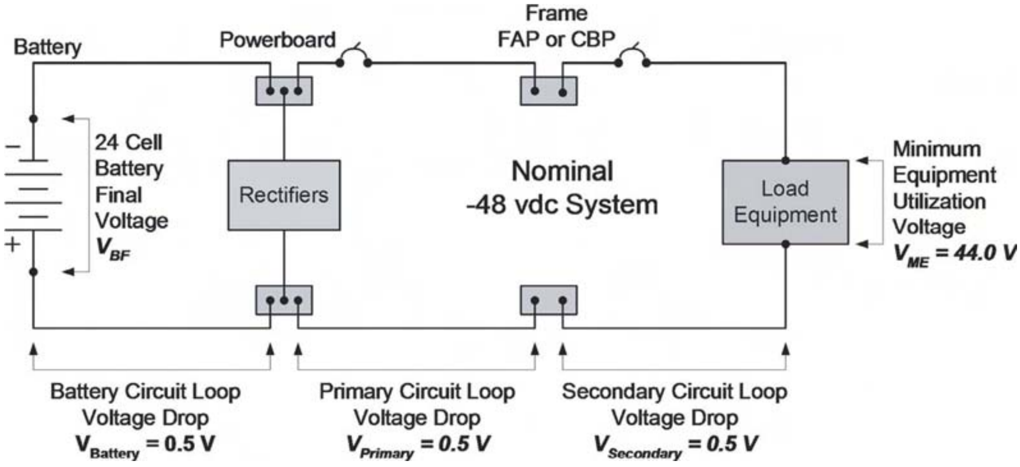


Fig. 5.12 Example 5-7 circuit diagram.

Solution The total voltage drop in this example is

$$V_{\text{Total}} = V_{\text{Battery}} + V_{\text{Primary}} + V_{\text{Secondary}} = 0.5 + 0.5 + 0.5 = 1.5 \text{ V}$$

The battery final voltage is

$$V_{\text{BF}} = V_{\text{Total}} + V_{\text{ME}} = 1.5 + 44.0 = 45.5 \text{ V}$$

and the cell final voltage is

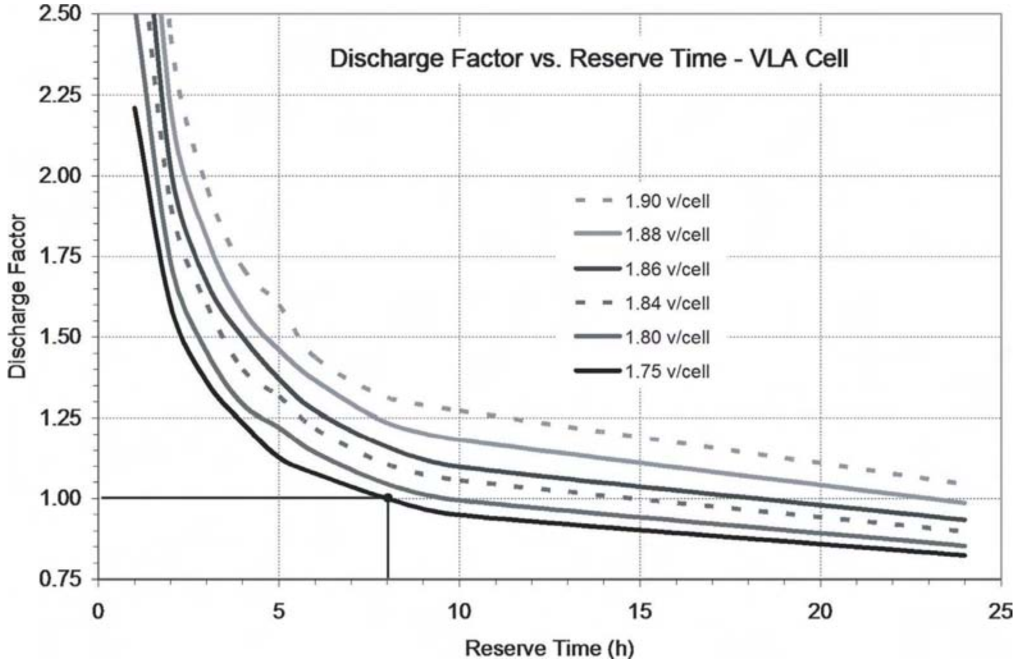
$$V_{\text{CF}} = \frac{V_{\text{BF}}}{N_{\text{Cell}}} = \frac{44.5}{24} = 1.90 \text{ V/cell}$$

Once the final cell voltage has been determined, the discharge factor can be read from charts depending on the technology [Figs. 5.13(a) and 5.13(b)]. These charts are based on typical VLA and VRLA battery systems and can be used for most system designs. Where higher precision is needed, discharge tables or curves should be obtained from the battery system manufacturer and used to develop the discharge factors.

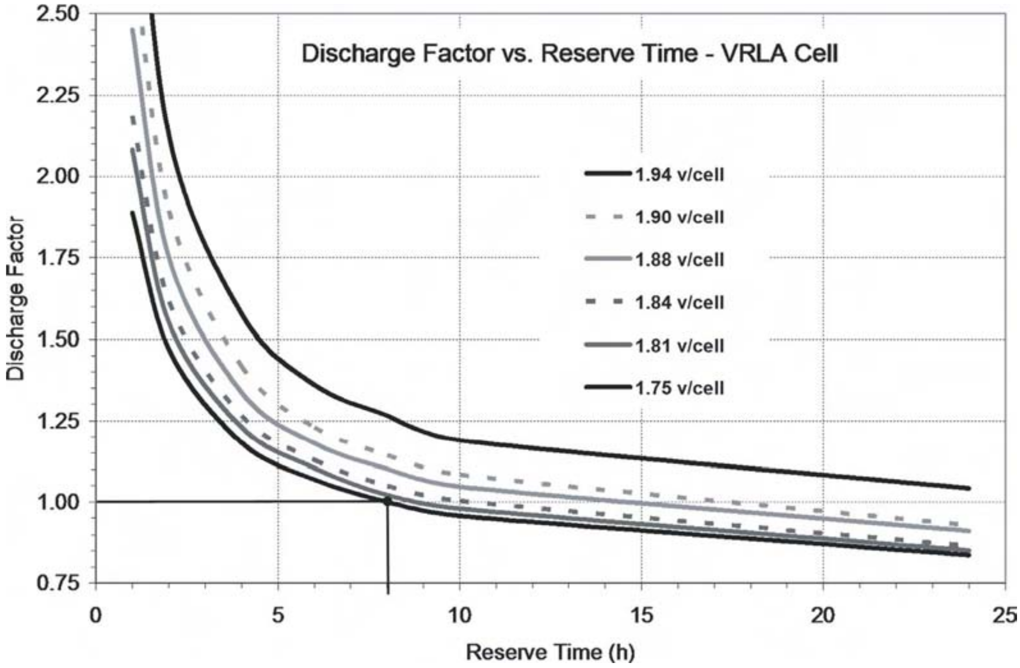
Example 5.8 Determine the discharge factors for VLA and VRLA batteries when the cell final voltage is 1.90 V/cell and the discharge time is 6 and 12 h.

Solution Enter the horizontal axis at 6 and 12 h and move vertically to intersect the desired cell final voltage curve and then left to the vertical axis to read the discharge factor. The discharge factors for VLA technology from Fig. 5.13(a) are approximately 1.45 for 6 h and 1.25 for 12 h. For VRLA, the discharge factors from Fig. 5.13(b) are approximately 1.25 for 6 h and 1.05 for 12 h.

Example 5.9 The required reserve time for a VRLA battery is 5 h to a final cell voltage of 1.92 V/cell. Determine the discharge factor.



(a)



(b)

Fig. 5.13 (a) Discharge factor for VLA batteries (typical); the solid horizontal and vertical lines represent the 8-h nameplate discharge rate at 25°C. (b) Discharge factor for VRLA batteries (typical); the solid horizontal and vertical lines represent the 8-h nameplate discharge rate at 25°C.

Solution Entering Figure 5.13(b) at 5 h on the horizontal axis and move up vertically. It is necessary to interpolate between the 1.90- and 1.94-V final cell voltage curves, then move left across to the vertical axis where the discharge factor of 1.35 is read. This can be interpreted to mean the battery will require 35% more capacity because of the higher than nameplate discharge rate and final cell voltage.

The two discharge factor curves can be approximated in terms of two independent variables (battery reserve time, t_{BR}, and cell final voltage, V_{CF}) by the following expression. This expression is based on regression curve fitting of data from several manufacturers and is sufficiently accurate for initial designs; expect variations when comparing to specific battery models.[15]

$$F_{\mathrm{Discharge}} = a + \frac{b}{t_{\mathrm{BR}}} + cV_{\mathrm{CF}} + \frac{d}{t_{\mathrm{BR}}^2} + eV_{\mathrm{CF}}^2 + f\frac{V_{\mathrm{CF}}}{t_{\mathrm{BR}}} + \frac{g}{t_{\mathrm{BR}}^3} + hV_{\mathrm{CF}}^3 + i\frac{V_{\mathrm{CF}}^2}{t_{\mathrm{BR}}} + j\frac{V_{\mathrm{CF}}}{t_{\mathrm{BR}}^2} \qquad (5.7)$$

where the coefficients are

Coefficient	**VLA**	**VRLA**
a	–1105.7643816	–295.4606616
b	201.7986178	79.2665474
c	1822.6791610	491.4691826
d	–9.1965015	–3.0649118
e	–1000.9629849	–271.8618864
f	–224.5513525	–88.2716728
g	1.3124170	0.7333677
h	183.2697637	50.1408711
i	63.3158840	25.2446729
j	3.8187552	0.7855183

5.2.2.3 End-of-Life Factor (Aging Factor)

The end-of-life factor for telecommunications batteries is, by definition, 1.25, since a battery is considered at end of life when its capacity has decreased to 80% of its nameplate ampere-hour rating. For example, if calculations reveal that the required battery capacity is 100 Ah at end of life, then a battery capacity of (100 Ah × 1.25 =) 125 Ah is required to be installed today.

5.2.2.4 Temperature Factor

Under normal circumstances, the temperature factor always is ≥ 1.0, where a factor of 1.0 indicates battery operation at the nameplate temperature of 25°C (77°F). Telecommunications batteries are not intentionally operated above nameplate temperature because their life is reduced even though they may have slightly more capacity (a temperature factor < 1.0). On the other hand, there are numerous instances where batteries may be intentionally operated at lower temperatures. For example, in remote mountaintop sites, the costs of heating the equipment enclosure to normal room temperatures may be prohibitively high so the equipment and batteries are operated at a temperature less than 25°C. In this case, for a given capacity requirement, a larger battery would be required.

The performance of telecommunications batteries at lower-than-normal temperatures depends on the brand, model, and technology, and only a general relationship between temperature and capacity is provided here (Fig. 5.14).

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[15] Curve-fitting program used to develop this expression is DataFit (V8.1) by Oakdale Engineering of Oakdale, PA (http://www.oakdaleengr.com/).

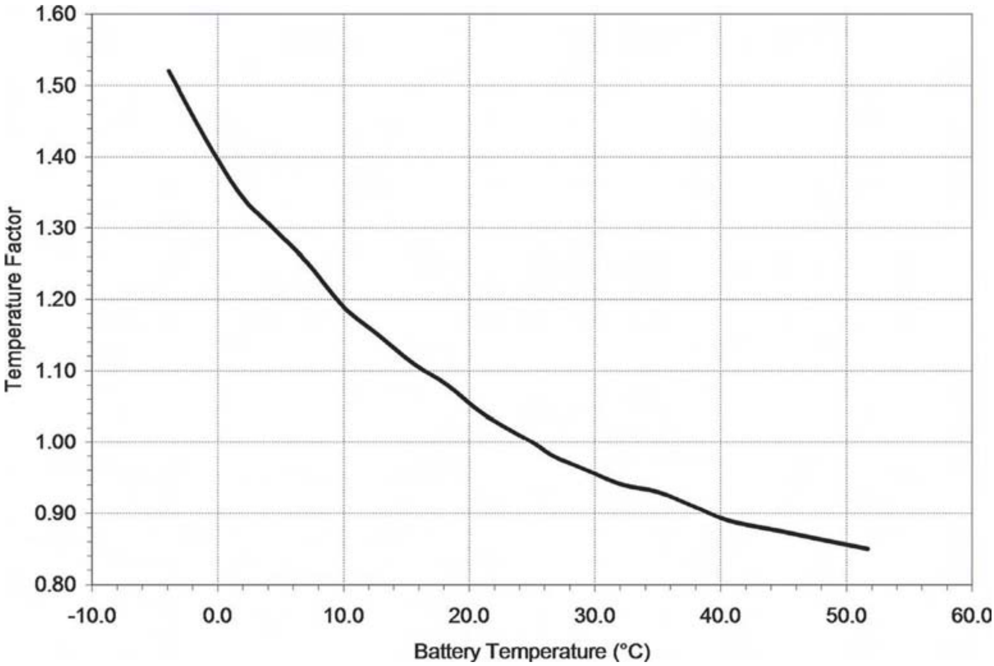

Fig. 5.14 Temperature factor. This chart shows the general relationship for typical batteries; there may be considerable variations across brands and models. To use this graph, enter it along the horizontal scale at the desired operating temperature, move up vertically to the intersection with the graph, move left horizontally to the vertical scale, and read the temperature factor. For example, the temperature factor at a temperature of 15°C (59°F) is approximately 1.12.

5.2.2.5 Design Margin (Uncertainty Factor)

All engineering problems involve a design margin that reflects the engineer's imperfect knowledge of the way real systems operate. In the case of battery system design, the design margin is ≥ 1.0 and typically 1.10 to 1.15.

5.2.2.6 Capacity Calculations

Battery capacity calculations are illustrated in the following example.

Example 5.10 Determine the required capacity for VLA and VRLA batteries based on the following parameters and a minimum equipment voltage of 40.0 V. Repeat for a minimum equipment voltage of 43.0 V and explain why there is a difference, if any:

$$I_{\mathrm{EQ}} = 100\ \mathrm{A}$$

$$t_{\mathrm{BR}} = 12\ \mathrm{h}$$

$$F_T = 1.0$$

$$F_{\mathrm{EL}} = 1.25$$

$$F_{\mathrm{Margin}} = 1.1$$

$$V_{\mathrm{Total}} = 2.0\ \mathrm{V}$$

Solution With a minimum equipment voltage of 40.0 V and total voltage drop of 2.0 V, the final battery voltage is 42.0 V or 1.75 V/cell. From the discharge factor curves for 1.75 V/cell and 12 h reserve time, the discharge factors are approximately 0.90 for both VLA and VRLA batteries (by coincidence). Therefore, from Eq. (5.3)

$$AH_{\text{8hour}} = I_{\text{EQ}} t_{\text{BR}} F_{\text{Discharge}} F_T F_{\text{EL}} F_{\text{Margin}}$$

$$AH_{\text{8hour}} = 100\text{ A} \times 12\text{ h} \times 0.90 \times 1.0 \times 1.25 \times 1.1 = 1485\text{ Ah (VLA)}$$

$$AH_{\text{8hour}} = 100\text{ A} \times 12\text{ h} \times 0.90 \times 1.0 \times 1.25 \times 1.1 = 1485\text{ Ah (VRLA)}$$

If the minimum equipment voltage is increased from 40.0 to 43.0 V, the final battery voltage also is increased from 42.0 to 45.0 V, or 1.88 V/cell. From the discharge factor curves, the discharge factors for 1.88 V/cell and 12 h reserve time are 1.15 for VLA and 1.05 for VRLA batteries.

$$AH_{\text{8hour}} = 100\text{ A} \times 12\text{ h} \times 1.15 \times 1.0 \times 1.25 \times 1.1 = 1898\text{ Ah (VLA)}$$

$$AH_{\text{8hour}} = 100\text{ A} \times 12\text{ h} \times 1.05 \times 1.0 \times 1.25 \times 1.1 = 1733\text{ Ah (VRLA)}$$

In the first part of this example, the battery is allowed to fully discharge to 1.75 V/cell, but in the second part it is allowed to only partially discharge before the required battery final voltage is reached. The effect of this partial discharge is to increase the required battery capacity by about 28% (VLA) and 17% (VRLA) to meet the same reserve time requirements. In this example, the choice of battery technology has a nominal effect on the calculated capacity.

5.2.3 Number of Strings

After calculating the total battery capacity, it is necessary to determine the number of battery strings. As a general rule, the number of battery strings should be the minimum necessary. Accurate voltage support of each cell during float operation is more difficult when more than one string is installed and operated in parallel. Also, achieving equal charge and discharge characteristics from each parallel string is notoriously difficult.

The battery capacity may be dictated by the anticipated growth pattern and the need to simplify expansion. It usually is easier to design and install additional strings of the same battery type and capacity as those already in place. It is not necessary that all battery strings have the same capacity, but the ratio of the capacity (in ampere-hours) of one string to another should not be greater than 2 : 1. Because of different float voltage, and charge and discharge characteristics, different battery technologies (VLA and VRLA) should not be connected in parallel except in temporary special circumstances. For example, when converting a facility from lead–calcium VLA to VRLA, the voltage of the VLA may be raised to equal the required VRLA float voltage, the VRLA string connected in parallel with the VLA string, and then the VLA disconnected.

The growth in battery capacity is related to the growth in rectifier capacity because both increase as load current increases. The battery capacity increment is approximately

$$\Delta\text{AH} = \frac{I_{\text{RM}} t_{\text{BR}}}{F_R} \tag{5.8}$$

where ΔAH = incremental battery capacity (Ah)
I_{RM} = rectifier module rating (A)
t_{BR} = battery reserve time (h)
F_R = recharge factor

The rectifier module rating and recharge factor is explained in Section 5.3.

If the total required battery system capacity is to be divided equally across two or more strings, the capacity of each string is determined from

$$AH_{\text{String}} = \frac{AH_{\text{8hour}}}{N_{\text{String}}} \tag{5.9}$$

where AH_{String} = individual battery string capacity (Ah)
N_{String} = number of battery strings in parallel

Where service availability is critical, and some level of battery redundancy is needed, it is good practice to install two or possibly three battery strings. Multiple strings allow easier battery maintenance without jeopardizing service to the load equipment. The battery redundancy can be calculated from

$$AH_{\text{String}} = \frac{F_{\text{Redundancy}} AH_{\text{8hour}}}{N_{\text{String}}} \tag{5.10}$$

At least three scenarios may be considered when redundancy is to be provided. In the first scenario, two battery strings are used, each with 50% ($\frac{1}{2}$) the required total capacity. In this case, $F_{\text{Redundancy}} = 1.00$ and $N_{\text{String}} = 2$. This method costs a little more and requires more floor space than one string of 100% capacity, but it ensures service continuity between the times a cell fails and it is replaced. It does not provide full reserve time when one string is out of service (it provides approximately one half the reserve time during that period).

The second scenario provides two battery strings, each with 67% ($\frac{2}{3}$) the total required capacity. In this case, $F_{\text{Redundancy}} = 1.33$ and $N_{\text{String}} = 2$. This scenario has higher cost than the first scenario but provides a longer reserve time (approximately two thirds the reserve time) while one string is out of service. The third scenario provides two battery strings, each with 100% of the total required capacity. In this case, $F_{\text{Redundancy}} = 2.00$ and $N_{\text{String}} = 2$. This scenario is twice the cost (in terms of battery material and floor space) of the first scenario but provides full reserve time while one string is out of service. Of course, other scenarios with other $F_{\text{Redundancy}}$ and N_{String} are possible, such as providing three strings, each with 50% of the total required capacity ($F_{\text{Redundancy}} = 1.50$ and $N_{\text{String}} = 3$). In this case, the loss of any one string does not affect the design reserve time. The cost is approximately 50% higher than the first scenario.

There is no technical limit on the number of battery strings that may be connected in parallel but there are practical limits. As a general rule, the battery manufacturer should be contacted if more than five strings are to be paralleled. Some manufacturers do not recommend more than four or five parallel strings.

Short circuit-currents and voltage drop usually dictate practical parallel string limits. Battery short-circuit currents from parallel strings may exceed the interrupt capacity of overcurrent devices or the mechanical strength of rigid busbar or cable bus mounting structures.


(a)

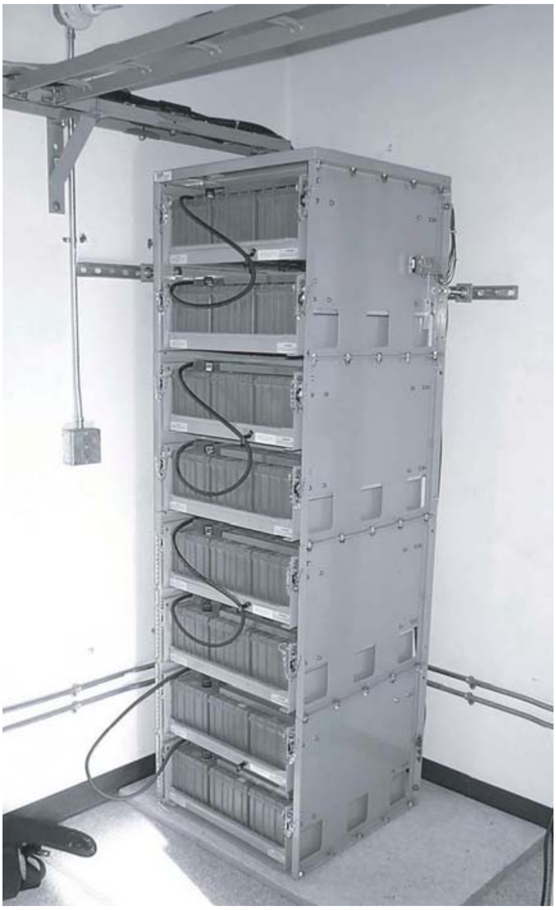
(b)

Fig. 5.15 Battery rack structures: (a) VRLA batteries—integral frame and rack components. Two of the same model batteries with different style insulating covers. (b) VRLA—24 modules in trays mounted in a box frame or cabinet assembly. The leads between tiers are flexible interconnect straps that connect the cells in each tray.

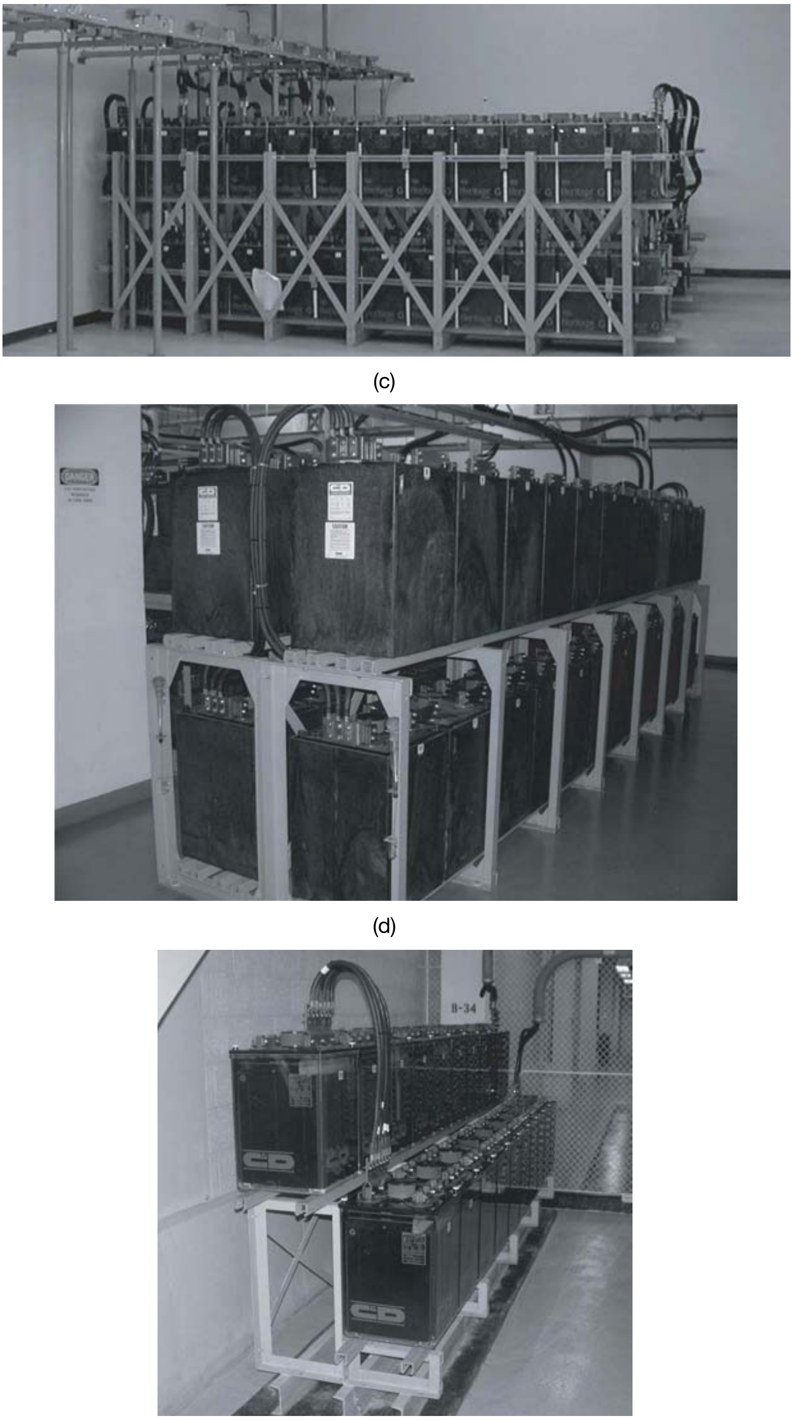

Fig. 5.15 (c) VLA—seismic battery rack. The cross braces and rails surrounding the cells indicate this battery rack is for seismic applications. (Photo courtesy of Schultz Brothers Electric Company.) (d) VLA—nonseismic battery rack. Note there are no rails around the cells. (Photo courtesy of M.W. Migliaro.) (e)—Stepped VLA rack. This photo shows a two-step installation that is difficult to maintain. The rack has no maintenance aisle in the back, and the cells on the upper step at the back are difficult to access for routine maintenance and for removal and replacement. (Photo courtesy of M.W. Migliaro.)

5.2.4 Battery Racks

Above approximately 150 Ah, VRLA batteries have an integral rack structure and can be stacked and bolted together [Fig. 5.15(a)] or placed in a specially made cabinet [Fig. 5.15(b)]; however, stacking heights may be limited and manufacturers should be consulted for high-risk seismic installations.[16] Below 150 Ah, the battery or cells are placed in a tray mounted in a regular equipment frame. However, in high-risk seismic areas, special equipment frames normally are required because of battery weight. In high-risk seismic areas, VLA racks are designed for specific battery and cell dimensions [Fig. 5.15(c)]. VLA racks for low-risk seismic areas have much less structure [Fig. 5.15(d)]. Racks must be designed and installed so the battery can be maintained, including removal and replacement of individual cells. This generally precludes VLA racks with more than two tiers and stepped racks [Fig. 5.15(e)]. Battery rack bonding and grounding is covered in Section 5.9.3.

5.2.5 Battery System Checklist

The following checklist can be used as a basic specification. Suggested wording is provided in parentheses, and variables are shown in brackets where:

a = number of module stacks (VRLA only)
b = number of cells in a module (VRLA only)
n = number of cells in a string
x = desired total ampere-hour rating
x' = desired individual string ampere-hour rating (for multiple string installations)
y = number of parallel strings
z = battery disconnect switch rating in amperes

1.	Application:	(Specify system application such as "Float application in telecommunications central office.")
2.	Battery type:	(VLA or VRLA with plate growth provision.)
3.	Nominal system voltage:	(–48 V or +24 V.)
4.	System float voltage:	(Specify voltage or voltage range.)
5.	Total capacity:	No less than [x] Ah total at 8 h rate to 1.75 V/cell at 25°C
6.	Battery arrangement:	[y] parallel [x'] Ah, [n]-cell battery strings, each string consisting of model (specify model if desired) with [a] stacks of [b] cells per stack.
6.	Cell container and cover:	Flame retardant 28% LOI or better.
7.	Design life:	20 years under float at 25°C.
8.	Safety vent:	Flame arrester [if VLA] or self-resealing with flame arrester [if VRLA].
9.	Cell interconnection straps:	Lead-plated solid copper with stainless steel hardware.
10.	Battery terminals:	Lead-plated solid copper drilled for at least two 2-hole lugs, side mounted with mounting insulators and brackets.
11.	Mounting and structure:	(Horizontal or vertical) with provisions for individual cell replacement.

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[16] Seismic risk areas, or zones, have been defined by four zones, where low-risk seismic zones were 0, 1, and 2 and high-risk seismic zones were 3 and 4. However, such zoning has been replaced in building codes [13] and national standards [14] by maps showing contours of design ground motion and are more indicative of what actually happens during an earthquake.

12. Seismic:	Zone (zone 1, 2, 3, or 4) or seismic description.
13. Temperature:	(Specify abnormal temperature requirements.)
14. Battery disconnect:	Each string with battery-mounted disconnect switch (circuit breaker) rated at least [*aa*] A, short-circuit withstand rating [*bb*] A, and including all mounting components and hardware.
15. Required accessories:	• Insulated interconnection strap covers • Insulated terminal covers • Cell number set (1-24 or 1-12) and polarity markings (+ and –) • Oxidation inhibitor compound • Installation, operation, and maintenance manual • Module lifting strap or lifting device

5.3 RECTIFIER SYSTEM DESIGN

Rectifier system design requires the selection of

- Technology
- Quantity
- Current rating
- Input voltage rating
- Features and options

Rectifiers used in telecommunications applications are equipped for $N + 1$ redundancy, operated in parallel, and almost always setup for load sharing. The rectifier system capacity must be large enough to not only operate the load equipment but simultaneously recharge the batteries in the desired time. If maximum efficiency is desired, only enough rectifier capacity is equipped to achieve this end and no more; otherwise, all rectifiers will operate in a low-current, inefficient condition. With modular rectifiers, it is relatively simple to adjust the capacity by unplugging unneeded rectifier modules or using modern controllers that can be programmed to activate only the necessary rectifiers. The controllers on some modern rectifier systems can be set up to automatically shutdown unneeded rectifiers during float operation and to bring them back online when needed for battery recharge.

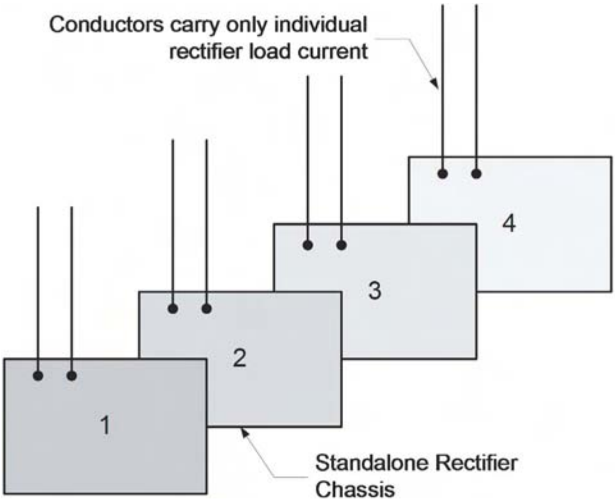
The rectifiers used for VLA batteries also may be used for VRLA batteries except that temperature compensation should be added or retrofitted when VRLA batteries replace VLA batteries. In some cases, the rectifiers may need to be replaced in order to provide temperature compensation. The rectifiers also must have adequate output filtering to protect the VRLA cells from ac ripple, which may lead to thermal run-away.

5.3.1 Technology

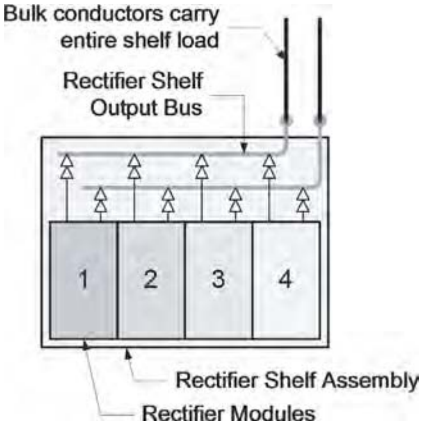
New systems almost always will use hot-swappable, modular switch-mode rectifier technology. If frame or floor space is limited, the logical choice is switch-mode technology. Existing systems that use ferroresonant rectifier technology may remain with that technology to ensure compatibility and to minimize spares and maintenance requirements. However, it may not be possible to retrofit some ferroresonant rectifiers for temperature-compensated charging.

5.3.2 Output Configurations

The different dc output circuit configurations from standalone rectifiers and modular rectifiers must be accounted for in the circuit design. Standalone rectifiers have individual output circuits that are connected by cabling or busbar to the charge bus or a rectifier termination bar that is part of the charge bus [Fig. 5.16(a)]. Modular rectifiers are installed in a shelf assembly that buses the outputs to one common termination point on the assembly [Fig. 5.16(b)]. This termination point is then connected to the charge bus by cabling or busbar.



(a)



(b)

Fig. 5.16 Rectifier output circuit configurations: (a) standalone rectifier chassis output circuit and (b) modular rectifier shelf assembly output circuit.

5.3.3 Rectifier Quantity

Even the smallest system will have at least two rectifiers—one to carry the load and recharge the battery and another configured for hot-standby operation. There is no technical limit to the number of rectifiers, but a simple economic analysis may reveal that a small number of large rectifiers is cheaper than a large number of small rectifiers, or the other way around. The capacity of a 7-ft × 23-in. bay with modular rectifiers is at least 900 A and can be much higher. It should be noted that a single bay with 1400-A capacity and operating at full load will dissipate around 7.5 kW due to the rectifiers not being 100% efficient. This is a large amount of heat in a small space and must be handled by the facility cooling system.

5.3.4 Rectifier System Capacity

Industry baseline requirements specify that the rectifier system should be designed to recharge a fully discharged battery to 95% of its nameplate capacity rating within at least 24 h while simultaneously operating all load equipment [11]. This requirement should be met when the equipment is operating at its busy hour load (normal condition).

If the rectifier system output current is equal to $AH_{8\text{hour}}/20$ A (where $\text{AH}_{8\text{hour}}$ is the battery nameplate capacity in ampere-hour at the 8-h rate and 25°C), the battery will recharge to about 95% of its rated capacity in 24 h. For example, a 450-Ah battery will recharge in 24 h if the available charging current is (450 ÷ 20 =) 23 A. This charging current is over and above that required to power the load. As battery cells age, they require longer recharge time for a given charging current.

The time required to recharge a battery to 100% of its nameplate capacity can be calculated from

$$t_{\text{Recharge}} = \frac{AH_{8\text{hour}}}{I_{\text{RS}} - I_{\text{EQ}}} F_{\text{BatLoss}} \text{ hours} \tag{5.11}$$

where t_{Recharge} = battery recharge time (h)
$AH_{8\text{hour}}$ = battery nameplate capacity at 25°C and 8-h rate to 1.75 V/cell (Ah)
I_{RS} = rectifier system capacity with N rectifiers (A)
I_{EQ} = normal condition equipment load current (A)
F_{BatLoss} = battery loss factor (typically 1.10 to 1.15 for lead–acid batteries)

Equation (5.11) assumes 25°C battery temperature. Battery temperatures below 16°C require that the calculated recharge time be doubled and battery temperatures below 5°C require that the recharge times be quadrupled.

Example 5.11 Determine the recharge time for a 660-Ah battery if the rectifier system capacity is 100 A and the load is 50 A.

Solution From Eq. (5.11)

$$t_{\text{Recharge}} = \frac{AH_{8\text{hour}}}{I_{\text{RS}} - I_{\text{EQ}}} F_{\text{BatLoss}} = \frac{660 \text{ Ah}}{100 \text{ A} - 50 \text{ A}} \times 1.15 = 15 \text{ h}$$

Typical recharge times are 12, 18, and 24 h. If the desired recharge time is 8 h or less, the manufacturer should be contacted for their recommended charging regimen.

The total normal condition load current is one parameter used to calculate rectifier system capacity. Note that normal condition load current is used here instead of peak (peak load currents are encountered only on battery discharge when the rectifiers are not operating and system voltage is decreasing).

Rectifier system capacity can be calculated two ways—(1) using the current required to recharge the battery in a certain time period or (2) using a recharge factor. The first method is advocated in [15] and allows more analytical control over battery recharge time.

With the first method, the rectifier system capacity is calculated by solving Eq. (5.11) for I_{RS}, or

$$I_{\mathrm{RS}} = I_{\mathrm{EQ}} + \frac{AH_{\mathrm{8hour}}}{t_{\mathrm{Recharge}}} F_{\mathrm{BatLoss}} \text{ amperes} \tag{5.12}$$

With the second method, the rectifier system capacity is calculated from

$$I_{\mathrm{RS}} = I_{\mathrm{EQ}} F_{\mathrm{Recharge}} \text{ amperes} \tag{5.13}$$

where F_{Recharge} = recharge factor
= 1.2–1.4 (typical for VLA)
= 1.15–1.2 (typical for VRLA)

Higher recharge factors allow faster recharge times but increase the possibility of thermal runaway in VRLA batteries (unless temperature-compensated charging is used).

Where the rectifier system is used at a site that is 3300 ft (1000 m) or more above sea level without a corresponding decrease in ambient temperature, rectifier output currents usually are derated to ensure proper cooling. However, if the ambient temperature is decreased by 2°C for every 1000-ft (300-m) altitude increase, derating may not be required. Rectifiers may also require derating or adjustment for high ambient temperatures. Typically, at ambient temperatures above 40 or 50°C the rectifier maximum output current needs to be decreased for proper cooling of the electronic components. Derating of rectifier output current for ambient temperatures and altitudes may be found in the manufacturer's data sheets.

Where modular rectifiers are to be used, the total number of modular rectifiers (N_{RM}) is determined from the rectifier module current rating (I_{RM}) from

$$N_{\mathrm{RM}} = \frac{I_{\mathrm{RS}}}{I_{\mathrm{RM}}} + 1 \tag{5.14}$$

rounded up to the next higher integer value. This assumes that all rectifier modules have the same rating, which would be true in new installations and replacements. Where additional rectifier capacity is added to an existing installation, the redundant rectifier (or rectifiers) must be at least as large as the largest rectifier in the system. For example, if an installation has two 50-A and one 100-A rectifiers for the load and battery recharge, redundancy would be provided by adding a second 100-A rectifier or two additional 50-A rectifiers. This protects the system from the failure of any rectifier in the system.

Example 5.12 An 800-Ah battery is used in a system where the equipment load current is 100 A. Determine the total rectifier system capacity and number of rectifier modules if each module is rated 50 A.

Solution Assuming $t_{\text{Recharge}} = 24$ h, then

$$I_{\text{RS}} = I_{\text{EQ}} + \frac{AH_{\text{8hour}}}{t_{\text{Recharge}}} F_{\text{BatteryLoss}} = 100\text{ A} + \frac{800\text{ Ah}}{24} \times 1.15 = 138\text{ A}$$

and

$$N_{\text{RM}} = \frac{I_{\text{RS}}}{I_{\text{RM}}} + 1 = \frac{138\text{ A}}{50\text{ A}} + 1 = 3.76 \text{ or rounded to } 4$$

In this example, the total rectifier capacity is (4 × 50 A =) 200 A, 150 A working plus 50 A standby.

5.3.5 Battery Voltage Sensing

Tight regulation of the battery terminal voltage is important for long battery life. The rectifiers control the voltage accuracy at the battery terminals and use voltage sensing connections for regulation. The sensing leads can be connected at the powerboard bus [Fig. 5.17(a)], directly to the battery terminals [Fig. 5.17(b)] or to a battery circuit collector bar [Fig. 5.17(c)]. The latter two have the advantage of sensing the voltage at the point where it is most important to regulate—at or near the battery terminals. However, these methods have the disadvantage that the small sense lead wires (typically 12 or 14 AWG) usually are installed in the same cable rack as the much larger battery wires and potentially may be damaged by the larger wires during installation or removal. One way to work around this problem is to put the voltage sense leads on L-brackets fastened to the cable rack carrying the battery leads.

When the battery voltage sense leads are connected directly to the battery terminals, they should have overcurrent protection as close as possible to the battery terminals; however, it is the practice of some companies to omit this protective device. The sense current is very small, and a small value fuse or circuit breaker (5 to 10 A) may be used but, in any case, the fuse or circuit breaker rating should not exceed the sense lead conductor current rating. In an installation with more than one battery string in parallel, the voltage sensing can be done at the battery collector bar. Another, simpler, way is to sense the battery voltage at the powerboard where the rectifiers are installed. During float operation, when tight voltage regulation is required, the current and voltage drop in the battery circuit is small, so there is little sacrifice in regulation accuracy.

5.3.6 Rectifier ac Input Circuit Requirements

The rectifier system must be matched to the ac service voltage. If the service voltage is lower or higher than the rectifier ac input rating, a step-up or step-down transformer is used to change the service voltage to the proper value. Power is delivered by electric utilities through either single-phase or three-phase connections. Common service voltages are discussed in Chapter 2, Electricity Review. The preferred voltages for most rectifier installations are 208 and 240 V with line–line connections. Large (400, 800, and 1600 A) ferroresonant rectifiers require 480-V line–line voltage. In large facilities, the service may be delivered at primary voltages, such as 12,470Y/7200 V, in which case an on-site step-down transformer converts the primary voltage to normal secondary utilization voltages.

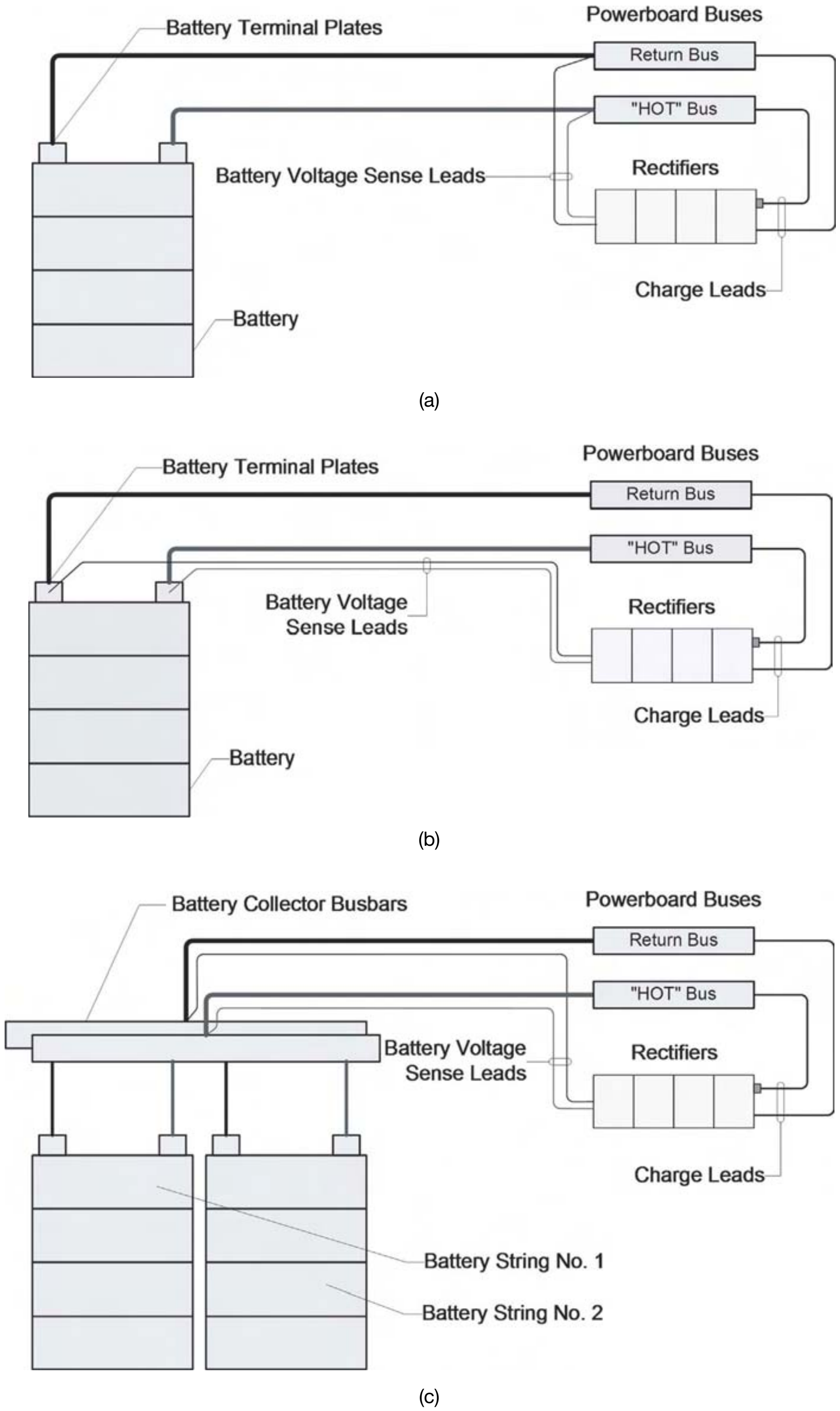


Fig. 5.17 (a) Battery voltage sensing at the powerboard bus. (b) Battery voltage sensing at the battery terminals. (c) Battery voltage sensing at the battery collector busbar.

Each individual rectifier chassis or module requires a dedicated ac input circuit. The importance of a dedicated circuit cannot be overemphasized. Feeding more than one rectifier from only one circuit breaker jeopardizes the system reliability. If that one circuit breaker opens for any reason, the remaining rectifier capacity may not be sufficient to operate the system properly. The ac input circuits are unlike the dc output circuits from modular rectifier systems, in which the outputs are bused across all rectifier modules in the chassis assembly. This arrangement ensures that the failure of any rectifier does not affect the dc bus (except for loss of rectifier capacity).

Rectifiers may be fed from a single dedicated panelboard or two panelboards for redundancy (Fig. 5.18). Installations with a large quantity of modular rectifiers may require more than one panelboard because lighting and appliance panelboards are limited to 42 poles and have space only for 21 two-pole circuit breakers (thus a maximum of 21 rectifiers with line–line connections may be connected to such a panelboard). The rectifier load on the ac panelboard should be balanced. If the rectifiers are connected to a single-phase panelboard, they are connected in such a way that each ac bus is loaded as evenly as possible. Since there are two buses in a single-phase panelboard, the load can be completely balanced if there is an even number of rectifiers. In a three-phase panelboard, perfect balance can be achieved only if the number of rectifiers is evenly divisible by 3. Small rectifiers (~500 W) usually are connected line-neutral [Figs. 5.19(a) and 5.19(b)], and larger rectifiers usually are connected line–line [Figs. 5.19(c) and 5.19(d)]. Rectifier ac circuit design is discussed in Section 5.8.

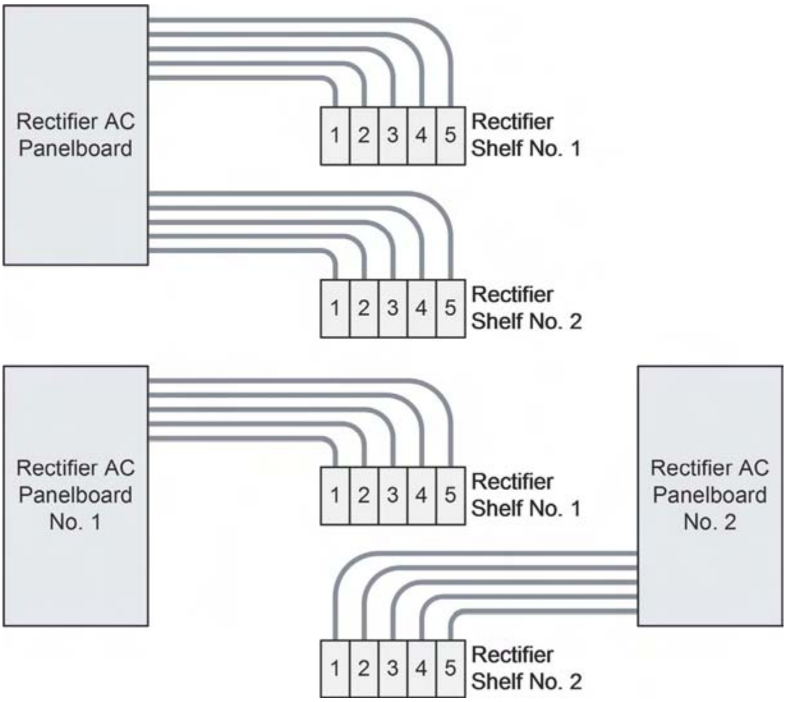
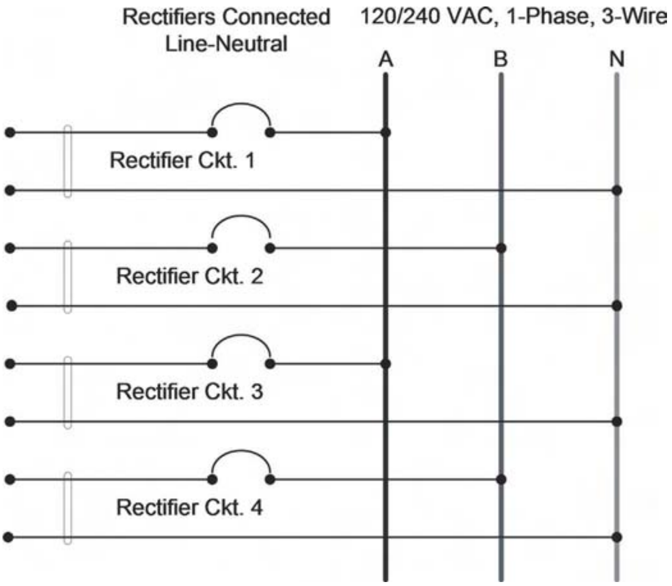
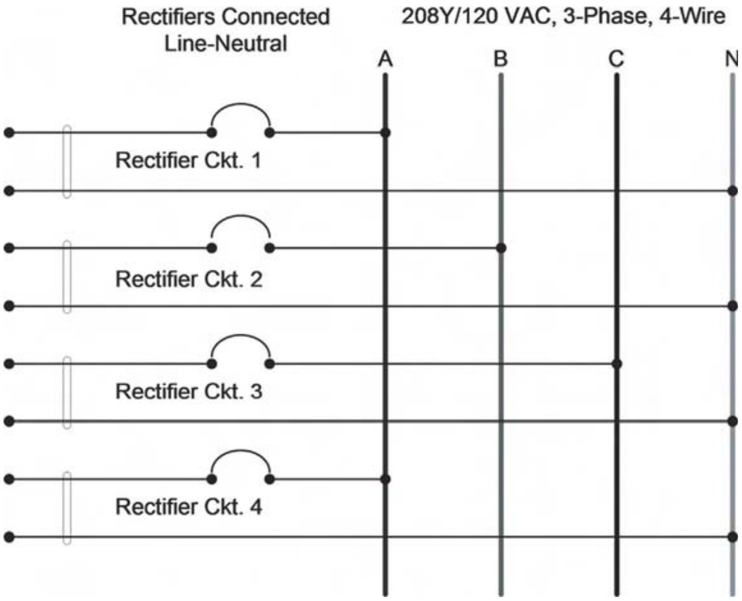


Fig. 5.18 Single and redundant ac panelboard configurations for rectifier input circuits. Modular rectifier shelf assemblies are shown, but the same concept applies to standalone rectifiers. Other ac wiring configurations are possible.

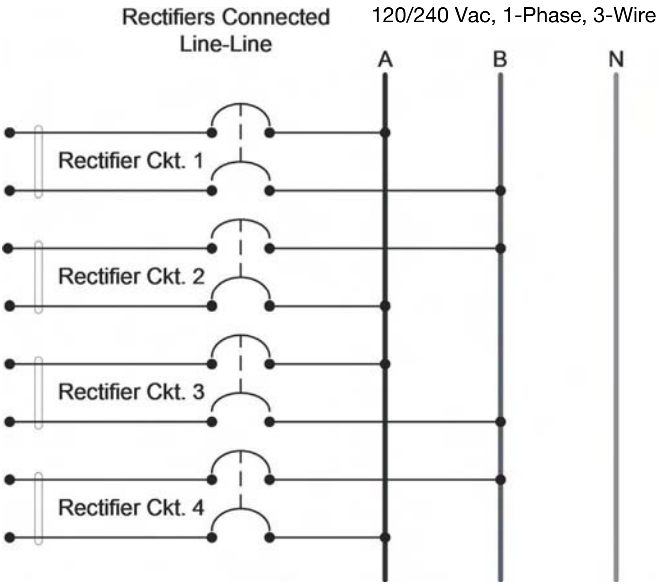


(a)

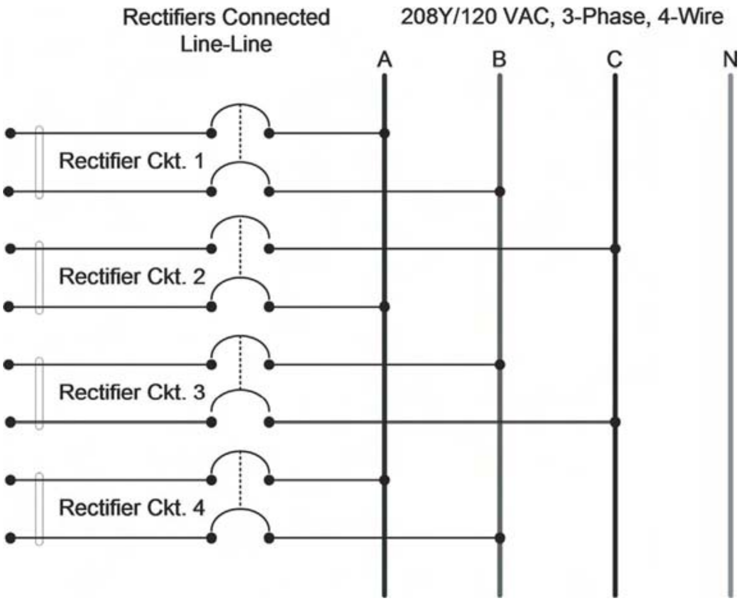


(b)

Fig. 5.19 The ac panelboard connections for rectifier ac circuits: (a) line-neutral connections in a single-phase panelboard using one-pole circuit breakers, (b) line-neutral connections in a three-phase panelboard using one-pole circuit breakers.



(c)



(d)

Fig. 5.19 (c) line–line connections in a single-phase panelboard using two-pole circuit breakers, and (d) line–line connections in a three-phase panelboard using two-pole circuit breakers.

Rectifiers are not 100% efficient and dissipate heat whenever powered, even when unloaded. Cooled air and ventilation are required in rooms with rectifiers to carry away this heat.

5.3.7 Rectifier dc Output Circuit Requirements

The voltage drop in the rectifier output circuits is not normally a serious design issue. Therefore, considerable leeway is available in the voltage drop of rectifier output circuits. They are typically designed for a maximum drop of 1.0 V (48-V systems) or 0.5 V (24-V systems) at full load from the rectifier output terminals to the charge bus. Low voltage drop is easy to achieve because of the normally short run.

In addition to voltage drop, the rectifier output circuits must adequately carry the full output current (including overload current). The output of many modern rectifiers is rated in watts (or kilowatts) rather than amperes, and the output current increases with decreasing voltage. However, controllers for these rectifiers can be set to operate the rectifier in a current limit mode. For example, a 1.5-kW rectifier can deliver 55.5 A at 27 V and 75 A at 20 V but could be set to current limit at 50 A regardless of its output voltage. Rectifier output circuits always are sized for the maximum output current. For power-limited rectifiers (and not current-limited rectifiers), the maximum output occurs at the lowest output voltage. For example, a rectifier rated 3.6 kW with minimum output voltage of 42.0 V, the maximum output current will be almost 86 A. Rectifier output circuit conductor sizing is covered in Section 5.8.

5.3.8 Rectifier System Checklist

The following checklist can be used as a basic specification when only rectifiers are being purchased. Suggested wording is provided in parentheses. When the rectifier system is being purchased with a powerboard, the requirements for temperature compensation and controls should be coordinated with the powerboard design; see Section 5.4.8.

1. Application:	(Specify system application such as “Telecommunications central office” or “Remote microwave repeater site.”)
2. Configuration:	(Specify standalone or modular.)
3. Ambient temperature and altitude:	(Specify expected ambient temperature range and altitude of site.)
4. Nominal system voltage:	(–48 V or +24 V)
5. dc output voltage:	(Specify voltage or voltage range.)
6. Rectifier system capacity:	No less than [x] A total at [y] V output at [z]°C.
7. Compatibility:	(If applicable, specify paralleling and load share requirements and type and model of existing rectifier system.)
8. Output terminations:	(Specify type of terminations for dc output circuits, such as rigid busbar or cable bus; provide details if specific hole spacings and diameters are required.)
9. ac input voltage:	(Specify ac input voltage and phase configuration to be used.)
10. Temperature-compensated charging:	(If VRLA, specify number of probes and distance from rectifier system or compensation controller to battery system.)
11. Alarm system:	(Specify type of alarms required and interface requirements for alarm system connections.)

12. Controls and craft interfaces:	(Specify if rectifier system will be used to equalize the battery and if an automatic equalize timer is required; also specify the craft interface requirements, local area network interfaces, serial port interfaces, and if data logging is required and the format.)
13. Spares:	(Specify fuse and other consumable spares, such as "For every fuse rating equipped, provide minimum of [*xxx*] spare fuses; provide factory recommended spares for all consumables (e.g., fan filters), if any." Sparing of modular rectifiers usually is handled by ordering an extra module.)
14. Documentation:	(Specify documents, such as "Two complete sets of documentation for installation, operation, and maintenance of all components provided under this specification.")

5.4 POWERBOARD DESIGN

Many powerboards are packaged such that rectifiers, controllers, meters and alarms, and primary distribution occupy one frame (sometimes called *initial bay*). Additional rectifiers and distribution can be configured in additional frames (sometimes called *supplementary bays*). In new installations, it may be desirable to order and install all supplementary bays for anticipated growth as part of the initial installation and equip them with busbars, low-voltage disconnects, and shunts for easy future connection of additional rectifiers or distribution (Fig. 5.20).

Powerboard bus design requires the selection of

- Voltage rating
- Bus type and current rating
- Conductor termination bars
- Current shunts
- Control options, including low-voltage disconnects
- Distribution options

5.4.1 Voltage Rating

Powerboards used in 24 and 48 telecommunications applications are 60-Vdc class unless they also serve higher voltage loads, such as 130 Vdc, in which case the powerboard must be 160-Vdc class. Although both 24- and 48-V powerboards have the same voltage class, individual components usually are set or adjusted for the actual operating voltages. For example, the alarm set points for 24-V systems are different than 48-V systems.

5.4.2 Bus Type and Amperage Rating

The powerboard bus usually is composed of a rigid copper busbar assembly, although small powerboards (50 and 100 A) may use a combination rigid and cable bus arrangement. The bus usually is designed for ultimate peak load currents. Ultimate current is used because it is very difficult if not impossible to increase the current rating of a powerboard without taking it out of service. Even then, physical limitations may preclude ex-

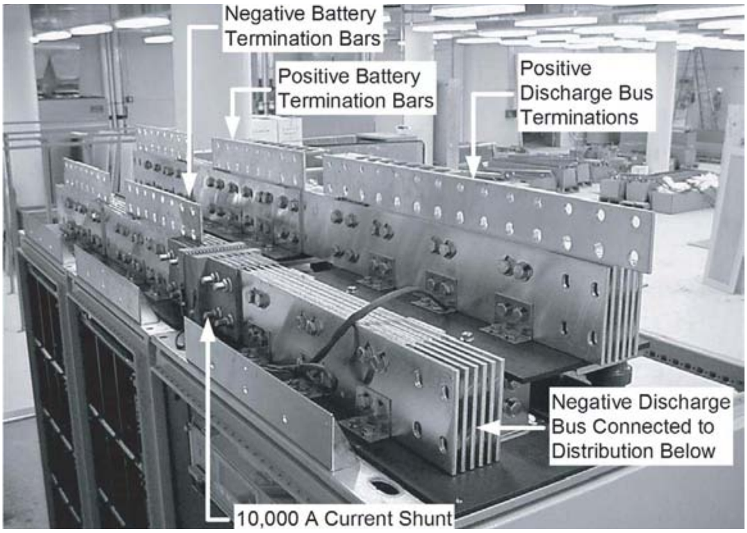


Fig. 5.20 10,000-A charge and discharge busbars with current shunt. Battery termination and distribution busbars are highlighted. (Photo Courtesy of Power-One, Inc.)

pansion, in which case the entire powerboard must be replaced. Packaged powerboards up to 1200 A rating are available in discrete sizes (typically 50, 100, 200, 400, 800, and 1200 A), and any design rating calculations should be rounded up to the next larger size. Larger powerboards usually are built in increments of 1000 to 2000 A (2000, 4000, 6000 A, etc.).

Powerboard buses should not be continuously loaded more than 80% of their rated capacity unless they are specifically designed to be loaded at 100%. The powerboard bus rating is

$$I_{\mathrm{Bus}} = 1.25 I_{\mathrm{RSU}} \text{ amperes} \tag{5.15}$$

where I_{Bus} = bus rating (A)
I_{RSU} = ultimate rectifier capacity (A)
1.25 = inverse of 80% derating factor

The ultimate rectifier system capacity is used because that is the maximum continuous operating current the powerboard bus will ever carry. The ultimate rectifier capacity is calculated using the methods described in Section 5.3 except the ultimate equipment load current is used. Depending on the rectifier capacity calculation method, an estimate also may be required of the ultimate battery system capacity. If the central office space is to comply with NEBS requirements, the calculations discussed in Section 5.1 can be used as a cross check.

An alternate method for calculating the powerboard bus rating is based on the recharge factor discussed in Section 5.3. In this case

$$I_{\mathrm{Bus}} = 1.25 I_{\mathrm{EqU}} F_{\mathrm{Recharge}} \text{ amperes} \tag{5.16}$$

where I_{Bus} = bus rating (A)
I_{EqU} = ultimate equipment load current (A)
F_{Recharge} = recharge factor

The ultimate equipment load current may be based on Section 5.1 estimates or some other estimating method.

5.4.3 Conductor Terminations

Sufficient space must be provided in the powerboard for terminating both feed and return conductors from

- Battery systems
- Rectifier systems
- Primary distribution systems

The busbars usually are predrilled for connector lugs with standard bolt-hole diameter and spacing. Lug sizes will depend on the conductor sizes. In telecommunications dc power systems, the voltage drop constraints usually require large or parallel sets of conductors. To minimize field installation problems, any requirements for larger than normal and for parallel conductor terminations should be given to the powerboard manufacturer before the powerboard is ordered.

Two-hole lugs are used wherever possible. In telecommunications applications, the hole diameters and hole spacings are smaller than in most industrial and commercial ac electrical equipment. Typical values are shown in Table 5.4. Also, to ensure low-resistance crimps, long barrel connector lugs should be used where space permits (crimping methods are discussed in Chapter 6, System Installation and Maintenance).

All power conductors are paired—for every feed conductor to be terminated on the charge bus, discharge bus, or overcurrent device, a return conductor must be terminated on a return bus. For example, if the powerboard is equipped with twenty primary distribution circuit breakers, the return bus must be able to terminate at least twenty return conductors for those circuits alone. If parallel conductors are used, the termination requirements increase by a factor of 2, 3 or more depending on the number of parallel conductors (Fig. 5.21). Connector lugs normally should not be stacked unless stacking is unavoidable because of space constraints. The actual stacking configuration and the use of special lugs for stacking or stacking spacers will depend on the situation (Fig. 5.22).

In many powerboards, separate termination bars are provided for the battery system and rectifier system feeds but a common termination bar is provided for all return conduc-

Table 5.4 Telecommunications Connector Lug Hole Diameter and Spacing (not all combinations are available)

Conductor Size	Nominal Bolt Size	Hole Spacing
8 AWG	0.25, 0.375 in.	0.625, 0.75, 0.8125, 1.0 in.
6—4/0 AWG	0.25, 0.375, 0.5 in.	0.625, 0.75, 0.8125, 1.0, 1.75 in.
250 kcmil	0.25, 0.375, 0.5 in.	0.75, 0.8125, 1.0, 1.75 in.
300–500 kcmil	0.25, 0.375, 0.5 in.	0.75, 1.0, 1.75 in.
600–750 kcmil	0.375, 0.5 in.	1.0, 1.75 in.
800 kcmil	0.5 in.	1.75 in.
1000 kcmil	0.375, 0.5 in.	1.0, 1.75 in.
1500–2000 kcmil	0.5 in.	1.75 in.

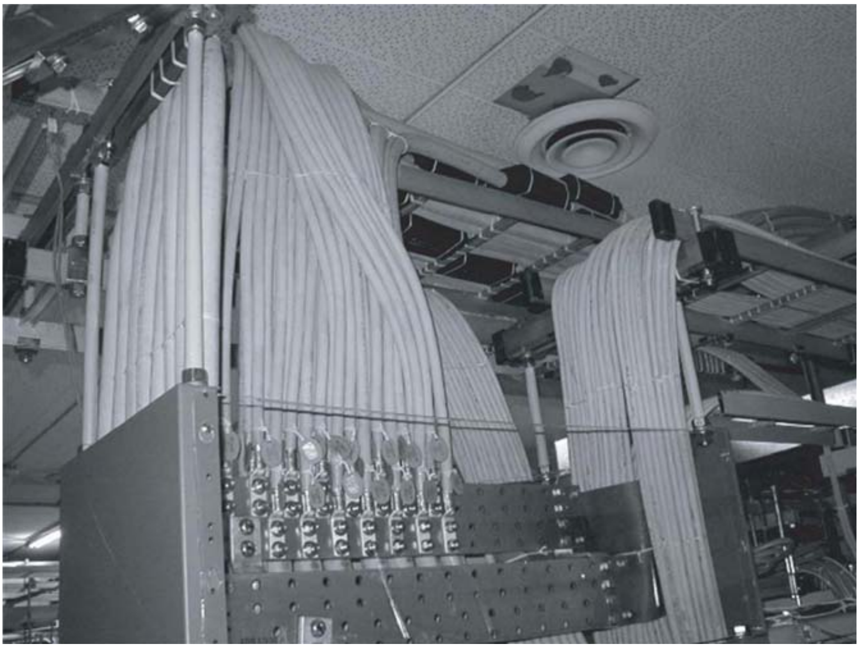


Fig. 5.21 Conductor terminations on termination bars (lower) in primary distribution bay. (Photo Courtesy of Schultz Brothers Electric Company.)

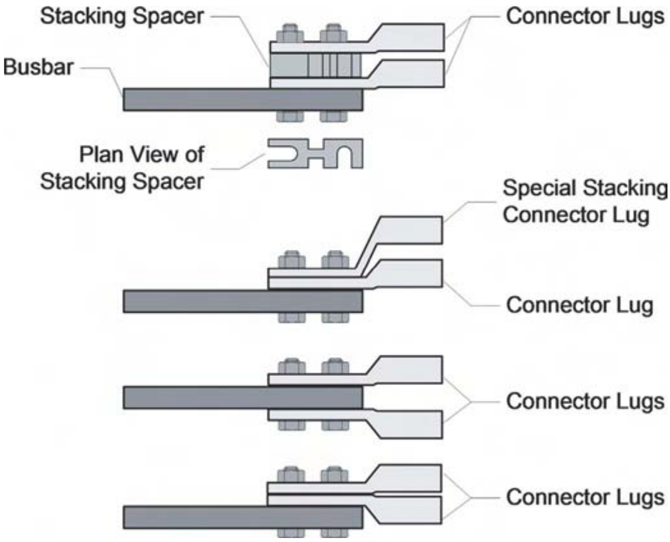


Fig. 5.22 Stacking configurations using special stacking lugs, stacking spacers, and back-to-back arrangements.

tors. This results in a large return bar compared to the individual feed bars to accommodate all of the conductors.

5.4.4 Current Shunts

Shunts must be matched to the bus rating, whether on the main bus or distribution buses. In some installations, the ultimate bus capacity is much larger than the initial load, and a smaller shunt is installed to accurately measure the lower initial currents. As the load grows, the shunt is replaced with a larger unit. Systems that have been properly planned will have provisions for mounting the new shunt before removing the old one, thus maintaining continuity of service. If provisions have not been made for changing out the shunt, a temporary jumper must be placed across the old shunt while it is removed and replaced. The jumper must have a current rating at least equal to the load during the change-out. Consideration should be given to changing the shunt when the load reaches 50 to 80% of the existing shunt rating.

5.4.6 Control Options

The powerboard controller handles alarm collecting and sending, low-voltage disconnect, rectifier control, craft interface, and data logging and monitoring. The controller may include an automatic equalize timer if a VLA battery system is used.

5.4.5.1 Equalizer Control Equalize timers normally are set for some fixed time period. The timer usually does not start until the batteries have been on discharge for a set period, such as 10 or 15 min (Fig. 5.23).

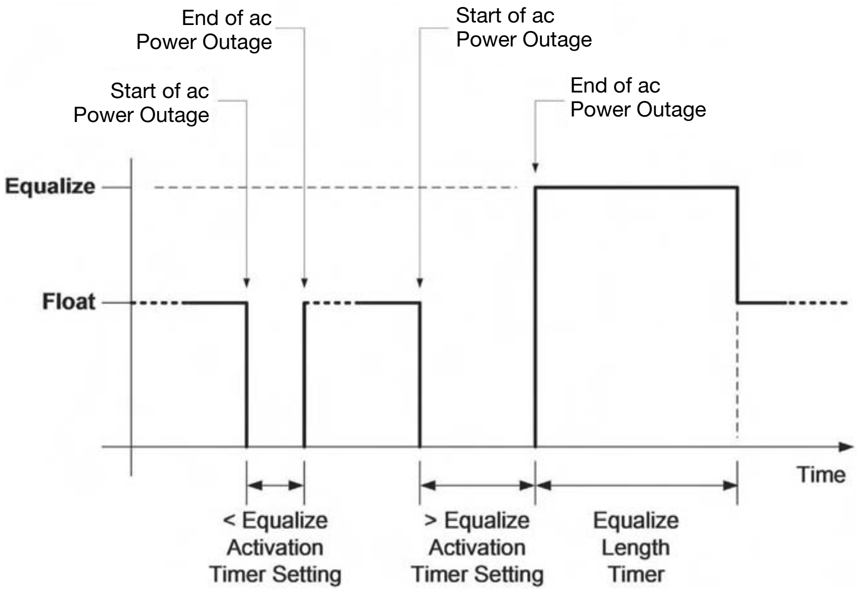


Fig. 5.23 Equalize timer operation. If the ac power is restored before the equalize activation timer expires, the rectifiers remain in the float state. If the ac power is restored after the equalize activation time expires, the rectifiers are switched to the equalize state. The rectifiers will remain in the equalize state until the equalize length timer expires and then switch back to float.

5.4.5.2 Low-Voltage Disconnects

Low-voltage disconnects (LVD) can serve a number of purposes, as described in Chapter 3, DC Power System Components. When an LVD is used to protect the battery from overdischarge, the set points can be determined as follows:

The LVD has two settings—one for disconnect on discharge of the battery and another for reconnect on recharge of the battery. Hysteresis is provided to allow the battery to be recharged to some extent before the load is reconnected to the rectifiers. The hysteresis normally is 7.0 V for 48-V systems and 3.5 V for 24-V systems but other values are used in practice.

The disconnect setting used in a given installation is based on the voltage drop between the battery terminals and the LVD voltage sensing point. The LVD and its voltage sensing point usually are in the powerboard on the battery side of the discharge bus (Fig. 5.24), so the voltage drop from the battery terminals to the powerboard is the important factor.

The battery should not be allowed to discharge below 1.75 V/cell, or 42.0 V for a 24-cell 48-V battery and 21.0 V for a 12-cell 24-V battery. The voltage drop between the battery terminals and the LVD must be added to the minimum allowed battery discharge voltage to arrive at the set point for the LVD. For example, if the voltage drop during discharge is 0.25 V for a 24-V system, the LVD would be set to drop out at 20.75 V. With 3.5-V hysteresis, the reconnect voltage set point would be 24.25 V. If the voltage drop during discharge is 0.75 V for a 48-V system, the LVD would be set to drop out at 41.25 and reconnect at 48.25 V.

5.4.5.3 Alarm and Control Set Points

Alarm and control set points in powerboard controllers will depend on the specific application, but typical values are shown in Tables 5.5(a), 5.5(b), and 5.5(c) for various battery technologies and configurations. These settings should be used as a starting point and may need to be adjusted for specific installations. For example, the battery manufacturer may recommend float and equalize settings outside the ranges shown, and low- or high-voltage alarm settings may need to be adjusted to compensate for specific equipment and battery settings. If a controller does not have a separate *battery-on discharge alarm,* the *low-voltage alarm* may be used to indicate battery discharge.

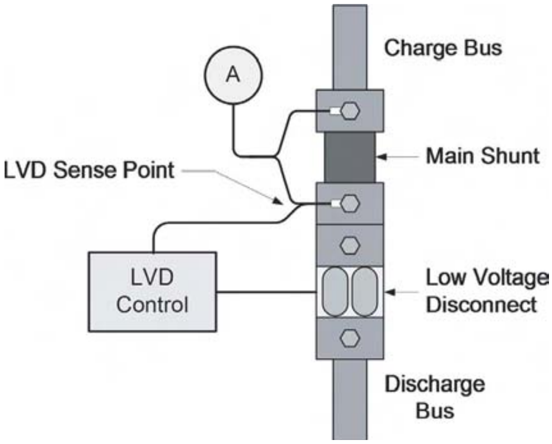


Fig. 5.24 Low-voltage disconnect voltage sensing location.

Table 5.5(a) Controller Settings (VRLA, No Temperature-Compensated Charging), at 25°C[a]

Parameter	48-V System	24-V System
Midrange VRLA float voltage (2.25 V/cell)	54.00 V	27.00 V
Maximum VRLA float voltage (2.27 V/cell)	54.48 V	27.24 V
Minimum VRLA float voltage (2.23 V/cell)	53.5 V	26.75 V
High-voltage shutdown	56.0–56.5 V	28.0–28.25 V
High-voltage alarm	55.5 V	27.75 V
Low-voltage alarm	47.0 V	23.5 V
Equalize voltage (if used)—higher than float voltage by	0.7 V	0.35 V
Battery-on-discharge alarm—lower than float voltage by	2.0 V	1.0 V
Low-voltage disconnect	See Section 5.4.5.2	

[a] Consult battery manufacturer before using minimum and maximum float voltages shown.

Table 5.5(b) Controller Settings (VRLA with Temperature-Compensated Charging) at 25°C[a]

Parameter	48-V System	24-V System
Midrange VRLA float voltage (2.25 V/cell)	54.00 V	27.00 V
Maximum VRLA float voltage (2.27 V/cell)	55.48 V	27.24 V
Minimum VRLA float voltage (2.23 V/cell)	52.5 V	26.75 V
High-voltage shutdown	56.0–56.5 V	28.0–28.25 V
High-voltage alarm	55.7 V	27.85 V
Low-voltage alarm	47.0 V	23.5 V
Equalize voltage (if used)—higher than float voltage by	0.0–0.7 V	0.0–0.35 V
Battery-on-discharge alarm—lower than float voltage by	2.5 V	1.25 V
Low-voltage disconnect	See Section 5.4.5.2	

[a] Consult battery manufacturer before using minimum and maximum float voltages shown.

Table 5.5(c) Controller Settings (Lead–Calcium VLA) at 25°C[a]

Parameter	48-V System	24-V System
Midrange VLA float voltage (2.17 V/cell)	52.08 V	26.04 V
Maximum VLA float voltage (2.22 V/cell)	53.28 V	26.64 V
Minimum VLA float voltage (2.15 V/cell)	51.60 V	25.8 V
High-voltage shutdown	57.6 V	28.8 V
High-voltage alarm	55.7 V	27.85 V
Low-voltage alarm	47.0 V	23.5 V
Equalize voltage (2.35 v/cell)	56.4 V	28.2 V
Battery-on-discharge alarm—lower than float voltage by	2.0 V	1.0 V
Low-voltage disconnect	See Section 5.4.5.2	

[a] Consult battery manufacturer before using minimum and maximum float voltages shown.

5.4.6 Distribution Options

The discharge bus normally has circuit breakers or fuses for primary distribution or at least provisions for extending the bus to where the primary overcurrent devices are located. All new powerboards should have spaces for at least six overcurrent devices for primary distribution:

- One pair (A and B) minimum to feed the secondary distribution system directly associated with a switching system, if applicable
- One pair (A and B) minimum to feed the secondary distribution system associated with transmission and other systems not normally powered through the switching system distribution
- One pair (A and B) minimum to feed future but as yet unidentified loads

This is an absolute minimum requirement. The spaces should be equipped as necessary for the loads to be served, including initial and growth during the planning period. In most cases, because of the difficulty in expanding in-service powerboards, ultimate load values will be used. Figure 5.25 shows a lineup of primary distribution bays.

In powerboards up to around 200 A bus rating, one or more circuit breaker or fuse panels are installed in the power distribution frame. These overcurrent devices may feed loads directly or indirectly through secondary fuse panels at the top of equipment frames. Where loads are fed directly from the powerboard, at least 20 overcurrent positions should be provided in new installations (this is sufficient to feed 10 dual-bus loads or secondary distribution systems). Where only the minimum is initially provided, the powerboard should have provisions for expanding the number of circuit breaker or fuse panels. These panels typically have a maximum current rating of 100 to 200 A per panel. It is desirable to install empty panels so that only the circuit breakers need to be installed as needed. Powerboards larger than approximately 1200 A should be equipped with at least 6 fuse or circuit breaker panels.

From a modern system design standpoint, it is best to abandon the historical practice of using large overcurrent devices to feed concentrated or centralized loads. A tripped overcurrent device will disable a large amount of equipment. If possible, the loads should be

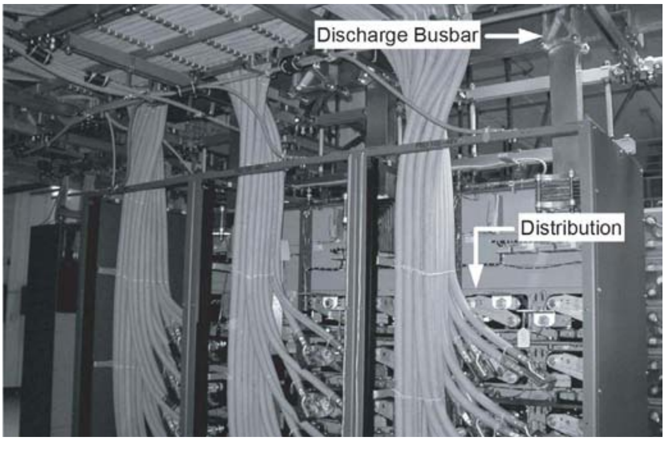


Fig. 5.25 Primary distribution bays—rear view. Discharge busbar connections are at the top and terminations for overcurrent devices are below. (Photo courtesy of Schultz Brothers Electric Company.)

split into increments of no more than approximately 100 to 200 A each. If it is necessary to feed larger centralized loads, such as the legacy end office circuit-switching systems made by Lucent, Nortel, and Siemens, the primary distribution may have to include 200-, 400-, or 600-A circuit breakers or fuses to comply with vendor requirements. The largest individual overcurrent device rating used in telecommunications usually is 600 A, although larger sizes are sometimes used in battery circuits.

Molded case circuit breakers are the most common overcurrent device in modern dc power systems. Circuit breaker current and voltage ratings are affected by altitude and may require derating or correction (Table 5.6). Other interrupting devices (e.g., low-voltage disconnects and switches) may have similar derating or correction requirements.

5.4.7 Powerboard Checklist

The following checklist can be used as a basic specification. Suggested wording is provided in parentheses, and variables such as dimensions and cable lengths are shown in brackets:

1. Application:	(Specify system application such as "Attended telecommunications central office, Unattended telecommunications central office, or Controlled Environment Vault.")
2. Ambient temperature and altitude:	(Specify expected ambient temperature range and altitude of site.)
3. Nominal operating voltages:	(Specify all voltages required, such as –48 V and +24 V.)
4. Main bus current rating:	(Specify current rating and short-circuit current withstand rating of main charge/discharge buses, such as "[*xxx*] A bus with insulated return bar and [*xxx*] A short-circuit withstand rating.")
5. Frame configuration:	(Specify equipment frame configuration, such as "Deadfront powerboard in (1) or (2) [*xxx*] ft × 23 in. boxed frames, equipped with insulating covers for all exposed busbars and energized equipment on rear and sides, front and rear access (prefer minimum depth with cable turning sections and cable supports on both sides".)
6. Controls and accessories	(Specify required items such as low-voltage disconnect and LVD configuration, voltage sensing configuration, such as (a) selectable remote or local battery voltage sensing for rectifiers with terminal block for remote sensing leads (factory set to local sensing), (b) control and alarm panel with serial and Ethernet/IP interface for monitoring and control, (c) digital voltmeter/ammeter panel to measure total

Table 5.6 Molded Case Circuit Breaker Altitude Correction Factors[a]

Altitude (ft/m)	Rated Continuous Current (A)	Rated Voltage (V)
< 6,600/2,000	1.00	1.00
8,500/2,600	0.99	0.95
13,000/3,900	0.96	0.80

[a] Use linear interpolation for intermediate altitudes. Source: From [16].

	bus and individual distribution buses, (d) alarm system with cables for external connections, [*xxx*] ft, (e) temperature-compensated charging control, (f) factory recommended voltage and alarm settings for [VLA or VRLA] batteries, (g) battery monitoring and data logging, (h) craft interfaces, and (i) data logging.)
7. Termination bars	(Specify termination bar requirements, such as “Battery/rectifier cable termination and return bars with lug landings to accommodate factory rectifier terminations and at least (Qty) [*xxxx*] kcmil copper conductors with 2-hole lugs on each bar for field battery lead terminations. Include lug landings for at least (Qty) [*xxxx*] kcmil dc grounding conductor with 2-hole lugs on return busbar.” Adjust number of conductor terminations to suit actual installation.)
8. Grounding provisions	(Specify ground bar configuration, such as “Insulated ground termination bar with space for [*xxx*] 2-hole lugs.)
9. Seismic	Seismic zone or description
10. Primary distribution	(Specify –48 V or +24 V or both circuit breaker or fuse distribution panels, dual feed bus (A & B) with bus meter shunts, trip handle guard, alarms, and return buses. Also specify the required overcurrent protective device quantities and ratings. Be sure to specify spaces for extra circuit breakers or fuses if required for future growth.)
11. Secondary distribution	(If required, this will include the same basic information as for primary distribution.)
12. Temperature-compensated charging	(If VRLA, specify details, such as “Provide (Qty) temperature probes with [*xxx*] ft cable lengths, and provide ambient temperature probe.”)
13. Rectifier system	(Specify requirements such as “Modular rectifier system with $N + 1$ redundancy and [*xxx*] A working capacity, factory set to float at [*xx.xx*] V. Input ac rating suitable for 208 or 240 V (or 480 V) service voltages. Rectifier alarms and automatic high-voltage shutdown required.”) (See also Section 5.3.)
14. Converters	(Specify DC–DC converters, if required. Include redundancy requirements, quantity, bus configuration, rating, input and output voltages, mounting arrangements, and distribution panels.)
15. Inverters	(Specify inverters, if required. Include redundancy requirements, quantity, bus configuration, rating, input and output voltages, mounting arrangements, and distribution panels.)
16. Spares	(Specify fuse and other consumable spares, such as “For every fuse rating equipped, provide minimum of [*xxx*] spare fuses; provide factory recommended spares for all consumables (e.g., fan filters), if any.”)
17. Documentation	(Specify job documents, such as “Two complete sets of documentation for installation, operation and maintenance of all components provided under this specification, including frame elevation drawings, termination bar configurations, hole patterns, and wiring diagrams”)

5.5 SECONDARY DISTRIBUTION DESIGN

Secondary distribution systems are similar to primary, the main differences are their location and overcurrent device ratings (secondary distribution systems usually have smaller ratings). The specification for secondary distribution systems includes

- Overcurrent protection device type (fuse or circuit breaker, or combination)
- Bus configuration (single bus or dual bus)
- Bus rating
- Input wire termination requirements
- Output wire termination requirements
- Mounting arrangements
- Alarm requirements
- Filtering requirements

Typical mounting arrangements for small fuse and circuit breaker panels in equipment frames are shown in Figure 5.26. A secondary distribution bay is shown in Figure 5.27.

5.6 VOLTAGE CONVERSION SYSTEMS DESIGN

5.6.1 The DC–DC Converters

Converter system design includes

- Capacity

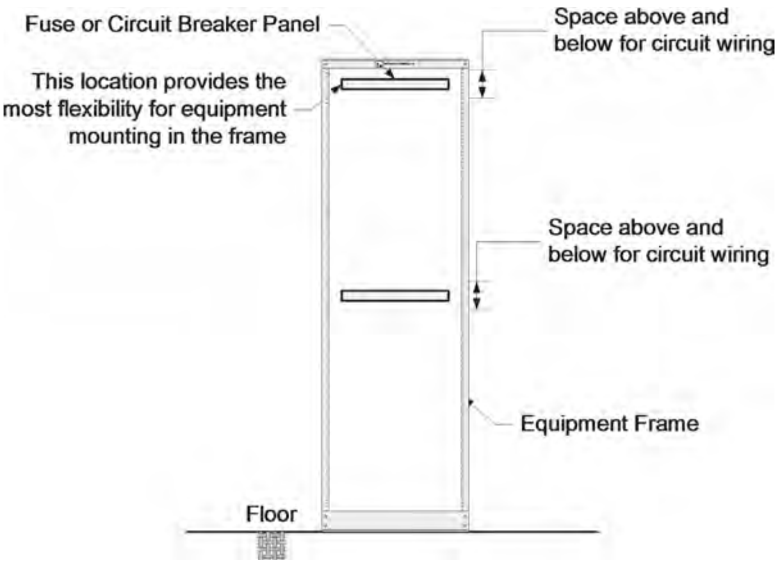


Fig. 5.26 Fuse and circuit breaker panel mounting arrangements. Midmounted fuse or circuit breaker panels can be dangerous unless the busbars are completely enclosed. Also, midmounted circuit breaker panels must have handle guards to prevent accidental tripping.

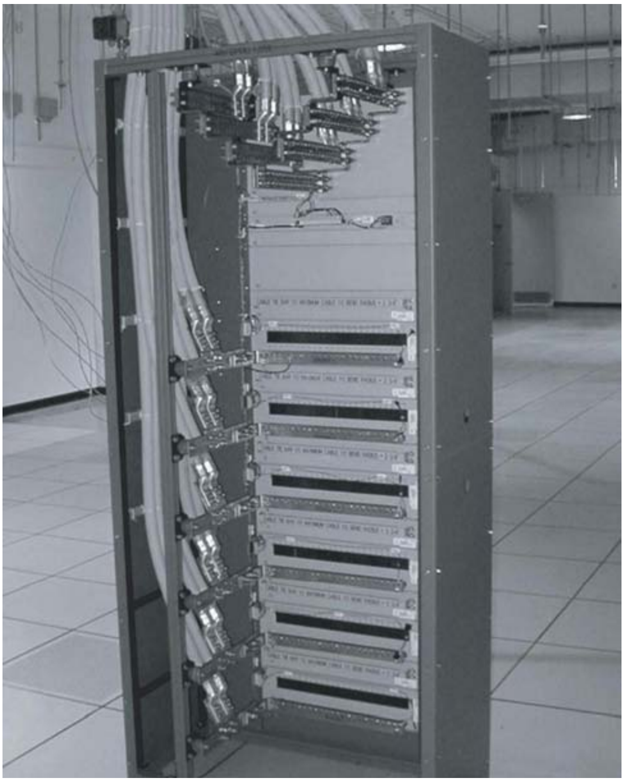


Fig. 5.27 Secondary distribution bay. The return busbars are at the top and the individual distribution busbars for each circuit breaker panel are below (the panels shown are empty). (Photo courtesy of Schultz Brothers Electric Company.)

- Redundancy requirements
- Bus configuration
- Location
- Input circuits
- Output circuits

Converter system capacity is determined using the same basic techniques as the primary voltage system (Section 5.1). The various bus configurations are discussed in Chapter 3, DC Power System Components. A typical converter system will use $N + 1$ converters with their outputs connected to a common bus with dual-bus (A and B) distribution.

Generally, but not always, converter systems are conveniently located close to their loads. The actual location will take into account the wire size and quantity required for the input and output circuit wiring. When the converters are used to convert from a higher to a lower voltage (e.g., from 48 to 24 V), the current on the inputs will be lower than the outputs and smaller wiring generally is needed on the input than output. In this case, it would be advantageous to locate the converters closer to the loads. For the opposite situation, converting from a lower to higher voltage, the converters could be located closer to the source. The wiring costs for either situation will have labor and material cost components and may influence the location.

Table 5.7 DC–DC Converter Input and Output Voltage Drops

Input/Output Voltage (Vdc)	Input Voltage Drop (V)	Output Voltage Drop (V)
48/48	2.0	2.0
48/24	2.0	1.0
24/48	1.0	2.0
24/24	1.0	1.0

Input and output circuits are designed according to the methods described in Section 5.8.2. There is nothing unique about converter circuits except that converters generally operate over a wider input voltage range than the load equipment they serve. Table 5.7 shows input and output voltage drops for common system voltages; the input voltage drops may be adjusted for the actual input voltage ranges of the converters used in a particular application.

5.6.1.1 Economic Analysis A converter system should not be chosen without first comparing its costs to the costs of a separate powerboard, rectifier system, and battery plant. These costs include material and installation labor costs, operating and maintenance costs, as well as building space costs. A battery system significantly adds to the maintenance and disposal costs. A separate battery system almost always requires more space than a converter system but almost always will have lower material and installation labor costs when the load is more than 100 to 200 A. When comparing a converter system to a conventional plant with a battery, it is necessary to consider that a converter system will affect the primary voltage system's battery reserve time and distribution (the converter system is an added dc load). If the secondary voltage system has its own battery, there will be no effect on the primary voltage system.

5.6.2 Inverter Systems

Inverter system design includes

- Capacity (VA)
- Configuration
- Redundancy requirements
- Input voltage and voltage range
- Output voltage and voltage range
- Output frequency and frequency range
- Input circuits
- Output circuits

Inverter input voltage and range must be compatible with the dc system voltage. Generally, inverters operate over a fairly wide range and operate at lower and higher voltages than most network equipment. The output voltages of inverters used in the United States correspond to the common ac utilization voltages described in Section 5.8.5. Small inverter systems up to around 1500 VA usually operate at 120 V, while larger inverter systems operate at 120/240 V single-phase or 208Y/120 V three-phase. Inverter operating frequency usually is 60 Hz ±3 Hz or ±2 Hz, although many modern types can provide a much tighter tolerance (e.g., ±0.01%). Older inverters are acoustically quite noisy but modern types are considerably quieter.

The dc input current should be obtained from manufacturers' data sheets whenever possible. Alternately, if the efficiency is known, the input current can be calculated from

$$I_{\text{dc}} = \frac{(\text{VA})(\text{PF})}{V_{\text{dcMin}}(\text{Eff})} \text{ amperes} \tag{5.17}$$

where I_{dc} = dc input current (A)
VA = output volt–ampere rating (VA)
V_{dcMin} = minimum dc input voltage (V)
Eff = efficiency at full load
PF = power factor

Generally, modern inverters operate at voltages as low as 40.0 to 42.0 Vdc input, but they have relatively low efficiency (in the range of below 70% to above 90%). Inverter dc input circuit design is the same as other dc load equipment circuits (Section 5.8.2).

The inverter operating configuration—active standby, passive standby, and continuous operation—depends on operational requirements. Both passive and active standby have been used in the past, but the most common configuration presently is continuous operation. With continuous operation, there is no connection to the commercial electrical service, which reduces the likelihood of ac power disturbances damaging the inverter and associated loads and also simplifies the inverter system bonding and grounding.

The first step in determining the inverter system capacity is to estimate the total load. Most inverter loads in telecommunications applications are continuous, although some may include motor starting and intermittent loads (such as test equipment). All ac-powered equipment has a label indicating the load in ac amperes at a specified operating voltage or the load in volt–amperes or watts. For ac power supplies labeled in amperes, the apparent power in volt–amperes can be calculated by multiplying the ac voltage by the ac current. As discussed in Chapter 2, Electricity Review, the load in watts is related to the load in volt–amperes by the load power factor.

Next, determine the load characteristics. The ac equipment connected to telecommunications inverter systems are broadly categorized as electronic loads. It may be possible that lighting and motor loads are connected, but that is unlikely. Electronic loads consist mostly of apparatus with switch-mode power supplies (SMPS), typically operational support systems such as servers, desktop computers (PCs), monitors, printers, and local area network (LAN) equipment. Electronic, lighting, and motor loads have different initial startup (surge) requirements. The startup currents for electronic and motor loads are considerably higher than the corresponding running loads, and lighting startup loads depend on the type of lighting technology (incandescent or gas discharge and the type of ballast used with gas discharge lighting).

Some switch-mode power supplies, particularly older products, have a low input power factor due to relatively high peak current and distorted input current waveform (high harmonics content). Many modern inverters, especially some high-frequency types, do not run well when heavily loaded by low power factor equipment and have to be derated. This is handled by using a 30 to 50% power factor when converting the load in watts to load in volt–amperes. For example, if an older switch-mode power supply is rated 250 W and is to be powered by a high-frequency inverter, the equivalent load rating is 250 W ÷

0.3 = 833 VA. Inverters with a true (or close to true) sine wave output waveform usually have an output transformer that reduces the effect of low load power factor. The estimated equivalent power supply load for this example is 250 W ÷ 0.5 = 500 VA.

In practice, desktop computer and monitor power supplies seldom operate a full rated load. For example, even though the power supply in a PC is rated 350 W, it may only draw 150 W when running. The extra capacity usually is required on initial startup of the PC or when the PC motherboard is completely filled with high-power interface cards.

Caution must be exercised when a high-frequency inverter is used to supply motor loads, such as compressor motors in transmission line dehydrators or pumps. Some types of inverters cannot deliver the required starting current. Low-frequency, transformer-isolated inverters or inverters specially designed for motor loads are better for this application. The required inverter capacity for motor starting can be found by multiplying the inverter output voltage by the motor's locked rotor (or surge) current, typically 6 to 10 times its full-load running current. For example, if a motor has 2.0 A full-load running current at 120 Vac, the locked rotor current is approximately 2.0 A × 6 = 12 A and the required inverter capacity is 12 A × 120 Vac = 1440 VA. If the load consists of more than one motor, they should be prevented from starting at the same time when powered by the inverter system.

Example 5.13 Various ac equipment items presently are connected to 120-Vac power strips in a small central office and are to be connected to an inverter system. The load information tabulated below is taken directly from the equipment nameplates. The total load current measured with an ac clamp-on ammeter is 8.5 A. Determine the required inverter capacity.

Item	**Description**
1	Remote access modem hub, 30-port—Nameplate 100 W at 100–240 Vac
2	Desktop server, email—Nameplate 230 W, 6.0 A
3	Desktop server, web—Nameplate 230 W, 6.0 A
4	Desktop server, router—Nameplate 230 W, 6.0 A
5	Color monitor—Nameplate 1.3–0.7 A at 100–125 Vac
6	Color monitor—Nameplate 1.5 A maximum at 100–240 Vac
7	Color monitor—Nameplate 1.5–0.6 A at 100–240 Vac
8	Dot matrix printer—Nameplate 0.8 A at 100–120 Vac
9	Dot matrix printer—Nameplate 2.0 A at 120 Vac
10	Modem—Nameplate 16 VA
11	Router—Nameplate 1.2–0.6 A at 100–240 Vac
12	10BaseT Ethernet hub, 8-port—Nameplate 10 W
13	Ethernet switch, 16-port—Nameplate 25 VA at 100–240 Vac
14	Data service unit (DSU), 56 kb/s—Nameplate 0.15 A at 115 Vac
15	Data service unit (DSU), 64 kb/s—Nameplate 0.22 A at 120 Vac

Solution The above load information is transferred to Table 5.8, where nameplate information (if available) is shown unshaded and calculated or estimated information is shown shaded. Assumptions are provided in notes below the table.

The total estimated load as indicated in the table is 1971 VA. The measured running load is 8.5 A × 120 Vac = 1020 VA, or about one-half the estimate. This indicates that the

Table 5.8 Inverter Load Tabulation Form with Example Data[a]

Description	Load Type	Nameplate Current (A)	Nameplate Voltage (Vac)	Nameplate (VA)	Starting Nameplate (W)	Surge Factor	Max. Starting (VA)	Max. Running (VA)	Running (W)
Remote access modem hub, 30-port	SMPS	—	100–240	—	100	2	200	~111	100
Desktop server, email	SMPS	6.0	—	—	230	2	460	~256	~230
Desktop server, web	SMPS	6.0	—	—	230	2	460	~256	~230
Desktop server, router	SMPS	6.0	—	—	230	2	460	~256	~230
Color monitor	SMPS	1.3–0.7	120–240	—	—	2	~280	156	~140
Color monitor	SMPS	1.5	120–240	—	—	2	~320	180	~160
Color monitor	SMPS	1.5–0.6	120–240	—	—	2	~320	180	~160
Dot matrix printer	SMPS	0.8	100–120	—	—	2	~172	96	~86
Dot matrix printer	SMPS	2.0	120	—	—	2	~432	240	~216
Modem	SMPS	—	—	16	—	2	~28	16	~14
Router	SMPS	1.2–0.6	100–240	—	—	2	~260	144	~130
Ethernet hub, 8-port	SMPS	—	—	—	10	2	~20	11	~10
Ethernet switch, 16-port	SMPS	—	100–240	25	—	2	~46	25	~23
Data service unit, 56 kb/s	SMPS	0.15	115	—	—	2	~32	18	~16
Data service unit, 65 kb/s	SMPS	0.22	120	—	—	2	~46	26	~23
						Total Estimated	~3,536	~1,971	~1,378
						Actual Measured	N/A	1,020	~920

[a] The "~" indicates an estimated or calculated value. 0.9 power factor is assumed for all power supplies; (therefore, Max. Running W = 0.9 × Max. Running VA).

equipment internal power supplies are somewhat oversized. The estimated starting VA, which assumes all loads start at the same time (in this case, a likely scenario) is about 3.5 times the actual running VA, although experience shows this to be somewhat overstated.

In this application, an inverter rated around 2000 to 2500 VA would serve the existing load equipment; however, the load is likely to increase over time. The actual inverter size would include not only the existing loads but a prediction of inverter load growth. A modular system with three or four 1000-VA inverter modules would serve existing loads and provide redundancy and some growth. If four modules are used initially, additional inverter modules will be required to meet $N + 1$ redundancy requirements when the actual load approaches 3000 VA.

Inverter ac output circuit design is the same as other ac branch circuits (Section 5.8.5). Since the inverter is a power source, the output circuit wiring must have overcurrent protection. Most load equipment operates at 120 Vac and is connected to an inverter system through common 15- or 20-A duplex receptacles (e.g., NEMA[17] 5-15R or 5-20R, two-pole, three-wire grounding, straight blade, 125-V receptacles). These circuits can be protected by 15- or 20-A circuit breakers, depending on the rating of the receptacle, and wired with 12 AWG wire.

Inverters typically have an output circuit breaker matched to the inverter output VA rating. Where this output circuit breaker is larger than 20 A or a modular systems is used in which the output exceeds the rating of 15- or 20-A branch circuits, the system cannot directly feed regular duplex receptacles. In this case, the output is connected to an ac circuit breaker panelboard that, in turn, feeds individual branch circuits (Fig. 5.28). Some inverter systems are available with an accessory ac distribution panel that is integrated with an inverter maintenance bypass switch. This simplifies branch circuit installation by eliminating the need for a separate panel.

In some inverters, the output is current limited in such a way that there is not enough fault current to trip protective devices in the event of a fault; others are specifically design to coordinate with their output protection device. Generally, inverter distribution circuits should use circuit breakers provided or recommended by the inverter manufacturer.

A maintenance bypass switch may be used to isolate the inverters and connect the loads directly to the commercial ac power source during maintenance (Fig. 5.29). The bypass switch normally applies only to passive standby or active standby operation. When an inverter system is set up for continuous operation, it is not connected to the commercial ac source.

5.7 OTHER DESIGN CONSIDERATIONS

5.7.1 Powerline Filter Applications

Powerline filters are required wherever electromagnetic interference (EMI) is coupled into dc power circuits by rectifier systems, load equipment, or other noise sources. The primary coupling mechanisms are conduction, radiation, and induction. Noise from rectifiers and load equipment usually is by conduction, and the coupling can be into or out of the equipment through the power circuit wiring. Radiation coupling usually is from wireless equipment such as radio transmitters or the oscillators and power supplies in load

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[17] National Electrical Manufacturers Association.

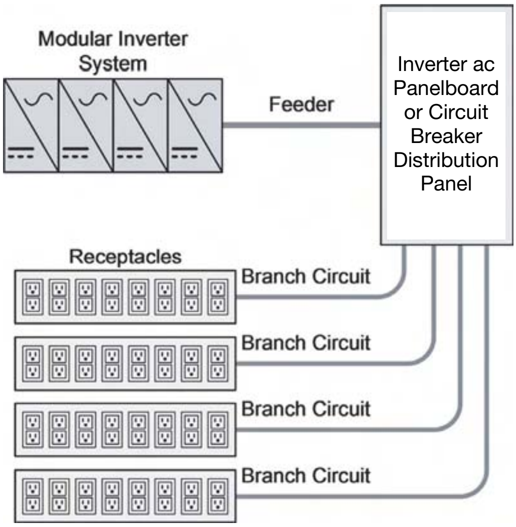
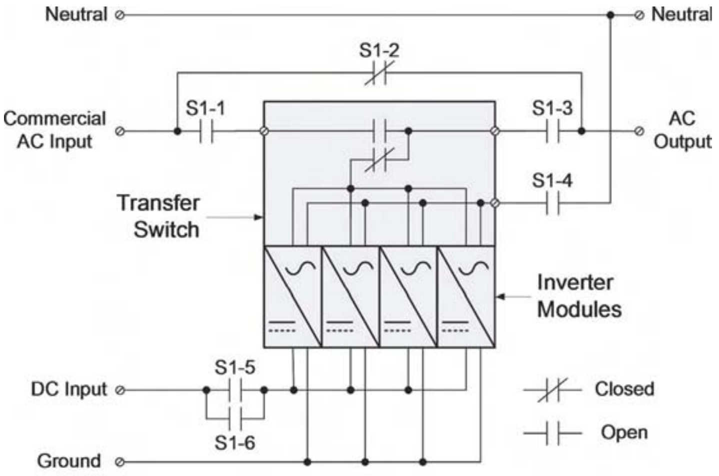


Fig. 5.28 Inverter output distribution.



Contacts	S1-5	S1-6	S1-3	S1-4	S1-2	S1-1
Maintenance					☒	
Test	☒	☒		☒	☒	☒
Online	☒	☒	☒	☒		☒

Fig. 5.29 Inverter maintenance bypass switch S1 consists of six contacts, S1-1 through S1-6. The switch is shown in the maintenance position in which S1-2 is closed and all other contacts are open. In this position, no dc is applied to the inverter modules and the inverter ac output and transfer switch are isolated from all external connections. When the maintenance bypass switch is in the on-line position, all contacts except S1-2 are closed, and the inverter system is in active standby operation. The transfer switch connects inverter ac output to the load through S1-3. If the inverter system fails, the transfer switch connects the commercial ac input to the load through S1-1 and S1-3. When the maintenance bypass switch is in the test position, all contacts except S1-3 are closed and dc is applied to the inverter modules, but inverter ac output is isolated from the load. The test position is used to verify inverter operation.

equipment. The radio transmitters do not have to be in the same room or building as the power circuits. Induction coupling is from nearby disturbing circuits that run parallel to the disturbed circuit.

Central offices in which the metallic components, such as equipment frames and grounding electrode systems, are not well bonded will have more noise problems than central offices in which great attention has been given to this aspect of equipment installation. Also, some equipment is more susceptible to noise than others and, in some cases, the equipment manufacturer will recommend powerline filtering.

There are no industry guidelines that describe the conditions under which powerline filters are installed, so their use and application becomes one of judgment and experience. All equipment installed in the vicinity of radio stations and known powerful noise sources should have powerline filters. Filters should be installed as close as possible to the equipment that requires filtering. An ideal location for the filter is in the fuse or circuit breaker panels typically located at the top of each equipment frame. Most equipment frame fuse and circuit breaker panels can be purchased with optional powerline filters.

Equipment installed in the United States must meet the conducted and radiated limits specified in 47CFR, part 15 of the FCC rules and regulations [17]. In some cases, NEBS requirements may be more stringent. As a result of these requirements, equipment deployed within the last 20 years is much less noisy (EMI) than older equipment.

5.7.2 Building Codes

Building codes have the effect of law when they have been adopted by governmental jurisdictions, such as states, counties, and municipalities. The codes relevant to dc power system design are[18]

- NFPA 70 National Electrical Code (NEC)
- International Fire Code (IFC)
- International Building Code (IBC)

5.7.2.1 NFPA 70 National Electrical Code (NEC) The purpose of the NEC [18] is to specify minimum safety requirements for electrical installation and not to serve as an electrical design manual. It does not apply to central offices or to spaces used exclusively for telecommunications unless company policy requires it to be used:

> Article 90.2(b) Not Covered—”(4) Installations of communications equipment under the exclusive control of communications utilities located outdoors or in building spaces used exclusively for such installations.” [18, page 70-23]

Although the NEC does not apply as stated above, all dc power systems should be made to comply with it wherever possible. Where the NEC does apply or is used, local county or municipal modifications, if any, also apply. The NEC historically has been a difficult document to use and interpret. An extensive rewrite in 2002 improved this situation

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[18] Not listed here is the National Electrical Safety Code (NESC), ANSI C2. The NESC has no specific requirements for telecommunications dc power systems, but it does have requirements for dc power systems used in electrical power facilities.

slightly, but disputes over interpretations still arise and interpretations by the Authority having jurisdiction (AHJ) will hold precedence.

5.7.2.2 International Fire Code (IFC, formerly Uniform Fire Code)

Certain sections of the IFC [19] apply to telecommunications dc power systems under limited circumstances. Specifically, Chapter 6, Section 608—Stationary Lead–Acid Battery Systems and Section 609—Valve-Regulated Lead–Acid (VRLA) Battery Systems address battery systems with more than 50 gal (189 liters) of electrolyte capacity. The IFC has no requirements for battery systems with less than 50 gal. Systems exceeding the 50-gal threshold must meet ventilation (see Section 5.7.4), spill control and other requirements. Spill control includes containing and neutralizing spilled electrolyte to a pH between 7.0 and 9.0 for 100% of capacity of the largest VLA cell or battery module and for 3% of the capacity of the largest VRLA cell or monoblock cells. For example, if the largest VLA cell or module holds 4 gal of electrolyte, there must be a method to control and neutralize a spill of 4 gal. If the largest VRLA cell or block contains 4 gal, control and neutralization must be available for 0.12 gal.

Although not a code (unless adopted by a government jurisdiction) and not directly related to the IFC, NFPA 76—Recommended Practice for the Fire Protection of Telecommunications Facilities [20] provides guidelines related to fire in telecommunications facilities. Chapter 6, Large Telecommunications Facilities applies to telecommunications equipment space >2500 ft^2 and includes fire detection, fire suppression, and limitation of combustibles. It details the requirements for each major area:

- Telecommunications equipment spaces
- Cable entrance facilities
- Power areas
- Main distribution frames
- Standby engine areas
- Technical support areas
- Administrative areas

NFPA 76, Chapter 7, Small Telecommunications Facilities, applies to telecommunications equipment spaces between 500 and 2500 ft^2 and includes fire detection, fire suppression, and limitation of combustibles but does not provide much detail.

NFPA 76 does not cover spaces <500 ft^2 even though there are a large number of remote enclosures (huts) and controlled environment vaults (CEVs) in the industry that fall within this dimension. It is up to the designer to determine if fire detection and fire suppression is to be provided. Small enclosures historically have not had fire problems and a catastrophe in one does not normally affect a large number of telecommunications users.

5.7.2.3 International Building Code (IBC)

The IBC [13] covers all aspects of building construction and indirectly affects the installation of dc power systems, particularly batteries because of their heavy floor loading.

5.7.3 Power Equipment Spaces

Battery systems normally are located in a room separate from network or electronic equipment, but this is impractical in small installations such as CEVs and remote equipment enclosures. When not located in a separate room, barriers or some type of mechanical protection should be provided to prevent inadvertent contact and damage to live components. In low voltage systems, these barriers typically are clear or opaque plastics such as Plexiglas, Acrylite, Lucite, and Lexan (Fig. 5.30).

Batteries require adequate space for routine maintenance, removal, and replacement and for air to freely circulate around them for cooling. Typical clearance requirements are shown in Figure 5.31. Properly ventilated battery rooms are not considered hazardous areas and special electrical wiring is not required.

The environmental requirements of dc power system equipment are similar to most network equipment. Some of the parameters that should be addressed are

- Absolute high and low temperatures
- Temperature rate of change
- Humidity (noncondensing)
- Altitude (derating at higher altitudes)

Estimates of the heat dissipated by rectifiers, dc–dc converters, and system monitors and controllers can be based on the equipment data sheets or based on estimates. Generally, the rectifiers, inverters, and converters will be responsible for most heat gain. Tables 5.9 and 5.10 may be used as a starting point to estimate the heat gain from rectifiers and other power system equipment.

5.7.4 Battery Room Ventilation

The telecommunications industry and other industries in the United States do not generally agree on the amount of ventilation required in battery rooms, and there are considerable variations in the ways ventilation calculations are made. This section will review the issues and methods in present use.

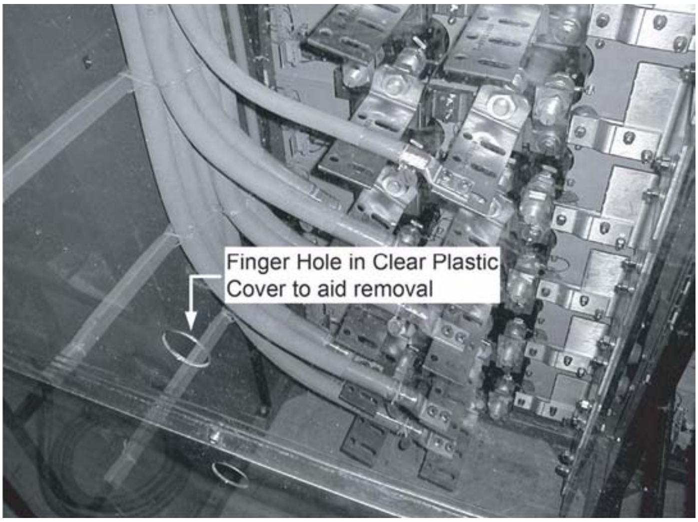

Fig. 5.30 Insulating plastic covers on the back of a power bay. (Photo courtesy of Schultz Brothers Electric Company.)

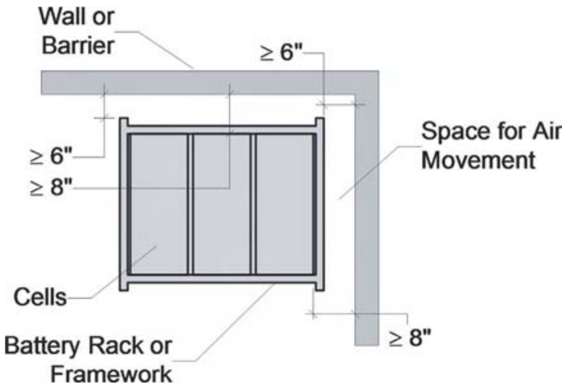

Fig. 5.31 Adequate space must be provided around a battery to allow free air movement and for movement during seismic events. Space for removal or replacement should be at least 30 in. Clearance from energized parts generally is 36 in.

Table 5.9 Approximate Heat Gain from Rectifiers (Based on 91.6% Efficiency)

48-V Rectifier Rating (A)	24-V Rectifier Rating (A)	Watts	Btu/h
25	50	125	425
50	100	250	850
100	200	500	1,700
200	400	1,000	3,400
400	800	2,000	6,800
800	1,600	4,000	14,000
1,600	3,200	8,200	28,000

Table 5.10 Approximate Additional Heat Gain from Miscellaneous Power Equipment (Not Including Rectifiers)

dc Power System Rating @ 48 V	dc Power System Rating @ 24 V	Watts	Btu/h
1,000 A	2,000 A	500	1,700
2,000 A	4,000 A	1,000	3,400
4,000 A	8,000 A	2,000	6,800
6,000 A	12,000 A	3,000	10,200
10,000 A	20,000 A	5,000	17,000

Under normal conditions, VLA cells release considerably more hydrogen gas than VRLA, but a VRLA cell with a failed valve acts as a VLA cell and vents as much gas as a VLA cell. Battery ventilation systems must be designed to account for abnormal conditions.

Hydrogen is a very flammable gas. Fire or an explosion may occur in spaces where the atmosphere is within the explosive limits of a flammable gas. Explosive limits (or flammable limits) are expressed in percentage by volume and are defined as the minimum and maximum concentrations of a flammable gas between which ignitions can occur. Concentrations below the lower explosive limit (LEL) are too lean to burn while those above the upper explosive limit (UEL) are too rich. For hydrogen in air at ordinary temperature and pressure, LEL = 4.0% and UEL = 74.2%. Therefore, for practical applications the ventilation must keep the concentration well below the LEL of 4%. A safety factor in the range of 2.0 to 5.0 is used, which limits the evolved hydrogen concentration to no more than 0.8 to 2% by volume. For example, if a room volume is 1000 ft^3, the hydrogen volume would be limited to 10 ft^3 for 1% concentration.

Hydrogen gas evolution can be estimated from [21]

$$Q_H = q_H I N_{\text{Cell}} \left(1 + \frac{T}{273} \right) \text{ liters/h} \tag{5.18a}$$

where Q_H = hydrogen gas evolution rate (liters/h) Note: 1000 liters/h = 1 m^3/h
q_H = volume of hydrogen gas evolved per cell per ampere-hour (0.42 liters/Ah)
I = current through cells (A)
N_{Cell} = number of cells in battery system
T = cell temperature (°C)

When the cell temperature is 25°C (77°F), Eq. (5.18a) becomes

$$Q_H = 0.46 \times I \times N_{\text{Cell}} \text{ liters/h} \tag{5.18b}$$

which is equivalent to the rate of hydrogen evolution given in [22]. To convert to cubic meters/hour, multiply liters/hour by 0.001. In more familiar units

$$Q_H = 0.00027 \times I \times N_{\text{Cell}} \text{ ft}^3\text{/min (CFM)} \tag{5.18c}$$

which is equivalent to the rate of hydrogen evolution given in [23].

The foregoing equations for hydrogen evolution give a higher gas evolution rate than is experienced in practice because only a portion of the current causes hydrogen gas to be generated. However, it is a useful starting point for ventilation calculations.

When the cells are fully charged and the voltage across them is the normal float voltage, the current I is the expected float current. Float current varies with the type of battery, float voltage, age, and temperature. Some typical values are shown in Table 5.11.

Battery room ventilation systems are not designed for normal float conditions but for abnormal conditions. There are at least four scenarios for abnormal operation of VLA and VRLA batteries:

- One or more cells in a string shorts out, exposing the remaining cells to a higher than normal float voltage and forcing them into an overcharge condition (barring more specific requirements, assume 10% of the cells are shorted for ventilation design purposes).

Table 5.11 Some Typical Float Currents for Fully Charged Lead–Acid Batteries[a]

Charge Voltage (V/cell) 1.215 SG	Charge Current at 25°C (mA/100 Ah) Pb–Sb 1.215 SG	Pb–Ca 1.240 SG	Pb–Sn
2.15	15–60	—	—
2.17	19–80	4	—
2.20	26–105	6	11
2.23	37–150	8	18
2.25	45–185	10	27
2.27	60–230	12	—
2.33	120–450	24	60
2.37	195–700	38	95
2.41	300–1100	58	—

[a] Data from [24].

- Rectifier system output voltage is incorrectly set too high or drifts out of adjustment, exposing all cells to a higher than normal float voltage and overcharge condition.
- A rectifier fails in a mode that causes its voltage to increase and the high-voltage shutdown circuits fail to operate.
- A cell fails, is removed from the string, and a shorting bar is installed in its place to keep the battery in service; unless the float voltage is decreased, this exposes the remaining cells to overcharge as in the first scenario above.

If any of these scenarios occur, the current through the cells is considerably higher than the normal float current, and the hydrogen evolution also is considerably higher.

One estimate for abnormal operation that is commonly used is 0.01 A/Ah (1 A/100 Ah) of cell capacity [that is, $I = 0.01 \times (AH_{8\text{hour}})$ A]. Using this value for float charge conditions

$$Q_H = 2.7 \times 10^{-6} \times (AH_{8\text{hour}})N_{\text{Cell}} \text{ CFM (float condition)} \tag{5.18d}$$

To convert from CFM to liters/hour, multiply by 1699.

The worst-case float current would be the maximum available rectifier system current; however, the maximum current is not ordinarily used to calculate hydrogen evolution because it is highly improbable that a battery or cell failure will sink the entire current available from the rectifier system. Instead, it is common practice to use one-fourth of the maximum available rectifier current. With this adjustment, Eq. (5.18b) and Eq. (5.18c) become

$$Q_H = 0.46\left(\frac{I_{\text{Max}}}{4}\right)N_{\text{Cell}} \text{ liters/h} \tag{5.18e}$$

$$= 0.00027\left(\frac{I_{\text{Max}}}{4}\right)N_{\text{Cell}} \text{ CFM} \tag{5.18f}$$

where I_{Max} is the maximum current available from the rectifier system when in overload (amperes).

Now that a method has been described to determine the rate at which hydrogen gas is evolved from a battery system, it is necessary to calculate the required ventilation rate. To limit the gas concentration to a particular concentration, the ventilation rate is

$$Q_{\text{VentRate}} = \frac{Q_H}{G_{\text{Limit}}} \tag{5.19}$$

where Q_{VentRate} = fan airflow rate (liters/h or CFM)
Q_H = hydrogen gassing rate (liters/h or CFM)
G_{Limit} = hydrogen gas concentration limit by volume (0.01–0.02)

Example 5.14 Determine (1) the hydrogen evolved during normal (float) and abnormal conditions and (2) the fan capacity to limit hydrogen concentration to 1% by volume during abnormal operation for the following system. Provide the answers in liters/hour and CFM for a cell temperature of 25°C (77°F):

Remote equipment enclosure: 8 ft (2.4 m) wide × 12 ft (3.7 m) long × 9 ft (2.7 m) high
48-V, 24-cell, 150-Ah battery
Rectifier capacity: 40 A (four 10-A rectifiers in $N + 1$ configuration, $N = 3$)
Equipment load 12 A

Solution The float current during normal operation is assumed to be 0.01 A/100 Ah × 150 Ah = 0.015 A. Therefore,

$$\begin{aligned} Q_H &= 0.46 N_{\text{Cell}} I = 0.46 \times 24 \times 0.015 = 0.166 \text{ liters/h} \\ &= 0.00027 \times 24 \times 0.015 = 0.000097 \text{ CFM} \end{aligned}$$

During abnormal operation, the calculations give

$$\begin{aligned} Q_H &= 0.46\left(\frac{I_{\text{Max}}}{4}\right) N_{\text{Cell}} = 0.46\left(\frac{40}{4}\right)24 = 110.4 \text{ liters/h} \\ &= 0.00027\left(\frac{40}{4}\right)24 = 0.065 \text{ CFM} \end{aligned}$$

To maintain a concentration no greater than 1% by volume,

$$\begin{aligned} Q_{\text{VentRate}} &= \frac{Q_H}{G_{\text{Limit}}} = \frac{110.4}{0.01} = 11{,}040 \text{ liters/h} \\ &= \frac{0.065}{0.01} = 6.5 \text{ CFM} \end{aligned}$$

As a point of reference, a typical residential bathroom fan is rated 50 to 100 CFM.

Hydrogen is very easily diluted by air, and in small installations (< 100 Ah) it is not always necessary to use fans if the space is equipped with inlet and outlet air vents. For natural ventilation, a common expression for the area of each vent (inlet and outlet) is

$$A_{\text{Vent}} \geq 2800 Q_H \text{ mm}^2 \text{ where } Q_H \text{ is in m}^3\text{/h}$$

or

$$A_{\text{Vent}} \geq 0.0178 Q_H \text{ ft}^2 \text{ where } Q_H \text{ is in ft}^3\text{/min (CFM)} \tag{5.20}$$

Battery rooms and spaces should have inlet vent louvers in the lower half of doors or walls and outlet louvers near the ceiling to outside air. The inlet vent area should be 1.5 times the outlet vent area to prevent fan starvation and to ensure free airflow (Fig. 5.32).

In larger installations, it is good practice to use at least one fan. If the battery room is air conditioned, the exhaust air from the battery room should not be returned to the air distribution system. Battery room exhaust systems or vents always should be directed outdoors. The exhaust requirements can be problematic in some climates, both hot and cold, and in those cases only a portion of the air is exhausted, with make-up air provided for that portion.

NFPA 111-2001, clause 5.3.2 [25] requires two air changes per hour in VLA battery rooms. Although no guidance is given for VRLA battery rooms, if the NFPA requirements are used, they should be applied to VRLA to be on the safe side. Note that these requirements do not take into account that a small battery may be installed in a big room or a big battery in a small room. Two air changes in one hour means that the ventilation system must move twice the room volume in one hour. To meet this requirement, the fan capacity is

$$Q_{\text{VentRate}} = 2(W_{\text{Room}} L_{\text{Room}} H_{\text{Room}}) \text{ m}^3\text{/h} \tag{5.21a}$$

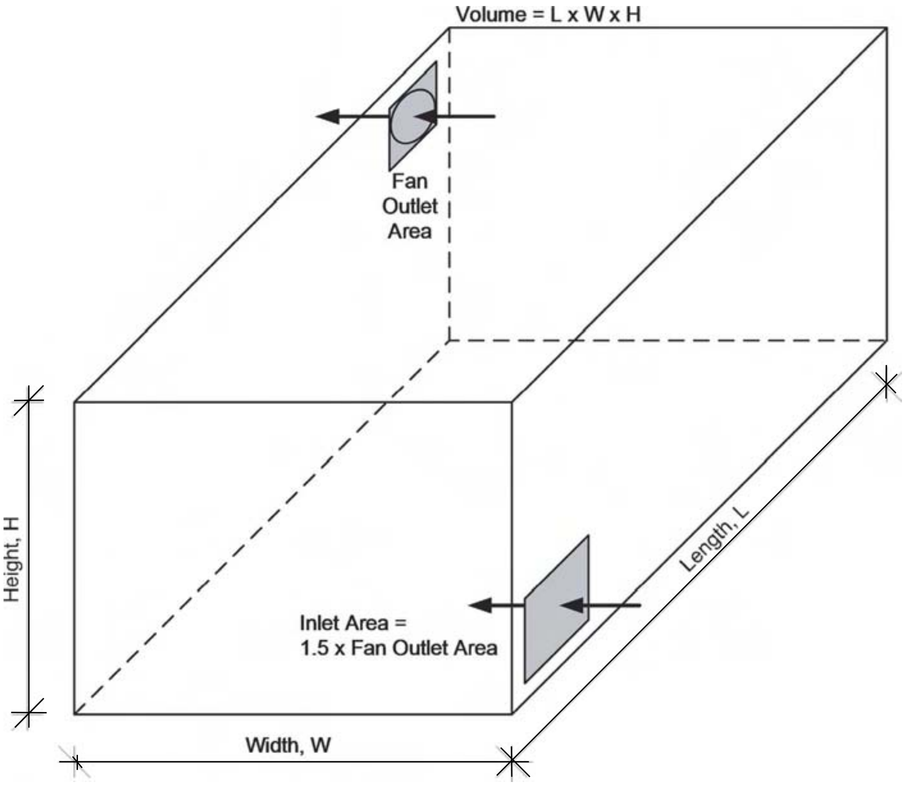

Fig. 5.32 Battery room ventilation layout.

where W_{Room} = room width (m)
L_{Room} = room length (m)
H_{Room} = room height (m)

To convert Q_{Fan} in m^3/h to ft^3/min, multiply by 0.589, or use

$$Q_{\text{VentRate}} = \tfrac{2}{60}(W_{\text{Room}}L_{\text{Room}}H_{\text{Room}}) \text{ CFM} \tag{5.21b}$$

where W_{Room} = room width (ft)
L_{Room} = room length (ft)
H_{Room} = room height (ft)

Example 5.15 Determine the fan capacity in liters/hour and CFM for the space in Example 5.14 if the requirements of NFPA 111 are followed.

Solution The room volume is 24.5 m^3 or 864 ft^3. To achieve two air changes per hour, the ventilation rate must be 49 m^3/h or 1728 ft^3/h, or in the specified units, 49,000 liters/h or 28.8 CFM.

Other criteria have been used to calculate battery room ventilation rate. For example, where the IFC applies and detailed calculations are not made to show otherwise, the required ventilation rate must be at least 1 ft^3 per minute (CFM) per ft^2 of floor space continuous, or as necessary to limit hydrogen to 1% by volume.

Example 5.16 Determine the fan capacity in CFM using IFC requirements for the space in Example 5.14.

Solution The space area is 8 ft × 12 ft = 96 ft^2 and the required ventilation rate is 1 CFM/ft^2 × 96 ft^2 = 96 CFM (163,105 liters/h).

A method that is frequently used outside the United States determines the amount of ventilation required to maintain the LEL and then applies a safety factor to increase the ventilation by a factor of 5, as in

$$Q_{\text{VentRate}} = Dq_H S N_{\text{Cell}} I \text{ liters/hour} \tag{5.22a}$$

where D = dilution factor for hydrogen in air at LEL = 100%/3.8% (Note: The LEL is 3.8% rather than 4.0% in this equation)
S = safety factor = 5
I = charge current = 0.02 A per ampere-hour of capacity

Substituting the above values gives

$$Q_{\text{VentRate}} = 26.3 \times 0.42 \times 5 \times N_{\text{Cell}} \times I = 55 \times N_{\text{Cell}} \times I \text{ liters/hour} \tag{5.22b}$$

Example 5.17 Determine the fan capacity in liters/hour and CFM for the space in Example 5.14 using Eq. (5.22b).

Solution Using the criteria given, the charging current for a 150-Ah battery is 0.02 × 150 = 3 A. Therefore,

$$Q_{\text{VentRate}} = 55 \times 24 \times 3 = 3960 \text{ liters/h}$$

To convert to CFM, multiply by 0.0005886, giving 2.3 CFM.

Another industry practice is to use the most stringent of the following criteria:

1. One air change every 4 h
2. Two CFM per battery string
3. Twenty CFM per person when the space is occupied
4. Applicable codes

Example 5.18 Using the first three criteria above, determine the required ventilation rate for the space in Example 5.14.

Solution

Criteria 1 One air change every 4 hours is equivalent to 0.25 air changes per hour. Since the space volume is 24.5 m^3 or 864 ft^3, the ventilation rate is 6125 liters/h or 3.6 CFM.

Criteria 2 Since there is one battery string, the required rate is 3398 liters/h or 2 CFM.

Criteria 3 Assuming the space is occupied by one person, the required rate is 33,979 liters/h or 20 CFM.

Example 5.19 Compare the results from the previous five examples.

Solution

Example	liters/h	ft^3/min	Remarks
5.14	11,040	6.5	Safety factor = 4 and $I_{\text{Max}}/4$
5.15	49,000	28.8	NFPA 111-2001, 2 air changes/h
5.16	163,105	96	IFC, 1 CFM/ft^2 of floor space
5.17	3,960	2.3	Safety factor = 5 and $I = 0.02$ A/Ah
5.18.1	6,125	3.6	Industry practice, 0.25 air change/h
5.18.2	3,398	2	Industry practice, 2 CFM/string
5.18.3	33,979	20	Industry practice, space occupied

As the previous examples show, the required ventilation rate can vary by a factor of 50 depending on the method used to calculate it.

Ventilation design should include a design margin or redundancy, such as vent louvers and fans sized twice as large as calculations indicate or using a minimum of two fans. It may be desirable to have two fans, one that ventilates the room when unoccupied by workers and another that can be manually turned on when workers are present. Also, in cold or hot climates, it may be desirable to run the fan intermittently (say every other hour) to conserve energy required for air conditioning. In this case, the fan should be sized with the appropriate safety factor (2 to 5) such that the LEL cannot be reached during the periods when the fan is off.

A hydrogen detector may be desirable in a battery installation, particularly in large ones. The following alarm thresholds are commonly used:

- Minor alarm: 10% LEL
- Major alarm: 25% LEL

Hydrogen detectors require relatively frequent calibration, and some types are easily contaminated by ordinary materials used in battery rooms. Three manufacturers of hydrogen gas detectors that are marketed to the telecommunications industry are Arrgh Manufacturing Co., (www.arrgh.com), General Monitors (www.generalmonitors.com), and RKI Instruments, Inc. (www.rkiinstruments.com).

5.7.5 Alternating Current Power

The ac distribution in dc power system spaces should include ac circuits for

- Rectifier system
- Inverter system (only if connected to the commercial ac system as in active or passive standby operation)
- Local lighting
- Convenience outlets
- Local heating, ventilating, and air conditioning equipment
- Other dedicated ac load equipment in the space

The ac distribution in telecommunications facilities (not just dc power system spaces) includes *essential* and *protected* circuits (see Chapter 1 for definitions) and the various ac loads normally are assigned as shown in Table 5.12.

Table 5.12 Minimum Equipment Load List for ac Essential and Protected Buses

Component	Essential	Protected
Network elements (switches, transmission, alarm systems)		✓
Network element workstations		✓
Internal telephone systems supporting network elements	✓	✓
Uninterruptible power systems (UPS)	✓	
Waveguide pressurization and dehydrators	✓	
Standby engine–generator set auxiliaries (louvers, fuel pumps, battery chargers, etc.)	✓	
Standby engine–generator set fuel transfer pumps		✓
Furnace pumps	✓	
Air conditioners serving network equipment	✓	
Water pumps for fire suppression	✓	
Fire alarm reporting systems	✓	
Building security systems (card readers, gate/door opening devices)		✓
Building automation controls		✓
Elevator (one per building bank, check local requirements)	✓	
Equipment area lighting	✓	
Exit and stairwell lighting		✓
Exterior security lighting	✓	
Tower lighting	✓	

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PART II DIRECT CURRENT POWER SYSTEMS CIRCUIT DESIGN

This part describes guidelines for designing dc circuits and dc power system bonding and grounding.

5.8 CIRCUIT DESIGN

Basic circuit design procedures include a few simple rules:

- Each equipment shelf, chassis, or assembly must be served by one or two dedicated power circuits, each protected by its own overcurrent protection device.
- Circuit conductors must be large enough to safely carry the current.
- Circuit conductors must be large enough to keep the voltage drop below the desired threshold.

5.8.1 General Considerations

5.8.1.1 Circuit Configurations All circuits must have an overcurrent device, and dedicated circuits are used for all equipment [Fig. 5.33(a)]. Loads do not share circuit overcurrent protection devices, and daisy chaining is not used [Figs. 5.33(b) and 5.33(c)].

5.8.1.2 Temperature Considerations Temperatures affect both voltage drop and current rating calculations. For design purposes, the following temperatures commonly are used:

Voltage drop:	30°C (86°F) or 75°C (167°F)
Current rating:	
Cable bus:	75°C (167°F) or 90°C (194°F)
Rigid bus:	70°C (158°F)

The 30°C (86°F) design temperature for voltage drop calculations reflects common practice in telecommunications and represents the wire temperature when self-heating is small. The higher values for current rating calculations also reflect common practice.

5.8.1.3 Conductors The basic properties of copper conductors are shown in Table 5.13. Both coarse-strand wire (ASTM B8-04, Class B, often called building wire) and fine-strand wire (ASTM B172-01a, Class I, often referred to as flexible, welding[19] or locomotive cable) are used in telecommunication applications. Other types may be used if they are properly rated and installed. Fine-strand wire usually is more expensive than coarse-strand, but installation labor savings in sizes larger than 4/0 AWG usually cancel the added material cost. Class I fine-strand wire also is used to allow movement during a seismic event. For example, rigid busbars may be used as the main conductors with Class

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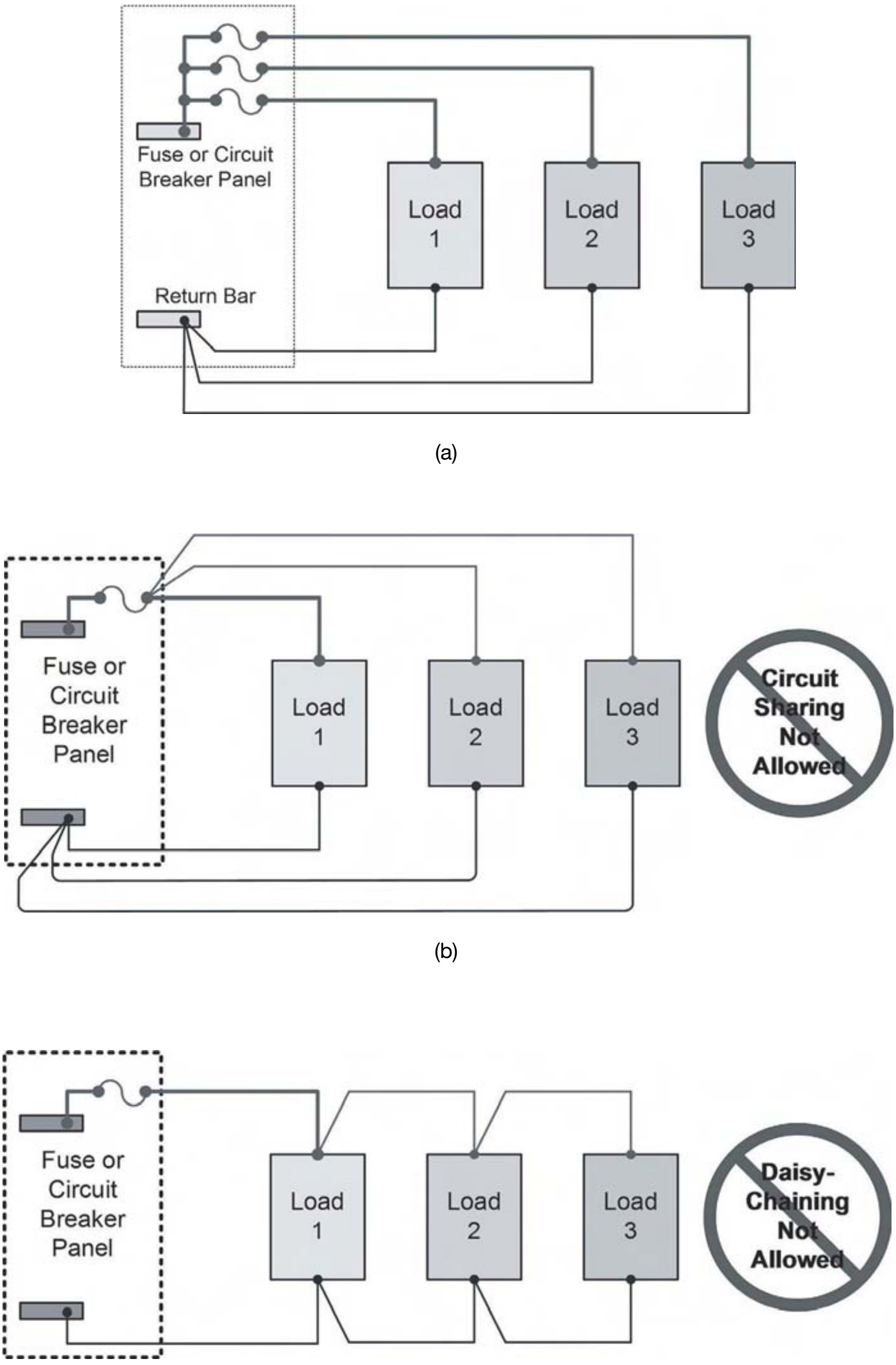
[19] Even though it has been used on some battery systems and even by battery manufacturers for interconnecting cables, welding cable typically is not listed by independent electrical testing laboratories, and, when it is, its use usually is limited to welding machines. If electrical testing laboratory approval is important in a particular application or as a matter of company policy, welding cable would not be a good choice.



(a)

(b)

(c)

Fig. 5.33 (a) Dedicated circuits each with its own overcurrent device. (b) Circuit overcurrent protection device sharing and load paralleling not allowed. (c) Circuit daisy chaining not allowed.

I wire for the final connections at the battery and powerboard charge bus. Some installations use Class B wire in the main run and transition by splice to Class I wire before the cable is terminated at the battery or rectifier frame.

The stranding of building wire is shown in Table 5.14 for conductors from 18 AWG to 2000 kcmil. The stranding of fine-strand wire used in telecommunications applications for the range of 8 AWG to 2000 kcmil also is shown in Table 5.14. In telecommunications applications, fine-strand wire normally is used only in sizes larger than 4/0 AWG, although some companies use it for all dc power wiring including wires as small as 8 AWG.

An important consideration in the selection of the wire insulation and jacket is the combustion products when the wire burns. The materials should not support flame and their smoke should have minimum toxicity and should not be corrosive. Low-smoke insulations and jackets are preferred for central office installations.

A number of different insulation types have been used over the years. Type RHW, RHW-2, and RHH insulated wires commonly are used in dc power systems as are THW

Table 5.13 Basic Properties of Stranded Copper Conductors (Building Wire)

Size (AWG or kcmil) (1)	Conductor Diameter (in.) (2)	Cross Section (Circular Mils)[a] (3)	DC Resistance (Ω/1000 ft)[b]			
			20°C (4)	30°C (5)	75°C (6)	90°C (7)
18	—	1,620	6.54	6.79702	7.95362	8.33915
16	—	2,580	4.10	4.26113	4.98622	5.22791
14	0.073	4,110	2.58	2.68139	3.13767	3.28976
12	0.092	6,530	1.63	1.69406	1.98232	2.07841
10	0.116	10,380	1.02	1.06009	1.24047	1.30060
8	0.146	16,510	0.64	0.66515	0.77834	0.81606
6	0.184	26,240	0.403	0.41884	0.49011	0.51387
4	0.232	41,740	0.253	0.26294	0.30769	0.32260
3	0.260	52,620	0.201	0.20890	0.24445	0.25630
2	0.292	66,360	0.159	0.16525	0.19337	0.20274
1	0.332	83,690	0.127	0.13199	0.15445	0.16194
1/0	0.372	105,600	0.100	0.10393	0.12162	0.12751
2/0	0.418	133,100	0.0795	0.08262	0.09668	0.10137
3/0	0.470	167,800	0.0630	0.06548	0.07662	0.08033
4/0	0.528	211,600	0.0500	0.05197	0.06081	0.06376
250	0.575	250 kcmil	0.0423	0.04396	0.05144	0.05394
350	0.681	350 kcmil	0.0302	0.03139	0.03673	0.03851
500	0.813	500 kcmil	0.0212	0.02203	0.02578	0.02703
750	0.998	750 kcmil	0.0141	0.01465	0.01715	0.01798
1,000	1.152	1,000 kcmil	0.0106	0.01102	0.01289	0.01352
1,250	1.289	1,250 kcmil	0.00847	0.00880	0.01030	0.01080
1,500	1.412	1,500 kcmil	0.00705	0.00733	0.00857	0.00899
2,000	1.632	2,000 kcmil	0.00529	0.00550	0.00643	0.00675

[a] Equivalent cross section (circular mils) is the sum of the circular mil area of the individual conductor strands. The overall wire diameter is slightly larger. The equivalent diameter (mils) is the square root of the equivalent cross section.

[b] Resistances at 20°C are from ASTM B-8 [27]; other resistances are adjusted to temperatures shown.

and THW-2. However, these types of wire insulations do not always have low smoke and flame characteristics. Care must be exercised when wire is selected from manufacturers' catalogs to ensure the correct insulation type (low smoke). Wires with thin insulations, such as THHW, THWN, and THHN, have been used in some installations, but the associated slick nylon outer jacket makes the wire more difficult to handle and secure during and after installation and their smoke products are undesirable.

For purposes of current rating calculations, the wire types are broadly classified as unjacketed and jacketed. The thicknesses of the insulations including jackets (if used) for various wire sizes and insulation types are shown in Table 5.15. Wire current ratings are shown in Table 5.16 for various installation conditions and physical layouts as follows:

Table 5.16(a)	Single copper wire in free air
Table 5.16(b)	Alternate current ratings for single copper wire in free air (based on NEC)
Table 5-16(c)	Two bundled copper wires
Table 5.16(d).1	Single unjacketed copper wires with no separation in one or more layers, 75°C

Table 5.14 Copper Conductor Strand Properties and Weights

Coarse Strand (ASTM B8-04 Class B)				Fine Strand[b] (ASTM B-172 Class I)			
AWG or kcmil	Strands	Strand Diameter (mils)	Weight with Insulation (lb/ft)[a]	AWG or kcmil	Strands	Strand Diameter (mils)	Weight with Insulation (lb/ft)[a]
18	7	15	—	—	—	—	—
16	7	19	—	—	—	—	—
14	7	24	0.022	—	—	—	—
12	7	30	0.031	—	—	—	—
10	7	38	0.045	—	—	—	—
8	7	49	0.074	8	41	20.1	0.082
6	7	61	0.108	6	63	20.1	0.117
4	7	77	0.161	4	105	20.1	0.175
3	7	87	0.198	3	133	20.1	—
2	7	97	0.244	2	161	20.1	0.253
1	19	66	0.319	1	210	20.1	—
1/0	19	74	0.392	1/0	266	20.1	0.423
2/0	19	84	0.484	2/0	342	20.1	0.538
3/0	19	94	0.599	3/0	418	20.1	—
4/0	19	106	0.743	4/0	532	20.1	0.790
250	37	82	0.889	250	637	—	—
350	37	97	1.217	350	882	20.1	1.302
500	37	116	1.703	500	1,225	20.1	1.831
750	61	111	2.540	750	1,862	20.1	2.752
1,000	61	128	3.343	1,000	2,527	20.1	—
1,250	91	117	4.310	1,250	3,059	20.1	—
1,500	91	128	5.110	1,500	3,724	20.1	—
2,000	127	126	6.910	2,000	4,921	20.1	—

[a] Weight varies slightly with the type of insulation.

[b] Variations exist between different types of fine-strand wire; the table above is based on wire designed for use in telecommunications central offices.

Table 5.15 Insulated Wire Properties[a]

AWG or kcmil	Conductor Diameter (in.)	Insulation Thickness (Mils)[b] Hookup	THW	RHH, RHW, RHW-2	Jacketed
18	0.046	15–30	—	—	—
16	0.058	15–30	—	—	—
14	0.073	15–30	30	45	60
12	0.092	15–30	30	45	60
10	0.116	15–30	30	45	60
8	0.146	—	45	60	90
6	0.184	—	60	60	90
4	0.232	—	60	60	90
3	0.260	—	60	60	90
2	0.292	—	60	60	90
1	0.332	—	80	80	125
1/0	0.372	—	80	80	125
2/0	0.418	—	80	80	125
3/0	0.470	—	80	80	125
4/0	0.528	—	80	80	125
250	0.575	—	95	95	160
350	0.681	—	95	95	160
500	0.813	—	95	95	160
750	0.998	—	110	110	175
1,000	1.152	—	110	110	175
1,250	1.289	—	125	125	220
1,500	1.412	—	125	125	220
2,000	1.632	—	125	125	220

[a] Hookup wire 300–600 V rating, all other wire 600 V rating.

[b] Outside diameter of insulated wire = Conductor diameter + 2 × Insulation thickness.

Table 5.16(d).2	Single jacketed copper wires with no separation in one or more layers, 75°C
Table 5.16(d).3	Single unjacketed copper wires with no separation in one or more layers, 90°C
Table 5.16(d).4	Single jacketed copper wires with no separation in one or more layers, 90°C
Table 5.16(e).1	Rounded bundle of unjacketed copper wires, 75° C
Table 5.16(e).2	Rounded bundle of jacketed copper wires, 75° C
Table 5.16(e).3	Rounded bundle of unjacketed copper wires, 90° C
Table 5.16(e).4	Rounded bundle of jacketed copper wires, 90° C

The descriptions of the installation conditions, physical layouts, and current rating calculations are provided in Section 5.8.1.6.

Rigid busbars are used where it is necessary to carry large currents over relatively long distances and typically are found in systems or circuits exceeding approximately 800 to 1000-A capacity. In most applications, rigid busbars are uninsulated (bare), although they usually are taped or covered with an insulating cover where subject to accidental contact.

Rigid copper busbar physical and electrical properties including current ratings are

Table 5.16(a) Calculated Current Ratings in Free Air for Unjacketed and Jacketed Single Copper Wires at 75°C and 90°C with 30°C Ambient Temperature

AWG or kcmil (1)	Insulation Thickness Unjacketed (in.) (2)	Unjacketed DC Current Rating 75°C (A) (3)	Unjacketed DC Current Rating 90°C (A) (4)	Insulation Thickness Jacketed (in.) (5)	Jacketed DC Current rating 75°C (A) (6)	Jacketed DC Current rating 90°C (A) (7)
14	0.045	34	39	0.060	34	40
12	0.045	44	51	0.060	45	52
10	0.045	59	68	0.060	60	69
8	0.060	79	92	0.090	81	93
6	0.060	105	122	0.090	107	124
4	0.060	141	164	0.090	143	165
3	0.060	163	190	0.090	165	191
2	0.060	190	220	0.090	191	221
1	0.080	221	256	0.125	222	257
1/0	0.080	257	299	0.125	258	298
2/0	0.080	299	347	0.125	299	346
3/0	0.080	348	404	0.125	347	402
4/0	0.080	406	471	0.125	404	467
250	0.095	453	525	0.160	448	518
350	0.095	566	657	0.160	558	646
500	0.095	718	834	0.160	706	816
750	0.110	943	1,094	0.175	923	1,068
1,000	0.110	1,146	1,330	0.175	1,120	1,295
1,250	0.125	1,330	1,541	0.220	1,284	1,482
1,500	0.125	1,509	1,749	0.220	1,454	1,679
2,000	0.125	1,842	2,135	0.220	1,771	2,045

shown in Table 5.17 (single busbar) and Table 5.18 (parallel busbars). Table 5.18 consists of:

Table 5-18(a)	¼ in. Parallel Busbars
Table 5-18(b)	⅜ in. Parallel Busbars
Table 5-18(c)	½ in. Parallel Busbars
Table 5-18(d)	¾ in. Parallel Busbars

Table 5.19 provides alternate ratings for some busbar configurations and is based on ANSI/T1.311 [28]. Refer to table notes for additional details on using these tables. Table 5.19 does not cover as many combinations, and the current ratings generally are higher than Tables 5.17 and 5.18, particularly for parallel bars. However, Table 5.19 values have been used successfully in the telecommunications industry for many years. Also, Table 5.19 provides current ratings for the situations where the busbar is mounted in such a way that its ability to dissipate heat is diminished, such as when the bars are spaced less than their thickness, run with the long edge horizontal, or run in the vertical direction. When there is doubt or any discrepancies in the current ratings in this book, the more conservative (lower) current ratings should be used.

Busbars used in electrical power applications generally are referred to as copper No. 110 busbars, also called electrolytic tough pitch (ETP) or ETP-110 or C11000 (copper

Table 5.16(b) DC Current Ratings in Free Air Calculated from the NEC [29] for Copper Wire at 75°C and 90°C

AWG or kcmil (1)	Skin Effect/Proximity Effect Factor, F_{SP}[a] (2)	NEC Free Air dc Current Rating 75°C (A)[b] (3)	NEC Free Air DC Current Rating 90°C (A)[b] (4)
14	1.00	30	35
12	1.00	35	40
10	1.00	50	55
8	1.00	70	80
6	1.00	95	105
4	1.00	125	140
3	1.00	145	165
2	1.00	170	190
1	1.00	195	220
1/0	1.00	230	260
2/0	1.00	265	300
3/0	1.00	310	350
4/0	1.00	360	405
250	1.00	405	455
350	1.00	505	570
500	1.01	626	707
750	1.02	801	903
1,000	1.03	963	1,087
1,250	1.05	1,118	1,260
1,500	1.07	1,257	1,418
2,000	1.11	1,537	1,732

[a] From [30].

[b] The dc current ratings in columns (3) and (4) are ac ampacities from Table 310.16 of [29] multiplied by the factors in column (2).

that has been refined electrolytically). The busbar is 99.90% pure copper by weight and has 101% IACS (International Annealed Copper Standard) electrical conductivity and 10.371 Ω-CM/ft resistivity at 20°C.

5.8.1.4 Parallel Conductors

It is frequently necessary to use parallel conductors to reduce voltage drop, increase current rating, or both (Fig. 5.34). Where wire conductors are connected in parallel, their length must be the same to ensure current sharing. The conductors must be the same size and type and same material, and they must be terminated using the same materials and methods. Where parallel conductors are to be used, they must be used on both sides of the circuit (feed and return)—in other words, if the feed uses parallel wires, the return also must use parallel wires.

The resistance of parallel conductors equals the resistance of one conductor divided by the number of conductors in parallel:

$$R_P = \frac{R_{\text{Cond}}}{N_{\text{Cond}}} \qquad (5.23)$$

where R_P = resistance of parallel conductors
R_{Cond} = resistance of one of the conductors
N_{Cond} = number of conductors connected in parallel

Table 5.16(c) Calculated Current Ratings for Two Bundled Unjacketed and Jacketed Copper Wires at 75°C and 90°C

AWG or kcmil (1)	Insulation Thickness Unjacketed (in.) (2)	Unjacketed DC Current Rating 75°C (A) (3)	Unjacketed DC Current Rating 90°C (A) (4)	Insulation Thickness Jacketed (in.) (5)	Jacketed DC Current Rating 75°C (A) (6)	Jacketed DC Current Rating 90°C (A) (7)
14	0.045	29	34	0.060	30	35
12	0.045	38	45	0.060	39	46
10	0.045	51	59	0.060	52	61
8	0.060	69	80	0.090	71	83
6	0.060	92	107	0.090	94	110
4	0.060	123	143	0.090	126	146
3	0.060	142	165	0.090	145	168
2	0.060	165	192	0.090	168	195
1	0.080	193	225	0.125	197	228
1/0	0.080	225	262	0.125	228	264
2/0	0.080	261	303	0.125	264	306
3/0	0.080	304	353	0.125	306	355
4/0	0.080	353	411	0.125	355	412
250	0.095	395	459	0.160	397	460
350	0.095	494	574	0.160	494	572
500	0.095	625	726	0.160	622	721
750	0.110	820	953	0.175	814	943
1,000	0.110	995	1,156	0.175	985	1,141
1,250	0.125	1,156	1,343	0.220	1,135	1,314
1,500	0.125	1,310	1,521	0.220	1,284	1,486
2,000	0.125	1,595	1,852	0.220	1,560	1,805

The circular mil area of parallel conductors equals the circular mil area of one of the conductors times the number of conductors in parallel:

$$\mathrm{CM}_P = \mathrm{CM}_{\mathrm{Cond}} N_{\mathrm{Cond}} \tag{5.24}$$

where CM_P = circular mil area of the parallel conductors
$\mathrm{CM}_{\mathrm{Cond}}$ = circular mil area of one of the conductors
N_{Cond} = number of conductors connected in parallel

It is not normal practice to use parallel conductors in sizes smaller than 1/0 AWG, but there are many exceptions to this practice, particularly in smaller systems. However, there is no reason to parallel conductors smaller than 2 AWG even in small systems. Parallel conductors smaller than 1/0 AWG are not allowed in installations covered by the National Electrical Code.[20]

5.8.1.5 Voltage Drop Calculations The dc voltage drop calculations are somewhat simpler than ac voltage drop calculations because with dc there is no skin effect or reactance due to operating frequency. Two methods are used:

- The first method is based on a simple factor (voltage drop factor, sometimes called

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[20] 2005 NEC, Article 310.4. [29].

Table 5.16(d).1 Current Ratings for Unjacketed Single (1/C) Copper Wires at 75°C with No Separation in One or More Layers—30°C Ambient Temperature[a]

AWG or kcmil (1)	Conductor Cross Section (CM) (2)	Wire Diameter[b] (in.) (3)	dc Resistance 75°C[c] (Ω per 1000 ft) (4)	Free Air DC Current Rating[d] 75°C (A) (5)	Current Rating Unjacketed 75°C (A)						
					Apparent (Calculated) Wire Mass Fill Depth						
					1 in. (6)	1.5 in. (7)	2 in. (8)	2.5 in. (9)	3 in. (10)	3.5 in. (11)	4 in. (12)
14	4,110	0.163	3.13767	34	6.5	5.1	4.2	3.6	3.2	2.8	2.6
12	6,530	0.182	1.98232	44	9.1	7.1	5.9	5.1	4.4	4.0	3.6
10	10,380	0.206	1.24047	59	13	10	8.4	7.2	6.4	5.7	5.2
8	16,510	0.266	0.77834	79	21	17	14	12	10	9.3	8.4
6	26,240	0.304	0.49011	105	31	24	20	17	15	13	12
4	41,740	0.352	0.30769	141	45	35	29	25	22	20	18
3	52,620	0.380	0.24445	163	54	42	35	30	26	24	21
2	66,360	0.412	0.19337	190	66	51	43	37	32	29	26
1	83,690	0.492	0.15445	221	88	69	57	49	43	39	35
1/0	105,600	0.532	0.12162	257	108	84	69	60	52	47	43
2/0	133,100	0.578	0.09668	299	131	102	85	73	64	57	52
3/0	167,800	0.630	0.07662	348	161	125	104	89	78	70	63
4/0	211,600	0.688	0.06081	406	197	153	127	109	96	86	78
250	250,000	0.765	0.05144	453	238	185	153	132	116	104	94
350	350,000	0.871	0.03673	566	321	250	207	178	156	140	127
500	500,000	1.003	0.02578	718	442	343	284	244	215	192	174
750	750,000	1.218	0.01715	943	657	511	423	363	320	286	259
1,000	1,000,000	1.372	0.01289	1,146	854	664	550	472	415	372	337
1,250	1,250,000	1.539	0.01030	1,330	1,072	833	690	593	521	467	423
1,500	1,500,000	1.662	0.00857	1,509	1,269	986	817	702	617	552	501
2,000	2,000,000	1.882	0.00643	1,842	1,659	1,289	1,068	917	807	722	654

[a] No diversity. Free air current rating is shown for reference.

[b] From NFPA 70-2005 (NEC®) Table 8 and Table 310.13 [28, nec]

[c] dc resistance from ASTM B8-04 [27, ASTM B8], adjusted to 75°C

[d] From Table 5.16(a)

Table 5.16(d).2 Current Ratings for Jacketed Single Copper Wires (1/C) at 75°C with No Separation in One or More Layers—30°C Ambient Temperature[a]

AWG or kcmil (1)	Conductor Cross Section (CM) (2)	Wire Diameter[b] (in.) (3)	DC Resistance 75°C[c] (Ω per 1000 ft) (4)	Free Air DC Current Rating[d] 75°C (A) (5)	DC Current Rating Jacketed 75°C (A)						
					Apparent (Calculated) Wire Mass Fill Depth						
					1 in. (6)	1.5 in. (7)	2 in. (8)	2.5 in. (9)	3 in. (10)	3.5 in. (11)	4 in. (12)
14	4,110	0.193	3.13767	34	7.7	6.0	5.0	4.3	3.7	3.4	3.0
12	6,530	0.212	1.98232	45	11	8.3	6.8	5.9	5.2	4.6	4.2
10	10,380	0.236	1.24047	60	15	12	9.6	8.3	7.3	6.5	5.9
8	16,510	0.326	0.77834	81	26	20	17	14	13	11	10
6	26,240	0.364	0.49011	107	37	29	24	20	18	16	15
4	41,740	0.412	0.30769	143	53	41	34	29	26	23	21
3	52,620	0.440	0.24445	165	63	49	41	35	31	27	25
2	66,360	0.472	0.19337	191	76	59	49	42	37	33	30
1	83,690	0.582	0.15445	222	105	81	67	58	51	46	41
1/0	105,600	0.622	0.12162	258	126	98	81	70	61	55	50
2/0	133,100	0.668	0.09668	299	152	118	98	84	74	66	60
3/0	167,800	0.720	0.07662	347	184	143	118	102	89	80	73
4/0	211,600	0.778	0.06081	404	223	173	144	123	108	97	88
250	250,000	0.895	0.05144	448	279	217	180	154	136	121	110
350	350,000	1.001	0.03673	558	369	287	238	204	180	161	146
500	500,000	1.133	0.02578	706	499	388	321	276	243	217	197
750	750,000	1.348	0.01715	923	728	565	468	402	354	317	287
1,000	1,000,000	1.502	0.01289	1,120	935	727	602	517	455	407	369
1,250	1,250,000	1.729	0.01030	1,284	1,204	936	775	666	586	524	475
1,500	1,500,000	1.852	0.00857	1,454	1,414	1,099	910	782	688	615	558
2,000	2,000,000	2.072	0.00643	1,771	1,826[e]	1,419	1,175	1,010	888	795	720

[a] No diversity. Free air current rating is shown for reference.

[b] From NFPA 70-2005 (NEC) Table 8 and Table 310.13 [28].

[c] dc resistance from ASTM B8-04 [27, ASTM B8], adjusted to 75°C.

[d] From Table 5.16(a).

[e] Use free air current rating.

Table 5.16(d).3 Current Ratings for Unjacketed Single Copper Wires (1/C) at 90°C with No Separation in One or More Layers—30°C Ambient Temperature[a]

AWG or kcmil (1)	Conductor Cross Section (CM) (2)	Wire Diameter[b] (in.) (3)	DC Resistance 90°C[c] (Ω per 1000 ft) (4)	Free Air DC Current Rating[d] 90°C (A) (5)	DC Current Rating Unjacketed 90°C (A)						
					Apparent (Calculated) Wire Mass Fill Depth						
					1 in. (6)	1.5 in. (7)	2 in. (8)	2.5 in. (9)	3 in. (10)	3.5 in. (11)	4 in. (12)
14	4,110	0.163	3.28976	39	7.5	5.8	4.8	4.1	3.6	3.2	2.9
12	6,530	0.182	2.07841	51	11	8.2	6.7	5.8	5.1	4.5	4.1
10	10,380	0.206	1.30060	68	15	12	9.7	8.3	7.3	6.5	5.9
8	16,510	0.266	0.81606	92	25	19	16	14	12	11	9.6
6	26,240	0.304	0.51387	122	35	27	23	20	17	15	14
4	41,740	0.352	0.32260	164	52	40	33	28	25	22	20
3	52,620	0.380	0.25630	190	63	49	40	34	30	27	24
2	66,360	0.412	0.20274	220	77	59	49	42	37	33	30
1	83,690	0.492	0.16194	256	102	79	65	56	49	44	40
1/0	105,600	0.532	0.12751	299	125	96	80	68	60	54	49
2/0	133,100	0.578	0.10137	347	152	118	97	83	73	65	59
3/0	167,800	0.630	0.08033	404	186	144	119	102	90	80	72
4/0	211,600	0.688	0.06376	471	228	176	146	125	110	98	89
250	250,000	0.765	0.05394	525	276	213	176	151	133	119	107
350	350,000	0.871	0.03851	657	371	287	238	204	179	160	145
500	500,000	1.003	0.02703	834	510	395	326	280	246	220	199
750	750,000	1.218	0.01798	1,094	760	588	486	417	366	327	296
1,000	1,000,000	1.372	0.01352	1,330	987	764	631	541	475	425	385
1,250	1,250,000	1.539	0.01080	1,541	1,239	959	792	679	597	533	483
1,500	1,500,000	1.662	0.00899	1,749	1,466	1,135	938	804	706	631	571
2,000	2,000,000	1.882	0.00675	2,135	1,916	1,484	1,226	1,051	923	825	747

[a] No diversity. Free air current rating is shown for reference.
[b] From NFPA 70-2005 (NEC) Table 8 and Table 310.13 [29].
[c] dc resistance from ASTM B8-04 [27], adjusted to 90°C.
[d] From Table 5.16(a).

Table 5.16(d).4 Current Ratings for Jacketed Single Copper Wires (1/C) at 90°C with No Separation in One or More Layers—30°C Ambient Temperature[a]

AWG or kcmil (1)	Conductor Cross Section (CM) (2)	Wire Diameter[b] (in.) (3)	DC Resistance 90°C[c] (Ω per 1000 ft) (4)	Free Air DC Current Rating[d] 90°C (A) (5)	DC Current Rating Jacketed 90°C (A)						
					Apparent (Calculated) Wire Mass Fill Depth						
					1 in. (6)	1.5 in. (7)	2 in. (8)	2.5 in. (9)	3 in. (10)	3.5 in. (11)	4 in. (12)
14	4,110	0.193	3.28976	40	8.9	6.9	5.7	4.9	4.3	3.8	3.5
12	6,530	0.212	2.07841	52	12	9.5	7.9	6.7	5.9	5.3	4.8
10	10,380	0.236	1.30060	69	17	13	11	9.5	8.3	7.5	6.7
8	16,510	0.326	0.81606	93	30	23	19	17	15	13	12
6	26,240	0.364	0.51387	124	42	33	27	23	20	18	17
4	41,740	0.412	0.32260	165	61	47	39	33	29	26	24
3	52,620	0.440	0.25630	191	73	56	47	40	35	31	28
2	66,360	0.472	0.20274	221	88	68	56	48	42	38	34
1	83,690	0.582	0.16194	257	121	94	77	66	58	52	47
1/0	105,600	0.622	0.12751	298	146	113	93	80	70	63	57
2/0	133,100	0.668	0.10137	346	175	136	112	96	85	76	68
3/0	167,800	0.720	0.08033	402	212	165	136	117	102	91	83
4/0	211,600	0.778	0.06376	467	258	200	165	141	124	111	100
250	250,000	0.895	0.05394	518	322	250	206	177	155	139	126
350	350,000	1.001	0.03851	646	427	330	273	234	206	184	166
500	500,000	1.133	0.02703	816	576	446	369	316	278	248	225
750	750,000	1.348	0.01798	1,068	841	651	538	461	405	362	328
1,000	1,000,000	1.502	0.01352	1,295	1,081	837	691	593	521	465	421
1,250	1,250,000	1.729	0.01080	1,482	1,392	1,078	890	763	670	599	542
1,500	1,500,000	1.852	0.00899	1,679	1,634	1,265	1,045	896	787	703	637
2,000	2,000,000	2.072	0.00675	2,045	2,110[e]	1,633	1,350	1,157	1,016	908	822

[a] No diversity. Free air current rating is shown for reference.

[b] From NFPA 70-2005 (NEC) Table 8 and Table 310.13 [29].

[c] dc resistance from ASTM B8-04 [27], adjusted to 90°C.

[d] From Table 5.16(a).

[e] Use free air current rating.

Table 5.16(e).1 Calculated Current Ratings for Rounded Bundles of 14–4/0 AWG Unjacketed Copper Wires[a]

AWG or kcmil (1)	Insulation Thickness Unjacketed (in.) (2)	DC Current Rating Unjacketed 75°C (A)						
		Number of Unjacketed Wires in Bundle						
		4 (3)	6 (4)	8 (5)	10 (6)	12 (7)	14 (8)	16 (9)
14	0.045	22	19	18	16	15	14	14
12	0.045	29	25	23	21	20	19	18
10	0.045	38	33	30	28	26	25	23
8	0.060	52	45	41	38	35	33	32
6	0.060	68	59	53	49	46	43	41
4	0.060	90	78	70	65	60	57	54
3	0.060	103	89	80	7	69	65	62
2	0.060	119	102	92	85	79	75	71
1	0.080	139	120	108	99	93	88	83
1/0	0.080	160	138	124	114	107	101	96
2/0	0.080	184	158	142	131	122	115	109
3/0	0.080	211	182	163	150	140	132	125
4/0	0.080	243	209	187	172	160	151	143

[a] Maximum temperature 75°C with ambient temperature 30°C. Applies only to bundles in which all wires are the same size.

Table 5.16(e).2 Calculated Current Ratings for Rounded Bundles of 14–4/0 AWG Jacketed Copper Wires[a]

AWG or kcmil (1)	Insulation Thickness Jacketed (in.) (2)	DC Current Rating Jacketed 75°C (A)						
		Number of Jacketed Wires in Bundle						
		4 (3)	6 (4)	8 (5)	10 (6)	12 (7)	14 (8)	16 (9)
14	0.060	24	20	18	17	16	15	14
12	0.060	31	26	24	22	21	20	19
10	0.060	40	35	31	29	27	26	24
8	0.090	55	48	43	40	37	35	33
6	0.090	72	62	56	52	48	46	43
4	0.090	94	81	73	67	63	59	56
3	0.090	107	93	83	77	72	68	64
2	0.090	123	106	96	88	82	77	74
1	0.125	146	126	113	104	97	91	87
1/0	0.125	167	144	129	119	111	104	99
2/0	0.125	191	164	147	135	126	119	113
3/0	0.125	219	188	168	155	144	136	129
4/0	0.125	251	215	193	177	164	155	147

[a] Maximum temperature 75°C with ambient temperature 30°C. Applies only to bundles in which all wires are the same size.

Table 5.16(e).3 Calculated Current Ratings for Rounded Bundles of 14–4/0 AWG Unjacketed Copper Wires[a]

AWG or kcmil (1)	Insulation Thickness Unjacketed (in.) (2)	DC Current Rating Unjacketed 90°C (A)						
		Number of Unjacketed Wires in Bundle						
		4 (3)	6 (4)	8 (5)	10 (6)	12 (7)	14 (8)	16 (9)
14	0.045	26	23	20	19	18	17	16
12	0.045	34	29	27	24	23	22	21
10	0.045	44	38	35	32	30	28	27
8	0.060	60	52	47	43	41	38	37
6	0.060	79	68	62	57	53	50	48
4	0.060	104	90	81	75	70	66	63
3	0.060	119	103	93	85	80	75	72
2	0.060	137	118	106	98	91	86	82
1	0.080	161	139	125	114	107	101	96
1/0	0.080	185	159	143	131	123	116	110
2/0	0.080	212	183	164	150	140	132	125
3/0	0.080	244	209	188	172	161	151	143
4/0	0.080	280	240	215	197	184	173	164

[a] Maximum temperature 90°C with ambient temperature 30°C. Applies only to bundles in which all wires are the same size.

Table 5.16(e).4 Calculated Current Ratings for Rounded Bundles of 14–4/0 AWG Jacketed Copper Wires[a]

AWG or kcmil (1)	Insulation Thickness Jacketed (in.) (2)	DC Current Rating Jacketed 90°C (A)						
		Number of Jacketed Wires in Bundle						
		4 (3)	6 (4)	8 (5)	10 (6)	12 (7)	14 (8)	16 (9)
14	0.060	27	24	21	20	19	18	17
12	0.060	35	31	28	26	24	23	22
10	0.060	46	40	36	33	31	29	28
8	0.090	64	55	50	46	43	41	39
6	0.090	83	72	65	60	56	53	50
4	0.090	109	94	84	78	72	68	65
3	0.090	124	107	96	89	83	78	74
2	0.090	142	123	110	101	95	89	85
1	0.125	168	145	130	119	111	105	99
1/0	0.125	193	166	149	136	127	120	114
2/0	0.125	220	189	69	155	145	136	129
3/0	0.125	252	216	194	178	165	156	148
4/0	0.125	289	247	221	203	189	177	168

[a] Maximum temperature 90°C with ambient temperature 30°C. Applies only to bundles in which all wires are the same size.

Table 5.17 Rigid Copper Bus Properties—1 Bar[a,b]

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^{2})	Area (kcmil)	Weight (lb/ft)	30°C (μΩ/ft)	70°C (μΩ/ft)	70°C (A)
$\frac{1}{4}$	$\frac{1}{2}$	0.125	159	0.483	68.39	81.82	241
$\frac{1}{4}$	$\frac{3}{4}$	0.188	239	0.726	45.52	54.47	322
$\frac{1}{4}$	1	0.250	318	0.966	34.19	40.91	404
$\frac{1}{4}$	$1\frac{1}{2}$	0.375	477	1.450	22.76	27.23	568
$\frac{1}{4}$	2	0.500	637	1.930	17.15	20.52	724
$\frac{1}{4}$	$2\frac{1}{2}$	0.625	796	2.410	13.72	16.41	875
$\frac{1}{4}$	3	0.750	955	2.900	11.43	13.68	1,029
$\frac{1}{4}$	$3\frac{1}{2}$	0.875	1,114	3.380	9.77	11.69	1,206
$\frac{1}{4}$	4	1.000	1,273	3.860	8.55	10.23	1,323
$\frac{1}{4}$	5	1.250	1,592	4.830	6.84	8.18	1,616
$\frac{1}{4}$	6	1.500	1,910	5.800	5.71	6.83	1,901
$\frac{1}{4}$	8	2.000	2,546	7.730	4.27	5.11	2,495
$\frac{1}{4}$	10	2.500	3,183	9.660	3.42	4.09	3,043
$\frac{1}{4}$	12	3.000	3,820	11.600	2.85	3.41	3,605
$\frac{3}{8}$	$\frac{3}{4}$	0.281	358	1.090	30.45	36.44	419
$\frac{3}{8}$	1	0.375	477	1.450	22.76	27.23	518
$\frac{3}{8}$	$1\frac{1}{2}$	0.563	716	2.170	15.17	18.16	728
$\frac{3}{8}$	2	0.750	955	2.900	11.43	13.68	915
$\frac{3}{8}$	$2\frac{1}{2}$	0.938	1,194	3.620	9.11	10.91	1,111
$\frac{3}{8}$	3	1.125	1,432	4.350	7.64	9.14	1,287
$\frac{3}{8}$	$3\frac{1}{2}$	1.313	1,671	5.060	6.53	7.81	1,466
$\frac{3}{8}$	4	1.500	1,910	5.800	5.71	6.83	1,643
$\frac{3}{8}$	5	1.875	2,387	7.260	4.55	5.45	2,004
$\frac{3}{8}$	6	2.250	2,865	8.690	3.80	4.55	2,367
$\frac{3}{8}$	8	3.000	3,820	11.600	2.85	3.41	3,056
$\frac{3}{8}$	10	3.750	4,775	14.500	2.28	2.72	3,759
$\frac{3}{8}$	12	4.500	5,730	17.400	1.90	2.28	4,409
$\frac{1}{2}$	1	0.500	637	1.930	17.15	20.52	632
$\frac{1}{2}$	$1\frac{1}{2}$	0.750	955	2.900	11.43	13.68	863
$\frac{1}{2}$	2	1.000	1,273	3.860	8.55	10.23	1,058
$\frac{1}{2}$	$2\frac{1}{2}$	1.250	1,592	4.830	6.84	8.18	1,292
$\frac{1}{2}$	3	1.500	1,910	5.800	5.71	6.83	1,534
$\frac{1}{2}$	$3\frac{1}{2}$	1.750	2,228	6.760	4.88	5.84	1,726
$\frac{1}{2}$	4	2.000	2,546	7.730	4.27	5.11	1,908
$\frac{1}{2}$	5	2.500	3,183	9.660	3.42	4.09	2,355
$\frac{1}{2}$	6	3.000	3,820	11.600	2.85	3.41	2,799
$\frac{1}{2}$	8	4.000	5,093	15.500	2.14	2.56	3,575
$\frac{1}{2}$	10	5.000	6,366	19.300	1.71	2.05	4,365
$\frac{1}{2}$	12	6.000	7,639	23.200	1.42	1.70	5,178
$\frac{3}{4}$	4	3.000	3,820	11.600	2.85	3.41	2,443
$\frac{3}{4}$	5	3.750	4,775	14.500	2.28	2.72	2,920
$\frac{3}{4}$	6	4.500	5,730	17.400	1.90	2.28	3,452
$\frac{3}{4}$	8	6.000	7,639	23.200	1.42	1.70	4,427
$\frac{3}{4}$	10	7.500	9,549	29.000	1.14	1.37	5,428
$\frac{3}{4}$	12	9.000	11,459	34.800	0.95	1.14	6,426

[a] 1 μΩ/ft = 1 × 10^{-6} Ω/ft. For example, 68.39 μΩ/ft = 68.39 × 10^{-6} Ω/ft.

[b] Current ratings apply when the busbar is oriented with its long edge vertical, and bar spacing ≥ bar thickness, and busbar is run in the horizontal plane. Current ratings based on 30°C rise above 40°C ambient temperature.

Source: Data from www.copper.org (Copper Development Association, Inc.).

Table 5.18(a) Rigid Copper Busbar Properties—$\frac{1}{4}$-in. Parallel Bars as Indicated[a,b]

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^{2})	Area (kcmil)	Weight (lb/ft)	30°C μΩ/ft	70°C μΩ/ft	70°C (A)
2 Parallel Bars							
$\frac{1}{4}$	$\frac{1}{2}$	0.250	318	0.966	34.195	40.910	434
$\frac{1}{4}$	$\frac{3}{4}$	0.375	477	1.452	22.760	27.235	579
$\frac{1}{4}$	1	0.500	637	1.932	17.095	20.455	727
$\frac{1}{4}$	$1\frac{1}{2}$	0.750	955	2.900	11.380	13.615	1,023
$\frac{1}{4}$	2	1.000	1,273	3.860	8.575	10.260	1,303
$\frac{1}{4}$	$2\frac{1}{2}$	1.250	1,592	4.820	6.860	8.205	1,575
$\frac{1}{4}$	3	1.500	1,910	5.800	5.715	6.840	1,852
$\frac{1}{4}$	$3\frac{1}{2}$	1.750	2,228	6.760	4.885	5.845	2,171
$\frac{1}{4}$	4	2.000	2,546	7.720	4.275	5.115	2,381
$\frac{1}{4}$	5	2.500	3,183	9.660	3.420	4.090	2,908
$\frac{1}{4}$	6	3.000	3,820	11.600	2.855	3.415	3,422
$\frac{1}{4}$	8	4.000	5,093	15.460	2.135	2.555	4,492
$\frac{1}{4}$	10	5.000	6,366	19.320	1.710	2.045	5,477
$\frac{1}{4}$	12	6.000	7,639	23.200	1.425	1.705	6,490
3 Parallel Bars							
$\frac{1}{4}$	$\frac{1}{2}$	0.375	477	1.449	22.797	27.273	603
$\frac{1}{4}$	$\frac{3}{4}$	0.563	716	2.178	15.173	18.157	804
$\frac{1}{4}$	1	0.750	955	2.898	11.397	13.637	1,010
$\frac{1}{4}$	$1\frac{1}{2}$	1.125	1,432	4.350	7.587	9.077	1,421
$\frac{1}{4}$	2	1.500	1,910	5.790	5.717	6.840	1,810
$\frac{1}{4}$	$2\frac{1}{2}$	1.875	2,387	7.230	4.573	5.470	2,188
$\frac{1}{4}$	3	2.250	2,865	8.700	3.810	4.560	2,572
$\frac{1}{4}$	$3\frac{1}{2}$	2.625	3,342	10.140	3.257	3.897	3,015
$\frac{1}{4}$	4	3.000	3,820	11.580	2.850	3.410	3,307
$\frac{1}{4}$	5	3.750	4,775	14.490	2.280	2.727	4,039
$\frac{1}{4}$	6	4.500	5,730	17.400	1.903	2.277	4,752
$\frac{1}{4}$	8	6.000	7,639	23.190	1.423	1.703	6,238
$\frac{1}{4}$	10	7.500	9,549	28.980	1.140	1.363	7,607
$\frac{1}{4}$	12	9.000	11,459	34.800	0.950	1.137	9,013
4 Parallel Bars							
$\frac{1}{4}$	$\frac{1}{2}$	0.500	637	1.932	17.098	20.455	772
$\frac{1}{4}$	$\frac{3}{4}$	0.750	955	2.904	11.380	13.618	1,029
$\frac{1}{4}$	1	1.000	1,273	3.864	8.548	10.228	1,293
$\frac{1}{4}$	$1\frac{1}{2}$	1.500	1,910	5.800	5.690	6.808	1,819
$\frac{1}{4}$	2	2.000	2,546	7.720	4.288	5.130	2,317
$\frac{1}{4}$	$2\frac{1}{2}$	2.500	3,183	9.640	3.430	4.103	2,800
$\frac{1}{4}$	3	3.000	3,820	11.600	2.858	3.420	3,292
$\frac{1}{4}$	$3\frac{1}{2}$	3.500	4,456	13.520	2.443	2.923	3,860
$\frac{1}{4}$	4	4.000	5,093	15.440	2.138	2.558	4,233
$\frac{1}{4}$	5	5.000	6,366	19.320	1.710	2.045	5,170
$\frac{1}{4}$	6	6.000	7,639	23.200	1.428	1.708	6,083
$\frac{1}{4}$	8	8.000	10,186	30.920	1.068	1.278	7,985
$\frac{1}{4}$	10	10.000	12,732	38.640	0.855	1.023	9,737
$\frac{1}{4}$	12	12.000	15,279	46.400	0.713	0.853	11,537

Table 5.18(a) Rigid Copper Busbar Properties—$\frac{1}{4}$-in. Parallel Bars as Indicated[a,b] (*Continued*)

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^{2})	Area (kcmil)	Weight (lb/ft)	30°C μΩ/ft	70°C μΩ/ft	70°C (A)
5 Parallel Bars							
$\frac{1}{4}$	$\frac{1}{2}$	0.625	796	2.415	13.678	16.364	941
$\frac{1}{4}$	$\frac{3}{4}$	0.938	1,194	3.630	9.104	10.894	1,254
$\frac{1}{4}$	1	1.250	1,592	4.830	6.838	8.182	1,576
$\frac{1}{4}$	$1\frac{1}{2}$	1.875	2,387	7.250	4.552	5.446	2,217
$\frac{1}{4}$	2	2.500	3,183	9.650	3.430	4.104	2,824
$\frac{1}{4}$	$2\frac{1}{2}$	3.125	3,979	12.050	2.744	3.282	3,413
$\frac{1}{4}$	3	3.750	4,775	14.500	2.286	2.736	4,012
$\frac{1}{4}$	$3\frac{1}{2}$	4.375	5,570	16.900	1.954	2.338	4,704
$\frac{1}{4}$	4	5.000	6,366	19.300	1.710	2.046	5,159
$\frac{1}{4}$	5	6.250	7,958	24.150	1.368	1.636	6,301
$\frac{1}{4}$	6	7.500	9,549	29.000	1.142	1.366	7,414
$\frac{1}{4}$	8	10.000	12,732	38.650	0.854	1.022	9,732
$\frac{1}{4}$	10	12.500	15,915	48.300	0.684	0.818	11,867
$\frac{1}{4}$	12	15.000	19,099	58.000	0.570	0.682	14,061
6 Parallel Bars							
$\frac{1}{4}$	$\frac{1}{2}$	0.750	955	2.898	11.398	13.637	1,061
$\frac{1}{4}$	$\frac{3}{4}$	1.125	1,432	4.356	7.587	9.078	1,415
$\frac{1}{4}$	1	1.500	1,910	5.796	5.698	6.818	1,778
$\frac{1}{4}$	$1\frac{1}{2}$	2.250	2,865	8.700	3.793	4.538	2,501
$\frac{1}{4}$	2	3.000	3,820	11.580	2.858	3.420	3,186
$\frac{1}{4}$	$2\frac{1}{2}$	3.750	4,775	14.460	2.287	2.735	3,851
$\frac{1}{4}$	3	4.500	5,730	17.400	1.905	2.280	4,527
$\frac{1}{4}$	$3\frac{1}{2}$	5.250	6,685	20.280	1.628	1.948	5,307
$\frac{1}{4}$	4	6.000	7,639	23.160	1.425	1.705	5,821
$\frac{1}{4}$	5	7.500	9,549	28.980	1.140	1.363	7,108
$\frac{1}{4}$	6	9.000	11,459	34.800	0.952	1.138	8,364
$\frac{1}{4}$	8	12.000	15,279	46.380	0.712	0.852	10,980
$\frac{1}{4}$	10	15.000	19,099	57.960	0.570	0.682	13,388
$\frac{1}{4}$	12	18.000	22,918	69.600	0.475	0.568	15,863
7 Parallel Bars							
$\frac{1}{4}$	$\frac{1}{2}$	0.875	1,114	3.381	9.770	11.689	1,206
$\frac{1}{4}$	$\frac{3}{4}$	1.313	1,671	5.082	6.503	7.781	1,608
$\frac{1}{4}$	1	1.750	2,228	6.762	4.884	5.844	2,020
$\frac{1}{4}$	$1\frac{1}{2}$	2.625	3,342	10.150	3.251	3.890	2,842
$\frac{1}{4}$	2	3.500	4,456	13.510	2.450	2.931	3,620
$\frac{1}{4}$	$2\frac{1}{2}$	4.375	5,570	16.870	1.960	2.344	4,376
$\frac{1}{4}$	3	5.250	6,685	20.300	1.633	1.954	5,144
$\frac{1}{4}$	$3\frac{1}{2}$	6.125	7,799	23.660	1.396	1.670	6,031
$\frac{1}{4}$	4	7.000	8,913	27.020	1.221	1.461	6,614
$\frac{1}{4}$	5	8.750	11,141	33.810	0.977	1.169	8,078
$\frac{1}{4}$	6	10.500	13,369	40.600	0.816	0.976	9,505
$\frac{1}{4}$	8	14.000	17,825	54.110	0.610	0.730	12,477
$\frac{1}{4}$	10	17.500	22,282	67.620	0.489	0.584	15,214
$\frac{1}{4}$	12	21.000	26,738	81.200	0.407	0.487	18,027

(*continued*)

Table 5.18(a) Rigid Copper Busbar Properties—¼-in. Parallel Bars as Indicated[a,b] (*Continued*)

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^{2})	Area (kcmil)	Weight (lb/ft)	30°C μΩ/ft	70°C μΩ/ft	70°C (A)
8 Parallel Bars							
¼	½	1.000	1,273	3.864	8.549	10.228	1,327
¼	¾	1.500	1,910	5.808	5.690	6.809	1,769
¼	1	2.000	2,546	7.728	4.274	5.114	2,222
¼	1½	3.000	3,820	11.600	2.845	3.404	3,126
¼	2	4.000	5,093	15.440	2.144	2.565	3,982
¼	2½	5.000	6,366	19.280	1.715	2.051	4,813
¼	3	6.000	7,639	23.200	1.429	1.710	5,659
¼	3½	7.000	8,913	27.040	1.221	1.461	6,634
¼	4	8.000	10,186	30.880	1.069	1.279	7,276
¼	5	10.000	12,732	38.640	0.855	1.023	8,886
¼	6	12.000	15,279	46.400	0.714	0.854	10,455
¼	8	16.000	20,372	61.840	0.534	0.639	13,725
¼	10	20.000	25,465	77.280	0.428	0.511	16,735
¼	12	24.000	30,558	92.800	0.356	0.426	19,829
9 Parallel Bars							
¼	½	1.125	1,432	4.347	7.599	9.091	1,447
¼	¾	1.688	2,149	6.534	5.058	6.052	1,930
¼	1	2.250	2,865	8.694	3.799	4.546	2,424
¼	1½	3.375	4,297	13.050	2.529	3.026	3,410
¼	2	4.500	5,730	17.370	1.906	2.280	4,344
¼	2½	5.625	7,162	21.690	1.524	1.823	5,251
¼	3	6.750	8,594	26.100	1.270	1.520	6,173
¼	3½	7.875	10,027	30.420	1.086	1.299	7,237
¼	4	9.000	11,459	34.740	0.950	1.137	7,937
¼	5	11.250	14,324	43.470	0.760	0.909	9,693
¼	6	13.500	17,189	52.200	0.634	0.759	11,406
¼	8	18.000	22,918	69.570	0.474	0.568	14,972
¼	10	22.500	28,648	86.940	0.380	0.454	18,256
¼	12	27.000	34,377	104.400	0.317	0.379	21,632
10 Parallel Bars							
¼	½	1.250	1,592	4.830	6.839	8.182	1,568
¼	¾	1.875	2,387	7.260	4.552	5.447	2,090
¼	1	2.500	3,183	9.660	3.419	4.091	2,626
¼	1½	3.750	4,775	14.500	2.276	2.723	3,694
¼	2	5.000	6,366	19.300	1.715	2.052	4,706
¼	2½	6.250	7,958	24.100	1.372	1.641	5,688
¼	3	7.500	9,549	29.000	1.143	1.368	6,687
¼	3½	8.750	11,141	33.800	0.977	1.169	7,840
¼	4	10.000	12,732	38.600	0.855	1.023	8,599
¼	5	12.500	15,915	48.300	0.684	0.818	10,501
¼	6	15.000	19,099	58.000	0.571	0.683	12,356
¼	8	20.000	25,465	77.300	0.427	0.511	16,220
¼	10	25.000	31,831	96.600	0.342	0.409	19,778
¼	12	30.000	38,197	116.000	0.285	0.341	23,435

Table 5.18(a) Rigid Copper Busbar Properties—$\frac{1}{4}$-in. Parallel Bars as Indicated[a,b] (*Continued*)

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^{2})	Area (kcmil)	Weight (lb/ft)	30°C μΩ/ft	70°C μΩ/ft	70°C (A)
11 Parallel Bars							
$\frac{1}{4}$	$\frac{1}{2}$	1.375	1,751	5.313	6.217	7.438	1,664
$\frac{1}{4}$	$\frac{3}{4}$	2.063	2,626	7.986	4.138	4.952	2,219
$\frac{1}{4}$	1	2.750	3,501	10.626	3.108	3.719	2,787
$\frac{1}{4}$	$1\frac{1}{2}$	4.125	5,252	15.950	2.069	2.475	3,922
$\frac{1}{4}$	2	5.500	7,003	21.230	1.559	1.865	4,996
$\frac{1}{4}$	$2\frac{1}{2}$	6.875	8,754	26.510	1.247	1.492	6,038
$\frac{1}{4}$	3	8.250	10,504	31.900	1.039	1.244	7,099
$\frac{1}{4}$	$3\frac{1}{2}$	9.625	12,255	37.180	0.888	1.063	8,322
$\frac{1}{4}$	4	11.000	14,006	42.460	0.777	0.930	9,128
$\frac{1}{4}$	5	13.750	17,507	53.130	0.622	0.744	11,147
$\frac{1}{4}$	6	16.500	21,008	63.800	0.519	0.621	13,117
$\frac{1}{4}$	8	22.000	28,011	85.030	0.388	0.465	17,218
$\frac{1}{4}$	10	27.500	35,014	106.260	0.311	0.372	20,995
$\frac{1}{4}$	12	33.000	42,017	127.600	0.259	0.310	24,877
12 Parallel Bars							
$\frac{1}{4}$	$\frac{1}{2}$	1.500	1,910	5.796	5.699	6.818	1,761
$\frac{1}{4}$	$\frac{3}{4}$	2.250	2,865	8.712	3.793	4.539	2,348
$\frac{1}{4}$	1	3.000	3,820	11.592	2.849	3.409	2,949
$\frac{1}{4}$	$1\frac{1}{2}$	4.500	5,730	17.400	1.897	2.269	4,149
$\frac{1}{4}$	2	6.000	7,639	23.160	1.429	1.710	5,286
$\frac{1}{4}$	$2\frac{1}{2}$	7.500	9,549	28.920	1.143	1.368	6,388
$\frac{1}{4}$	3	9.000	11,459	34.800	0.953	1.140	7,511
$\frac{1}{4}$	$3\frac{1}{2}$	10.500	13,369	40.560	0.814	0.974	8,805
$\frac{1}{4}$	4	12.000	15,279	46.320	0.713	0.853	9,657
$\frac{1}{4}$	5	15.000	19,099	57.960	0.570	0.682	11,794
$\frac{1}{4}$	6	18.000	22,918	69.600	0.476	0.569	13,877
$\frac{1}{4}$	8	24.000	30,558	92.760	0.356	0.426	18,216
$\frac{1}{4}$	10	30.000	38,197	115.920	0.285	0.341	22,212
$\frac{1}{4}$	12	36.000	45,837	139.200	0.238	0.284	26,319

[a] 1 μΩ/ft = 1 × 10^{-6} Ω/ft. For example, 68.39 μΩ/ft = 68.39 × 10^{-6} Ω/ft.

[b] Current ratings apply when the busbar is oriented with its long edge vertical, and bar spacing ≥ bar thickness, and busbar is run in the horizontal plane. Current ratings based on 30°C rise above 40°C ambient temperature.

Source: Data from www.copper.org (Copper Development Association, Inc.) with adjustments.

K factor) to arrive at the circular mil area required to keep voltage drop below some specified threshold at a given temperature.

- The second method is based on a conventional application of Ohm's law.

Both methods yield equivalent results, and both methods require knowledge of the conductor length as determined from the conductor path distance. The path distance is the one-way distance from termination to termination, including vertical and horizontal runs, as shown in Figure 5.35. Since dc power conductors always are installed in a paired

Table 5.18(b) Rigid Copper Busbar Properties—$\frac{3}{8}$-in. Parallel Bars as Indicated^{a,b}

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^{2})	Area (kcmil)	Weight (lb/ft)	30°C (μΩ/ft)	70°C (μΩ/ft)	70°C (A)
2 Parallel Bars							
$\frac{3}{8}$	$\frac{3}{4}$	0.5625	716	2.18	15.225	18.220	754
$\frac{3}{8}$	1	0.750	955	2.90	11.380	13.615	932
$\frac{3}{8}$	$1\frac{1}{2}$	1.125	1,432	4.34	7.585	9.080	1,310
$\frac{3}{8}$	2	1.500	1,910	5.80	5.715	6.840	1,646
$\frac{3}{8}$	$2\frac{1}{2}$	1.875	2,387	7.24	4.555	5.455	2,000
$\frac{3}{8}$	3	2.250	2,865	8.70	3.820	4.570	2,316
$\frac{3}{8}$	$3\frac{1}{2}$	2.625	3,342	10.12	3.265	3.905	2,640
$\frac{3}{8}$	4	3.000	3,820	11.60	2.855	3.415	2,958
$\frac{3}{8}$	5	3.750	4,775	14.52	2.275	2.725	3,608
$\frac{3}{8}$	6	4.500	5,730	17.38	1.900	2.275	4,260
$\frac{3}{8}$	8	6.000	7,639	23.20	1.425	1.705	5,501
$\frac{3}{8}$	10	7.500	9,549	29.00	1.140	1.360	6,766
$\frac{3}{8}$	12	9.000	11,459	34.80	0.950	1.140	7,936
3 Parallel Bars							
$\frac{3}{8}$	$\frac{3}{4}$	0.844	1,074	3.27	10.150	12.147	1,048
$\frac{3}{8}$	1	1.125	1,432	4.35	7.587	9.077	1,294
$\frac{3}{8}$	$1\frac{1}{2}$	1.688	2,149	6.51	5.057	6.053	1,819
$\frac{3}{8}$	2	2.250	2,865	8.70	3.810	4.560	2,286
$\frac{3}{8}$	$2\frac{1}{2}$	2.813	3,581	10.86	3.037	3.637	2,778
$\frac{3}{8}$	3	3.375	4,297	13.05	2.547	3.047	3,217
$\frac{3}{8}$	$3\frac{1}{2}$	3.938	5,013	15.18	2.177	2.603	3,666
$\frac{3}{8}$	4	4.500	5,730	17.40	1.903	2.277	4,108
$\frac{3}{8}$	5	5.625	7,162	21.78	1.517	1.817	5,011
$\frac{3}{8}$	6	6.750	8,594	26.07	1.267	1.517	5,916
$\frac{3}{8}$	8	9.000	11,459	34.80	0.950	1.137	7,640
$\frac{3}{8}$	10	11.250	14,324	43.50	0.760	0.907	9,398
$\frac{3}{8}$	12	13.500	17,189	52.20	0.633	0.760	11,023
4 Parallel Bars							
$\frac{3}{8}$	$\frac{3}{4}$	1.125	1,432	4.36	7.613	9.110	1,341
$\frac{3}{8}$	1	1.500	1,910	5.80	5.690	6.808	1,656
$\frac{3}{8}$	$1\frac{1}{2}$	2.250	2,865	8.68	3.793	4.540	2,328
$\frac{3}{8}$	2	3.000	3,820	11.60	2.858	3.420	2,926
$\frac{3}{8}$	$2\frac{1}{2}$	3.750	4,775	14.48	2.278	2.728	3,556
$\frac{3}{8}$	3	4.500	5,730	17.40	1.910	2.285	4,118
$\frac{3}{8}$	$3\frac{1}{2}$	5.250	6,685	20.24	1.633	1.953	4,693
$\frac{3}{8}$	4	6.000	7,639	23.20	1.428	1.708	5,258
$\frac{3}{8}$	5	7.500	9,549	29.04	1.138	1.363	6,414
$\frac{3}{8}$	6	9.000	11,459	34.76	0.950	1.138	7,573
$\frac{3}{8}$	8	12.000	15,279	46.40	0.713	0.853	9,780
$\frac{3}{8}$	10	15.000	19,099	58.00	0.570	0.680	12,029
$\frac{3}{8}$	12	18.000	22,918	69.60	0.475	0.570	14,109
5 Parallel Bars							
$\frac{3}{8}$	$\frac{3}{4}$	1.406	1,790	5.45	6.090	7.288	1,635
$\frac{3}{8}$	1	1.875	2,387	7.25	4.552	5.446	2,019
$\frac{3}{8}$	$1\frac{1}{2}$	2.813	3,581	10.85	3.034	3.632	2,837

Table 5.18(b) Rigid Copper Busbar Properties—⅜-in. Parallel Bars as Indicated[a,b] (*Continued*)

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^2)	Area (kcmil)	Weight (lb/ft)	30°C (μΩ/ft)	70°C (μΩ/ft)	70°C (A)
5 Parallel Bars							
⅜	2	3.750	4,775	14.50	2.286	2.736	3,567
⅜	2½	4.688	5,968	18.10	1.822	2.182	4,334
⅜	3	5.625	7,162	21.75	1.528	1.828	5,019
⅜	3½	6.563	8,356	25.30	1.306	1.562	5,719
⅜	4	7.500	9,549	29.00	1.142	1.366	6,408
⅜	5	9.375	11,937	36.30	0.910	1.090	7,817
⅜	6	11.250	14,324	43.45	0.760	0.910	9,230
⅜	8	15.000	19,099	58.00	0.570	0.682	11,919
⅜	10	18.750	23,873	72.50	0.456	0.544	14,661
⅜	12	22.500	28,648	87.00	0.380	0.456	17,195
6 Parallel Bars							
⅜	¾	1.688	2,149	6.54	5.075	6.073	1,844
⅜	1	2.250	2,865	8.70	3.793	4.538	2,277
⅜	1½	3.375	4,297	13.02	2.528	3.027	3,201
⅜	2	4.500	5,730	17.40	1.905	2.280	4,024
⅜	2½	5.625	7,162	21.72	1.518	1.818	4,889
⅜	3	6.750	8,594	26.10	1.273	1.523	5,662
⅜	3½	7.875	10,027	30.36	1.088	1.302	6,452
⅜	4	9.000	11,459	34.80	0.952	1.138	7,230
⅜	5	11.250	14,324	43.56	0.758	0.908	8,819
⅜	6	13.500	17,189	52.14	0.633	0.758	10,413
⅜	8	18.000	22,918	69.60	0.475	0.568	13,447
⅜	10	22.500	28,648	87.00	0.380	0.453	16,540
⅜	12	27.000	34,377	104.40	0.317	0.380	19,400
7 Parallel Bars							
⅜	¾	1.969	2,507	7.63	4.350	5.206	2,096
⅜	1	2.625	3,342	10.15	3.251	3.890	2,588
⅜	1½	3.938	5,013	15.19	2.167	2.594	3,638
⅜	2	5.250	6,685	20.30	1.633	1.954	4,573
⅜	2½	6.563	8,356	25.34	1.301	1.559	5,556
⅜	3	7.875	10,027	30.45	1.091	1.306	6,434
⅜	3½	9.188	11,698	35.42	0.933	1.116	7,332
⅜	4	10.500	13,369	40.60	0.816	0.976	8,216
⅜	5	13.125	16,711	50.82	0.650	0.779	10,022
⅜	6	15.750	20,054	60.83	0.543	0.650	11,833
⅜	8	21.000	26,738	81.20	0.407	0.487	15,281
⅜	10	26.250	33,423	101.50	0.326	0.389	18,796
⅜	12	31.500	40,107	121.80	0.271	0.326	22,045
8 Parallel Bars							
⅜	¾	2.250	2,865	8.72	3.806	4.555	2,305
⅜	1	3.000	3,820	11.60	2.845	3.404	2,847
⅜	1½	4.500	5,730	17.36	1.896	2.270	4,001
⅜	2	6.000	7,639	23.20	1.429	1.710	5,030
⅜	2½	7.500	9,549	28.96	1.139	1.364	6,112
⅜	3	9.000	11,459	34.80	0.955	1.143	7,078

(*continued*)

Table 5.18(b) Rigid Copper Busbar Properties—$\frac{3}{8}$-in. Parallel Bars as Indicated[a,b] (*Continued*)

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^{2})	Area (kcmil)	Weight (lb/ft)	30°C (μΩ/ft)	70°C (μΩ/ft)	70°C (A)
8 Parallel Bars							
$\frac{3}{8}$	$3\frac{1}{2}$	10.500	13,369	40.48	0.816	0.976	8,066
$\frac{3}{8}$	4	12.000	15,279	46.40	0.714	0.854	9,037
$\frac{3}{8}$	5	15.000	19,099	58.08	0.569	0.681	11,024
$\frac{3}{8}$	6	18.000	22,918	69.52	0.475	0.569	13,016
$\frac{3}{8}$	8	24.000	30,558	92.80	0.356	0.426	16,809
$\frac{3}{8}$	10	30.000	38,197	116.00	0.285	0.340	20,675
$\frac{3}{8}$	12	36.000	45,837	139.20	0.238	0.285	24,250
9 Parallel Bars							
$\frac{3}{8}$	$\frac{3}{4}$	2.531	3,223	9.81	3.383	4.049	2,515
$\frac{3}{8}$	1	3.375	4,297	13.05	2.529	3.026	3,106
$\frac{3}{8}$	$1\frac{1}{2}$	5.063	6,446	19.53	1.686	2.018	4,365
$\frac{3}{8}$	2	6.750	8,594	26.10	1.270	1.520	5,487
$\frac{3}{8}$	$2\frac{1}{2}$	8.438	10,743	32.58	1.012	1.212	6,667
$\frac{3}{8}$	3	10.125	12,892	39.15	0.849	1.016	7,721
$\frac{3}{8}$	$3\frac{1}{2}$	11.813	15,040	45.54	0.726	0.868	8,799
$\frac{3}{8}$	4	13.500	17,189	52.20	0.634	0.759	9,859
$\frac{3}{8}$	5	16.875	21,486	65.34	0.506	0.606	12,026
$\frac{3}{8}$	6	20.250	25,783	78.21	0.422	0.506	14,199
$\frac{3}{8}$	8	27.000	34,377	104.40	0.317	0.379	18,337
$\frac{3}{8}$	10	33.750	42,972	130.50	0.253	0.302	22,555
$\frac{3}{8}$	12	40.500	51,566	156.60	0.211	0.253	26,454
10 Parallel Bars							
$\frac{3}{8}$	$\frac{3}{4}$	2.813	3,581	10.90	3.045	3.644	2,724
$\frac{3}{8}$	1	3.750	4,775	14.50	2.276	2.723	3,364
$\frac{3}{8}$	$1\frac{1}{2}$	5.625	7,162	21.70	1.517	1.816	4,729
$\frac{3}{8}$	2	7.500	9,549	29.00	1.143	1.368	5,944
$\frac{3}{8}$	$2\frac{1}{2}$	9.375	11,937	36.20	0.911	1.091	7,223
$\frac{3}{8}$	3	11.250	14,324	43.50	0.764	0.914	8,365
$\frac{3}{8}$	$3\frac{1}{2}$	13.125	16,711	50.60	0.653	0.781	9,532
$\frac{3}{8}$	4	15.000	19,099	58.00	0.571	0.683	10,681
$\frac{3}{8}$	5	18.750	23,873	72.60	0.455	0.545	13,029
$\frac{3}{8}$	6	22.500	28,648	86.90	0.380	0.455	15,383
$\frac{3}{8}$	8	30.000	38,197	116.00	0.285	0.341	19,865
$\frac{3}{8}$	10	37.500	47,746	145.00	0.228	0.272	24,434
$\frac{3}{8}$	12	45.000	57,296	174.00	0.190	0.228	28,659
11 Parallel Bars							
$\frac{3}{8}$	$\frac{3}{4}$	3.094	3,939	11.99	2.768	3.313	2,892
$\frac{3}{8}$	1	4.125	5,252	15.95	2.069	2.475	3,571
$\frac{3}{8}$	$1\frac{1}{2}$	6.188	7,878	23.87	1.379	1.651	5,020
$\frac{3}{8}$	2	8.250	10,504	31.90	1.039	1.244	6,310
$\frac{3}{8}$	$2\frac{1}{2}$	10.313	13,130	39.82	0.828	0.992	7,667
$\frac{3}{8}$	3	12.375	15,756	47.85	0.695	0.831	8,879
$\frac{3}{8}$	$3\frac{1}{2}$	14.438	18,382	55.66	0.594	0.710	10,119
$\frac{3}{8}$	4	16.500	21,008	63.80	0.519	0.621	11,338
$\frac{3}{8}$	5	20.625	26,261	79.86	0.414	0.495	13,830

Table 5.18(b) Rigid Copper Busbar Properties—$\frac{1}{2}$-in. Parallel Bars as Indicated[a,b] (*Continued*)

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^{2})	Area (kcmil)	Weight (lb/ft)	30°C (μΩ/ft)	70°C (μΩ/ft)	70°C (A)
11 Parallel Bars							
$\frac{3}{8}$	6	24.750	31,513	95.59	0.345	0.414	16,329
$\frac{3}{8}$	8	33.000	42,017	127.60	0.259	0.310	21,087
$\frac{3}{8}$	10	41.250	52,521	159.50	0.207	0.247	25,938
$\frac{3}{8}$	12	49.500	63,025	191.40	0.173	0.207	30,423
12 Parallel Bars							
$\frac{3}{8}$	$\frac{3}{4}$	3.375	4,297	13.08	2.538	3.037	3,060
$\frac{3}{8}$	1	4.500	5,730	17.40	1.897	2.269	3,778
$\frac{3}{8}$	$1\frac{1}{2}$	6.750	8,594	26.04	1.264	1.513	5,311
$\frac{3}{8}$	2	9.000	11,459	34.80	0.953	1.140	6,676
$\frac{3}{8}$	$2\frac{1}{2}$	11.250	14,324	43.44	0.759	0.909	8,112
$\frac{3}{8}$	3	13.500	17,189	52.20	0.637	0.762	9,394
$\frac{3}{8}$	$3\frac{1}{2}$	15.750	20,054	60.72	0.544	0.651	10,705
$\frac{3}{8}$	4	18.000	22,918	69.60	0.476	0.569	11,995
$\frac{3}{8}$	5	22.500	28,648	87.12	0.379	0.454	14,632
$\frac{3}{8}$	6	27.000	34,377	104.28	0.317	0.379	17,276
$\frac{3}{8}$	8	36.000	45,837	139.20	0.238	0.284	22,310
$\frac{3}{8}$	10	45.000	57,296	174.00	0.190	0.227	27,442
$\frac{3}{8}$	12	54.000	68,755	208.80	0.158	0.190	32,186

[a] 1 μΩ/ft = 1 × 10^{-6} Ω/ft. For example, 68.39 μΩ/ft = 68.39 × 10^{-6} Ω/ft.

[b] Current ratings apply when the busbar is oriented with its long edge vertical, and bar spacing ≥ bar thickness, and busbar is run in the horizontal plane. Current ratings based on 30°C rise above 40°C ambient temperature.

Source: Data from www.copper.org (Copper Development Association, Inc.) with adjustments.

Table 5.18(c) Rigid Copper Busbar Properties—$\frac{1}{2}$-in. Parallel Bars as Indicated[a,b]

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^{2})	Area (kcmil)	Weight (lb/ft)	30°C (μΩ/ft)	70°C (μΩ/ft)	70°C (A)
2 Parallel Bars							
$\frac{1}{2}$	1	1.000	1,273	3.860	8.575	10.260	1,138
$\frac{1}{2}$	$1\frac{1}{2}$	1.500	1,910	5.800	5.715	6.840	1,553
$\frac{1}{2}$	2	2.000	2,546	7.720	4.275	5.115	1,905
$\frac{1}{2}$	$2\frac{1}{2}$	2.500	3,183	9.660	3.420	4.090	2,326
$\frac{1}{2}$	3	3.000	3,820	11.600	2.855	3.415	2,761
$\frac{1}{2}$	$3\frac{1}{2}$	3.500	4,456	13.520	2.440	2.920	3,107
$\frac{1}{2}$	4	4.000	5,093	15.460	2.135	2.555	3,435
$\frac{1}{2}$	5	5.000	6,366	19.320	1.710	2.045	4,239
$\frac{1}{2}$	6	6.000	7,639	23.200	1.425	1.705	5,038
$\frac{1}{2}$	8	8.000	10,186	31.000	1.070	1.280	6,435
$\frac{1}{2}$	10	10.000	12,732	38.600	0.855	1.025	7,857
$\frac{1}{2}$	12	12.000	15,279	46.400	0.710	0.850	9,321

(*continued*)

Table 5.18(c) Rigid Copper Busbar Properties—$\frac{1}{2}$-in. Parallel Bars as Indicated[a,b] (*Continued*)

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^{2})	Area (kcmil)	Weight (lb/ft)	30°C (μΩ/ft)	70°C (μΩ/ft)	70°C (A)
3 Parallel Bars							
$\frac{1}{2}$	1	1.500	1,910	5.790	5.717	6.840	1,581
$\frac{1}{2}$	$1\frac{1}{2}$	2.250	2,865	8.700	3.810	4.560	2,156
$\frac{1}{2}$	2	3.000	3,820	11.580	2.850	3.410	2,646
$\frac{1}{2}$	$2\frac{1}{2}$	3.750	4,775	14.490	2.280	2.727	3,231
$\frac{1}{2}$	3	4.500	5,730	17.400	1.903	2.277	3,834
$\frac{1}{2}$	$3\frac{1}{2}$	5.250	6,685	20.280	1.627	1.947	4,315
$\frac{1}{2}$	4	6.000	7,639	23.190	1.423	1.703	4,771
$\frac{1}{2}$	5	7.500	9,549	28.980	1.140	1.363	5,888
$\frac{1}{2}$	6	9.000	11,459	34.800	0.950	1.137	6,997
$\frac{1}{2}$	8	12.000	15,279	46.500	0.713	0.853	8,937
$\frac{1}{2}$	10	15.000	19,099	57.900	0.570	0.683	10,912
$\frac{1}{2}$	12	18.000	22,918	69.600	0.473	0.567	12,945
4 Parallel Bars							
$\frac{1}{2}$	1	2.000	2,546	7.720	4.288	5.130	2,023
$\frac{1}{2}$	$1\frac{1}{2}$	3.000	3,820	11.600	2.858	3.420	2,760
$\frac{1}{2}$	2	4.000	5,093	15.440	2.138	2.558	3,387
$\frac{1}{2}$	$2\frac{1}{2}$	5.000	6,366	19.320	1.710	2.045	4,136
$\frac{1}{2}$	3	6.000	7,639	23.200	1.428	1.708	4,908
$\frac{1}{2}$	$3\frac{1}{2}$	7.000	8,913	27.040	1.220	1.460	5,523
$\frac{1}{2}$	4	8.000	10,186	30.920	1.068	1.278	6,106
$\frac{1}{2}$	5	10.000	12,732	38.640	0.855	1.023	7,537
$\frac{1}{2}$	6	12.000	15,279	46.400	0.713	0.853	8,956
$\frac{1}{2}$	8	16.000	20,372	62.000	0.535	0.640	11,440
$\frac{1}{2}$	10	20.000	25,465	77.200	0.428	0.513	13,967
$\frac{1}{2}$	12	24.000	30,558	92.800	0.355	0.425	16,570
5 Parallel Bars							
$\frac{1}{2}$	1	2.500	3,183	9.650	3.430	4.104	2,466
$\frac{1}{2}$	$1\frac{1}{2}$	3.750	4,775	14.500	2.286	2.736	3,364
$\frac{1}{2}$	2	5.000	6,366	19.300	1.710	2.046	4,127
$\frac{1}{2}$	$2\frac{1}{2}$	6.250	7,958	24.150	1.368	1.636	5,041
$\frac{1}{2}$	3	7.500	9,549	29.000	1.142	1.366	5,981
$\frac{1}{2}$	$3\frac{1}{2}$	8.750	11,141	33.800	0.976	1.168	6,731
$\frac{1}{2}$	4	10.000	12,732	38.650	0.854	1.022	7,442
$\frac{1}{2}$	5	12.500	15,915	48.300	0.684	0.818	9,186
$\frac{1}{2}$	6	15.000	19,099	58.000	0.570	0.682	10,916
$\frac{1}{2}$	8	20.000	25,465	77.500	0.428	0.512	13,942
$\frac{1}{2}$	10	25.000	31,831	96.500	0.342	0.410	17,023
$\frac{1}{2}$	12	30.000	38,197	116.000	0.284	0.340	20,195
6 Parallel Bars							
$\frac{1}{2}$	1	3.000	3,820	11.580	2.858	3.420	2,782
$\frac{1}{2}$	$1\frac{1}{2}$	4.500	5,730	17.400	1.905	2.280	3,795
$\frac{1}{2}$	2	6.000	7,639	23.160	1.425	1.705	4,657
$\frac{1}{2}$	$2\frac{1}{2}$	7.500	9,549	28.980	1.140	1.363	5,687
$\frac{1}{2}$	3	9.000	11,459	34.800	0.952	1.138	6,748
$\frac{1}{2}$	$3\frac{1}{2}$	10.500	13,369	40.560	0.813	0.973	7,594

Table 5.18(c) Rigid Copper Busbar Properties—$\frac{1}{2}$-in. Parallel Bars as Indicated[a,b] (*Continued*)

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^{2})	Area (kcmil)	Weight (lb/ft)	30°C (μΩ/ft)	70°C (μΩ/ft)	70°C (A)
6 Parallel Bars							
$\frac{1}{2}$	4	12.000	15,279	46.380	0.712	0.852	8,396
$\frac{1}{2}$	5	15.000	19,099	57.960	0.570	0.682	10,363
$\frac{1}{2}$	6	18.000	22,918	69.600	0.475	0.568	12,315
$\frac{1}{2}$	8	24.000	30,558	93.000	0.357	0.427	15,730
$\frac{1}{2}$	10	30.000	38,197	115.800	0.285	0.342	19,205
$\frac{1}{2}$	12	36.000	45,837	139.200	0.237	0.283	22,784
7 Parallel Bars							
$\frac{1}{2}$	1	3.500	4,456	13.510	2.450	2.931	3,161
$\frac{1}{2}$	$1\frac{1}{2}$	5.250	6,685	20.300	1.633	1.954	4,313
$\frac{1}{2}$	2	7.000	8,913	27.020	1.221	1.461	5,292
$\frac{1}{2}$	$2\frac{1}{2}$	8.750	11,141	33.810	0.977	1.169	6,462
$\frac{1}{2}$	3	10.500	13,369	40.600	0.816	0.976	7,668
$\frac{1}{2}$	$3\frac{1}{2}$	12.250	15,597	47.320	0.697	0.834	8,630
$\frac{1}{2}$	4	14.000	17,825	54.110	0.610	0.730	9,541
$\frac{1}{2}$	5	17.500	22,282	67.620	0.489	0.584	11,776
$\frac{1}{2}$	6	21.000	26,738	81.200	0.407	0.487	13,994
$\frac{1}{2}$	8	28.000	35,651	108.500	0.306	0.366	17,875
$\frac{1}{2}$	10	35.000	44,563	135.100	0.244	0.293	21,824
$\frac{1}{2}$	12	42.000	53,476	162.400	0.203	0.243	25,891
8 Parallel Bars							
$\frac{1}{2}$	1	4.000	5,093	15.440	2.144	2.565	3,478
$\frac{1}{2}$	$1\frac{1}{2}$	6.000	7,639	23.200	1.429	1.710	4,744
$\frac{1}{2}$	2	8.000	10,186	30.880	1.069	1.279	5,821
$\frac{1}{2}$	$2\frac{1}{2}$	10.000	12,732	38.640	0.855	1.023	7,108
$\frac{1}{2}$	3	12.000	15,279	46.400	0.714	0.854	8,435
$\frac{1}{2}$	$3\frac{1}{2}$	14.000	17,825	54.080	0.610	0.730	9,493
$\frac{1}{2}$	4	16.000	20,372	61.840	0.534	0.639	10,495
$\frac{1}{2}$	5	20.000	25,465	77.280	0.428	0.511	12,954
$\frac{1}{2}$	6	24.000	30,558	92.800	0.356	0.426	15,394
$\frac{1}{2}$	8	32.000	40,744	124.000	0.268	0.320	19,662
$\frac{1}{2}$	10	40.000	50,930	154.400	0.214	0.256	24,006
$\frac{1}{2}$	12	48.000	61,115	185.600	0.178	0.213	28,480
9 Parallel Bars							
$\frac{1}{2}$	1	4.500	5,730	17.370	1.906	2.280	3,794
$\frac{1}{2}$	$1\frac{1}{2}$	6.750	8,594	26.100	1.270	1.520	5,175
$\frac{1}{2}$	2	9.000	11,459	34.740	0.950	1.137	6,350
$\frac{1}{2}$	$2\frac{1}{2}$	11.250	14,324	43.470	0.760	0.909	7,755
$\frac{1}{2}$	3	13.500	17,189	52.200	0.634	0.759	9,202
$\frac{1}{2}$	$3\frac{1}{2}$	15.750	20,054	60.840	0.542	0.649	10,356
$\frac{1}{2}$	4	18.000	22,918	69.570	0.474	0.568	11,449
$\frac{1}{2}$	5	22.500	28,648	86.940	0.380	0.454	14,132
$\frac{1}{2}$	6	27.000	34,377	104.400	0.317	0.379	16,793
$\frac{1}{2}$	8	36.000	45,837	139.500	0.238	0.284	21,449
$\frac{1}{2}$	10	45.000	57,296	173.700	0.190	0.228	26,189
$\frac{1}{2}$	12	54.000	68,755	208.800	0.158	0.189	31,069

(*continued*)

Table 5.18(c) Rigid Copper Busbar Properties—$\frac{1}{2}$-in. Parallel Bars as Indicated[a,b] (*Continued*)

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area (in.^{2})	Area (kcmil)	Weight (lb/ft)	30°C (μΩ/ft)	70°C (μΩ/ft)	70°C (A)
10 Parallel Bars							
$\frac{1}{2}$	1	5.000	6,366	19.300	1.715	2.052	4,110
$\frac{1}{2}$	$1\frac{1}{2}$	7.500	9,549	29.000	1.143	1.368	5,607
$\frac{1}{2}$	2	10.000	12,732	38.600	0.855	1.023	6,879
$\frac{1}{2}$	$2\frac{1}{2}$	12.500	15,915	48.300	0.684	0.818	8,401
$\frac{1}{2}$	3	15.000	19,099	58.000	0.571	0.683	9,969
$\frac{1}{2}$	$3\frac{1}{2}$	17.500	22,282	67.600	0.488	0.584	11,219
$\frac{1}{2}$	4	20.000	25,465	77.300	0.427	0.511	12,404
$\frac{1}{2}$	5	25.000	31,831	96.600	0.342	0.409	15,309
$\frac{1}{2}$	6	30.000	38,197	116.000	0.285	0.341	18,193
$\frac{1}{2}$	8	40.000	50,930	155.000	0.214	0.256	23,237
$\frac{1}{2}$	10	50.000	63,662	193.000	0.171	0.205	28,371
$\frac{1}{2}$	12	60.000	76,394	232.000	0.142	0.170	33,658
11 Parallel Bars							
$\frac{1}{2}$	1	5.500	7,003	21.230	1.559	1.865	4,363
$\frac{1}{2}$	$1\frac{1}{2}$	8.250	10,504	31.900	1.039	1.244	5,952
$\frac{1}{2}$	2	11.000	14,006	42.460	0.777	0.930	7,302
$\frac{1}{2}$	$2\frac{1}{2}$	13.750	17,507	53.130	0.622	0.744	8,918
$\frac{1}{2}$	3	16.500	21,008	63.800	0.519	0.621	10,582
$\frac{1}{2}$	$3\frac{1}{2}$	19.250	24,510	74.360	0.444	0.531	11,909
$\frac{1}{2}$	4	22.000	28,011	85.030	0.388	0.465	13,167
$\frac{1}{2}$	5	27.500	35,014	106.260	0.311	0.372	16,251
$\frac{1}{2}$	6	33.000	42,017	127.600	0.259	0.310	19,312
$\frac{1}{2}$	8	44.000	56,023	170.500	0.195	0.233	24,667
$\frac{1}{2}$	10	55.000	70,028	212.300	0.155	0.186	30,117
$\frac{1}{2}$	12	66.000	84,034	255.200	0.129	0.155	35,729
12 Parallel Bars							
$\frac{1}{2}$	1	6.000	7,639	23.160	1.429	1.710	4,616
$\frac{1}{2}$	$1\frac{1}{2}$	9.000	11,459	34.800	0.953	1.140	6,297
$\frac{1}{2}$	2	12.000	15,279	46.320	0.713	0.853	7,726
$\frac{1}{2}$	$2\frac{1}{2}$	15.000	19,099	57.960	0.570	0.682	9,435
$\frac{1}{2}$	3	18.000	22,918	69.600	0.476	0.569	11,195
$\frac{1}{2}$	$3\frac{1}{2}$	21.000	26,738	81.120	0.407	0.487	12,600
$\frac{1}{2}$	4	24.000	30,558	92.760	0.356	0.426	13,930
$\frac{1}{2}$	5	30.000	38,197	115.920	0.285	0.341	17,193
$\frac{1}{2}$	6	36.000	45,837	139.200	0.238	0.284	20,432
$\frac{1}{2}$	8	48.000	61,115	186.000	0.178	0.213	26,097
$\frac{1}{2}$	10	60.000	76,394	231.600	0.143	0.171	31,863
$\frac{1}{2}$	12	72.000	91,673	278.400	0.118	0.142	37,800

[a] 1 μΩ/ft = 1 × 10^{-6} Ω/ft. For example, 68.39 μΩ/ft = 68.39 × 10^{-6} Ω/ft.

[b] Current ratings apply when the busbar is oriented with its long edge vertical, and bar spacing ≥ bar thickness, and busbar is run in the horizontal plane. Current ratings based on 30°C rise above 40°C ambient temperature.

Source: Data from www.copper.org (Copper Development Association, Inc.) with adjustments.

Table 5.18(d) Rigid Copper Busbar Properties—$\frac{3}{4}$-in. Parallel Bars as Indicated[a,b]

Dimensions					DC Resistance		DC Current Rating
Thickness (in.)	Width (in.)	Area ($in.^2$)	Area (kcmil)	Weight (lb/ft)	30°C (μΩ/ft)	70°C (μΩ/ft)	70°C (A)
2 Parallel Bars							
$\frac{3}{4}$	4	6.00	7,639	23.2	1.425	1.705	4,397
$\frac{3}{4}$	5	7.50	9,549	29.0	1.140	1.360	5,256
$\frac{3}{4}$	6	9.00	11,459	34.8	0.950	1.140	6,214
$\frac{3}{4}$	8	12.00	15,279	46.4	0.710	0.850	7,969
$\frac{3}{4}$	10	15.00	19,099	58.0	0.570	0.685	9,770
$\frac{3}{4}$	12	18.00	22,918	69.6	0.475	0.570	11,567
3 Parallel Bars							
$\frac{3}{4}$	4	9.00	11,459	34.8	0.950	1.137	6,107
$\frac{3}{4}$	5	11.25	14,324	43.5	0.760	0.907	7,299
$\frac{3}{4}$	6	13.50	17,189	52.2	0.633	0.760	8,630
$\frac{3}{4}$	8	18.00	22,918	69.6	0.473	0.567	11,068
$\frac{3}{4}$	10	22.50	28,648	87.0	0.380	0.457	13,569
$\frac{3}{4}$	12	27.00	34,377	104.4	0.317	0.380	16,066
4 Parallel Bars							
$\frac{3}{4}$	4	12.00	15,279	46.4	0.713	0.853	7,817
$\frac{3}{4}$	5	15.00	19,099	58.0	0.570	0.680	9,343
$\frac{3}{4}$	6	18.00	22,918	69.6	0.475	0.570	11,047
$\frac{3}{4}$	8	24.00	30,558	92.8	0.355	0.425	14,167
$\frac{3}{4}$	10	30.00	38,197	116.0	0.285	0.343	17,368
$\frac{3}{4}$	12	36.00	45,837	139.2	0.238	0.285	20,564
5 Parallel Bars							
$\frac{3}{4}$	4	15.00	19,099	58.0	0.570	0.682	9,527
$\frac{3}{4}$	5	18.75	23,873	72.5	0.456	0.544	11,387
$\frac{3}{4}$	6	22.5	28,648	87.0	0.380	0.456	13,463
$\frac{3}{4}$	8	30.0	38,197	116.0	0.284	0.340	17,266
$\frac{3}{4}$	10	37.5	47,746	145.0	0.228	0.274	21,168
$\frac{3}{4}$	12	45.0	57,296	174.0	0.190	0.228	25,063
6 Parallel Bars							
$\frac{3}{4}$	4	18.0	22,918	69.6	0.475	0.568	10,749
$\frac{3}{4}$	5	22.5	28,648	87.0	0.380	0.453	12,847
$\frac{3}{4}$	6	27.0	34,377	104.4	0.317	0.380	15,189
$\frac{3}{4}$	8	36.0	45,837	139.2	0.237	0.283	19,480
$\frac{3}{4}$	10	45.0	57,296	174.0	0.190	0.228	23,881
$\frac{3}{4}$	12	54.0	68,755	208.8	0.158	0.190	28,276
7 Parallel Bars							
$\frac{3}{4}$	4	21.0	26,738	81.2	0.407	0.487	12,214
$\frac{3}{4}$	5	26.2	33,423	101.5	0.326	0.389	14,599
$\frac{3}{4}$	6	31.5	40,107	121.8	0.271	0.326	17,260
$\frac{3}{4}$	8	42.0	53,476	162.4	0.203	0.243	22,136
$\frac{3}{4}$	10	52.5	66,845	203.0	0.163	0.196	27,138
$\frac{3}{4}$	12	63.0	80,214	243.6	0.136	0.163	32,131
8 Parallel Bars							
$\frac{3}{4}$	4	24.0	30,558	92.8	0.356	0.426	13,436
$\frac{3}{4}$	5	30.0	38,197	116.0	0.285	0.340	16,058
$\frac{3}{4}$	6	36.0	45,837	139.2	0.238	0.285	18,986

(*continued*)

Table 5.18(d) Rigid Copper Busbar Properties—$\frac{3}{4}$-in. Parallel Bars as Indicated[a,b] (*Continued*)

Dimensions					DC Resistance		DC Current Rating
Thickness	Width	Area		Weight	30°C	70°C	70°C
(in.)	(in.)	(in.^{2})	(kcmil)	(lb/ft)	(μΩ/ft)	(μΩ/ft)	(A)
8 Parallel Bars							
$\frac{3}{4}$	8	48.0	61,115	185.6	0.178	0.213	24,350
$\frac{3}{4}$	10	60.0	76,394	232.0	0.143	0.171	29,852
$\frac{3}{4}$	12	72.0	91,673	278.4	0.119	0.143	35,345
9 Parallel Bars							
$\frac{3}{4}$	4	27.0	34,377	104.4	0.317	0.379	14,657
$\frac{3}{4}$	5	33.7	42,972	130.5	0.253	0.302	17,518
$\frac{3}{4}$	6	40.5	51,566	156.6	0.211	0.253	20,712
$\frac{3}{4}$	8	54.0	68,755	208.8	0.158	0.189	26,563
$\frac{3}{4}$	10	67.5	85,944	261.0	0.127	0.152	32,566
$\frac{3}{4}$	12	81.0	103,132	313.2	0.106	0.127	38,558
10 Parallel Bars							
$\frac{3}{4}$	4	30.0	38,197	116.0	0.285	0.341	15,879
$\frac{3}{4}$	5	37.5	47,746	145.0	0.228	0.272	18,978
$\frac{3}{4}$	6	45.0	57,296	174.0	0.190	0.228	22,438
$\frac{3}{4}$	8	60.0	76,394	232.0	0.142	0.170	28,777
$\frac{3}{4}$	10	75.0	95,493	290.0	0.114	0.137	35,279
$\frac{3}{4}$	12	90.0	114,592	348.0	0.095	0.114	41,771
11 Parallel Bars							
$\frac{3}{4}$	4	33.0	42,017	127.6	0.259	0.310	16,856
$\frac{3}{4}$	5	41.2	52,521	159.5	0.207	0.247	20,146
$\frac{3}{4}$	6	49.5	63,025	191.4	0.173	0.207	23,819
$\frac{3}{4}$	8	66.0	84,034	255.2	0.129	0.155	30,548
$\frac{3}{4}$	10	82.5	105,042	319.0	0.104	0.125	37,450
$\frac{3}{4}$	12	99.0	126,051	382.8	0.086	0.104	44,341
12 Parallel Bars							
$\frac{3}{4}$	4	36.0	45,837	139.2	0.238	0.284	17,833
$\frac{3}{4}$	5	45.0	57,296	174.0	0.190	0.227	21,314
$\frac{3}{4}$	6	54.0	68,755	208.8	0.158	0.190	25,200
$\frac{3}{4}$	8	72.0	91,673	278.4	0.118	0.142	32,318
$\frac{3}{4}$	10	90.0	114,592	348.0	0.095	0.114	39,621
$\frac{3}{4}$	12	108.0	137,510	417.6	0.079	0.095	46,912

[a] 1 μΩ/ft = 1 × 10^{-6} Ω/ft. For example, 68.39 μΩ/ft = 68.39 × 10^{-6} Ω/ft.

[b] Current ratings apply when the busbar is oriented with its long edge vertical, and bar spacing ≥ bar thickness, and busbar is run in the horizontal plane. Current ratings based on 30°C rise above 40°C ambient temperature.

Source: Data from www.copper.org (Copper Development Association, Inc.) with adjustments.

Table 5.19 Alternate Values of DC Current Ratings for Rigid Copper Busbar—$\frac{1}{4}$-in. and $\frac{1}{2}$-in. Parallel Bars as Indicated[a,b,c]

		DC Current Rating				DC Current Rating	
Dimensions		70°C	70°C	Dimensions		70°C	70°C
Thickness (in.)	Width (in.)	Vertical (A)	Other (A)	Thickness (in.)	Width (in.)	Vertical (A)	Other (A)
1 Bar							
$\frac{1}{4}$	2	731	721	$\frac{1}{2}$	2	1,088	1,073
$\frac{1}{4}$	3	1,040	1,019	$\frac{1}{2}$	3	1,525	1,494
$\frac{1}{4}$	4	1,342	1,296	$\frac{1}{2}$	4	1,951	1,887
$\frac{1}{4}$	6	1,931	1,820	$\frac{1}{2}$	6	2,783	2,623
$\frac{1}{4}$	8	2,506	2,292	$\frac{1}{2}$	8	3,596	3,289
2 Parallel Bars							
$\frac{1}{4}$	2	1,301	1,259	$\frac{1}{2}$	2	1,961	1,902
$\frac{1}{4}$	3	1,834	1,735	$\frac{1}{2}$	3	2,715	2,577
$\frac{1}{4}$	4	2,350	2,163	$\frac{1}{2}$	4	3,445	3,182
$\frac{1}{4}$	6	3,352	2,937	$\frac{1}{2}$	6	4,861	4,275
$\frac{1}{4}$	8	4,325	3,583	$\frac{1}{2}$	8	6,236	5,189
3 Parallel Bars							
$\frac{1}{4}$	2	1,865	1,787	—	—	—	—
$\frac{1}{4}$	3	2,616	2,432	—	—	—	—
$\frac{1}{4}$	4	3,342	2,996	$\frac{1}{2}$	4	4,918	4,437
$\frac{1}{4}$	6	4,745	3,992	$\frac{1}{2}$	6	6,902	5,848
$\frac{1}{4}$	8	6,105	4,770	$\frac{1}{2}$	8	8,824	6,950
4 Parallel Bars							
$\frac{1}{4}$	2	2,426	2,313	—	—	—	—
$\frac{1}{4}$	3	3,394	3,123	—	—	—	—
$\frac{1}{4}$	4	4,328	3,819	$\frac{1}{2}$	4	6,384	5,673
$\frac{1}{4}$	6	6,130	5,026	$\frac{1}{2}$	6	8,933	7,392
$\frac{1}{4}$	8	7,872	5,916	$\frac{1}{2}$	8	11,395	8,659
5 Parallel Bars							
$\frac{1}{4}$	4	5,312	4,637	$\frac{1}{2}$	4	7,847	6,915
$\frac{1}{4}$	6	7,512	6,048	$\frac{1}{2}$	6	10,960	8,921
$\frac{1}{4}$	8	9,634	7,041	$\frac{1}{2}$	8	13,960	10,340
6 Parallel Bars							
$\frac{1}{4}$	4	6,295	5,452	$\frac{1}{2}$	4	9,309	8,148
$\frac{1}{4}$	6	8,891	7,064	$\frac{1}{2}$	6	12,980	10,445
$\frac{1}{4}$	8	11,395	8,154	$\frac{1}{2}$	8	16,520	12,005
7 Parallel Bars							
$\frac{1}{4}$	6	10,270	8,076	$\frac{1}{2}$	6	15,000	11,960
$\frac{1}{4}$	8	13,150	9,259	$\frac{1}{2}$	8	19,080	13,660
8 Parallel Bars							
$\frac{1}{4}$	6	11,645	9,086	$\frac{1}{2}$	6	17,020	13,475
$\frac{1}{4}$	8	14,905	10,360	$\frac{1}{2}$	8	21,635	15,310
9 Parallel Bars							
$\frac{1}{4}$	6	13,020	10,095	$\frac{1}{2}$	6	19,040	14,985
$\frac{1}{4}$	8	16,660	11,455	$\frac{1}{2}$	8	24,190	16,955
10 Parallel Bars							
$\frac{1}{4}$	6	14,400	11,100	$\frac{1}{2}$	6	21,060	16,495
$\frac{1}{4}$	8	18,415	12,545	$\frac{1}{2}$	8	26,745	18,600

(*continued*)

Table 5.19 Alternate Values of DC Current Ratings for Rigid Copper Busbar—$\frac{1}{4}$-in. and $\frac{1}{2}$-in. Parallel Bars as Indicated[a,b,c] (*Continued*)

Dimensions		DC Current Rating 70°C	DC Current Rating 70°C	Dimensions		DC Current Rating 70°C	DC Current Rating 70°C
Thickness (in.)	Width (in.)	Vertical (A)	Other (A)	Thickness (in.)	Width (in.)	Vertical (A)	Other (A)
11 Parallel Bars							
$\frac{1}{4}$	6	15,775	12,105	—	—	—	—
$\frac{1}{4}$	8	20,170	13,640	—	—	—	—
12 Parallel Bars							
$\frac{1}{4}$	6	17,150	13,110	—	—	—	—
$\frac{1}{4}$	8	21,925	14,725	—	—	—	—

[a] Some current ratings in this table differ slightly from the current ratings given in previous tables. The differences are due to historic precedent.

[b] Current ratings in the “Vertical” column apply when the busbars are oriented with their long edge vertical, and bar spacing ≥ bar thickness, and busbar is run in the horizontal direction.

[c] Current ratings in the “Other” column apply with the busbars are oriented with their long edge horizontal, or when bar spacing < bar thickness, or when the bar is run in the vertical direction.

[d] Current ratings based on 30°C rise above 40°C ambient temperature.

Source: Data from [28].

arrangement with a feed and return leads following the same path, the actual conductor length for a given circuit, or *loop length,* is twice (2×) the path distance. Because of bus mechanical arrangements, it is possible the feed and return conductors have slightly different lengths. In this case, the estimated path distance would be two times the average of the feed and return distances.

As mentioned in Section 5.2.2.2, industry standards suggest no more than 2.0 V total drop between the battery terminals and load equipment for 48-V systems and 1.0 V for 24-V systems. These voltage drops are not fixed throughout any given system (the voltage drop can be less or more in any particular circuit) but are *target* maximum values that are used to rationalize circuit design. The target values will be considered *specified* maximum values for the purposes of circuit design in this book.

Since the important parameter is the total voltage drop from the battery terminals to the load equipment terminals, the voltage drop in each segment (battery, primary distribution, and secondary distribution circuits) can be designed for any value as long as the sum of the voltage drops does not exceed the maximum.

The voltage drop between the battery terminals and the discharge bus normally is in the range of 0.25 to 0.75 V for 48-V systems, with 0.5 V being a good starting value for design purposes (one-half these values for 24-V systems). These values work particularly well if the battery is near the powerboard discharge bus and the loads are farther away. Where the situation is reversed, and the battery is far away and the load is near, the battery circuit usually is designed for a higher voltage drop to reduce conductor size. Since only the total voltage drop is specified, the designer has flexibility in circuit segment design. Typical values for each circuit segment are shown in Table 5.20.

For the first voltage drop calculation method

$$\mathrm{CM} = \frac{F_{\mathrm{VD}}\, L_{\mathrm{Load}}\, L_{\mathrm{Loop}}}{V_{\mathrm{Drop}}} \tag{5.25}$$

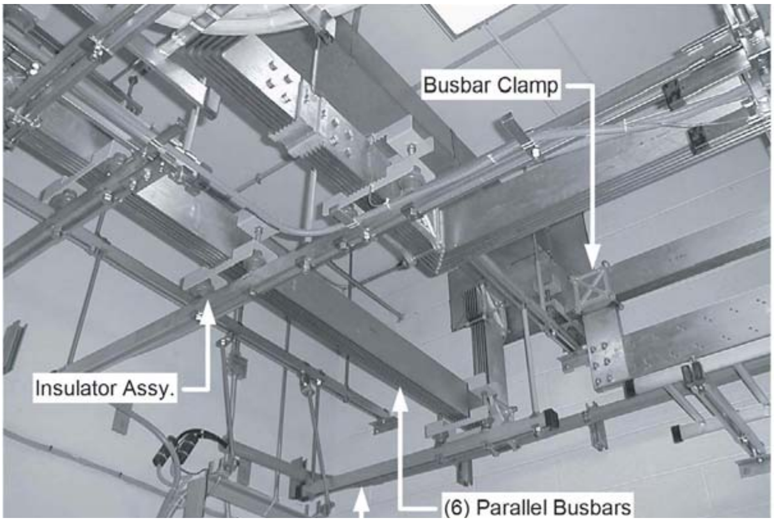

Fig. 5.34 Parallel busbars. (Photo courtesy of Schultz Brothers Electric Company.)

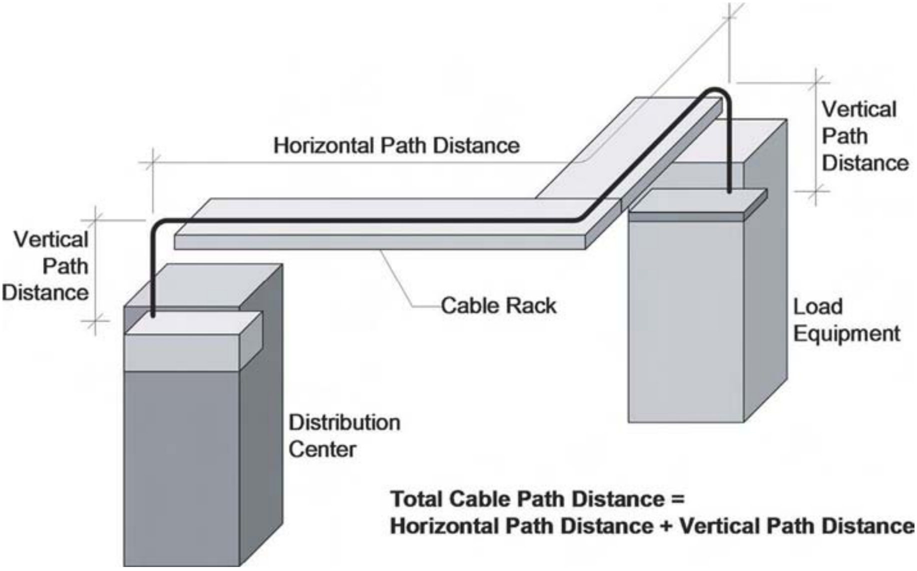

Fig. 5.35 Cable path distance.

Table 5.20 Typical Circuit Segment Voltage Drops

	Circuit Segment	48-V Systems (V)	24-V Systems (V)
(1)	Battery	0.25–0.75	0.13–0.38
(2)	Primary	0.5–1.5	0.25–0.75
(3)	Secondary	0.5–1.5	0.25–0.75
(4)	Maximum total (1) + (2) + (3)	2.0	1.0
(5)	Rectifier (maximum)	1.0	0.5

where CM = conductor area (CM)

F_{VD} = copper wire resistivity at desired design temperature in Ω-CM/ft (11.1 at 30°C and 12.9 at 75°C)

I_{Load} = load current (A)

L_{Loop} = conductor loop length, feed + return (ft)

V_{Drop} = voltage drop (V)

For rectifier output circuits, the load current, I_{Load}, used in Eq. (5.25) is the maximum possible output current as follows:

- *Power rated rectifiers* Output power divided by the lowest possible output voltage.
- *Current rated rectifiers* Maximum rated output current.
- Rectifiers with overload capability Rated output current plus overload current capability.
- Where a modular rectifier shelf or chassis is used, the circuit conductor current rating is based on the maximum rated capacity of the shelf.

Example 5.20 Calculate the cross-sectional area and conductor size so that the voltage drop does not exceed 0.5 V on a 50-ft circuit loop (feed + return) when the load current is 55 A and the conductor temperature is 30°C.

Solution For the specified situation:

$$F_{\text{VD}} = 11.1$$

$$I = 55 \text{ A}$$

$$L_{\text{Loop}} = 50 \text{ ft}$$

$$V_{\text{Drop}} = 0.5 \text{ V}$$

The CM cross-sectional area is

$$\text{CM} = \frac{11.1 \times 55 \text{ A} \times 50 \text{ ft}}{0.5 \text{ V}} = 61{,}050 \text{ CM}$$

Therefore, a single set of conductors or parallel set of conductors having a total cross section ≥ 61,050 CM will meet the 0.5-V voltage drop requirement. The nearest conductor size (exceeding the minimum CM requirement) is 2 AWG with a cross section of 66,360 CM (from Table 5.13). The actual voltage drop with this conductor can be determined by solving Eq. (5.25) for V_{Drop}:

$$V_{\text{Drop}} = \frac{F_{\text{VD}} I L_{\text{Loop}}}{\text{CM}} \tag{5.26}$$

$$= \frac{11.1 \times 55 \text{ A} \times 50 \text{ ft}}{66{,}360 \text{ CM}} = 0.46 \text{ V}$$

Example 5.21 Calculate the cross-sectional area and conductor size so that the voltage drop does not exceed 0.5 V on a 50-ft circuit loop when the load current is 55 A and the conductor temperature is 75°C.

$$F_{VD} = 12.9$$

$$I = 55\ \text{A}$$

$$L_{\text{Loop}} = 50\ \text{ft}$$

$$V_{\text{Drop}} = 0.5\ \text{V}$$

Solution

$$\text{CM} = \frac{12.9 \times 55\ \text{A} \times 50\ \text{ft}}{0.5\ \text{V}} = 70{,}950\ \text{CM}$$

Referring to Table 5.13, it is seen that 1 AWG conductors with a cross-sectional area of 83,690 CM meet the requirements. The actual voltage drop is

$$V_{\text{Drop}} = \frac{12.9 \times 55\ \text{A} \times 50\ \text{ft}}{83{,}690\ \text{CM}} = 0.42$$

Because copper conductors have higher resistance at higher temperatures, the voltage drop at 75°C (167°F) is higher than at 30°C (86°F) and a larger wire is needed to keep it at or below the specified value.

The second method mentioned above a variation of Ohm's law, that is, the voltage drop across a resistance is directly proportional to the resistance and the current through the resistance, or

$$V_{\text{Drop}} = IR \tag{5.27}$$

where V_{Drop} = voltage drop (V)
I = load current (A)
R = circuit resistance (Ω)

If parallel conductors are used in a circuit, the resistance would be of the parallel combination. Since circuit resistance is proportional to conductor length, Eq. (5.27) can be rewritten as

$$V_{\text{Drop}} = IR_{\text{Unit}}L_{\text{Loop}} \tag{5.28}$$

where V_{Drop} = voltage drop (V)
I = load current (A)
R_{Unit} = circuit unit resistance (Ω/ft)
L_{Loop} = circuit conductor loop length (ft)

Usually, the maximum voltage drop is known and it is necessary to calculate the maximum circuit resistance. In this case, the voltage drop equation is rearranged to solve for R_{Unit} as in

$$R_{\text{Unit}} = \frac{V_{\text{Drop}}}{IL_{\text{Loop}}} \tag{5.29}$$

Once the unit resistance is known, it only is necessary to choose a conductor whose resistance does not exceed the calculated value.

Example 5.22 Calculate the conductor size required to keep voltage drop below 0.5 V on a 50-ft circuit loop (feed + return) when the load current is 55 A and the conductor temperature is 30°C.

Solution

$$I = 55 \text{ A}$$

$$L_{\text{Loop}} = 50 \text{ ft}$$

$$V_{\text{Drop}} = 0.5 \text{ V}$$

$$R_{\text{Unit}} = \frac{0.5 \text{ V}}{55 \text{ A} \times 50 \text{ ft}} = 0.000182 \ \Omega/\text{ft}$$

Entering Table 5.13 at a temperature of 30°C (86°F), it is seen that 2 AWG has a unit resistance of 0.000166 Ω/ft, which is less than the maximum calculated above. The actual voltage drop is calculated from

$$V_{\text{Drop}} = 55 \text{ A} \times 0.000166 \ \Omega/\text{ft} \times 50 \text{ ft} = 0.46 \text{ V}$$

Note that this result agrees with the results in Example 5.21, which was calculated using the voltage drop factor.

5.8.1.6 Current Rating in Cable Racks

Current rating (current-carrying capacity or ampacity) is the current that a wire may safely carry under the specified conditions without overheating. Current rating varies with ambient temperature, allowable temperature rise of the wire, and installation conditions. Wire current ratings usually are specified at 60°C (140°F), 75°C (167°F), or 90°C (194°F) with the latter two being the most common in telecommunications applications. In some cases, the temperature rating of the termination may determine the maximum temperature rating of the wire insulation. For example, some circuit breakers and switch devices are rated for continuous load only if the connecting wires have a 90°C rating. Similarly, a 90°C wire *current rating* cannot be used on a 75°C termination—the wire must be used at its 75°C current rating.

Power wiring in modern telecommunications systems is continuously loaded, and the continuous load current normally is increased by 25% (1.25 multiplier) to provide a design margin in current rating calculations. This design margin includes uncertainty in the current-carrying capacity of the wire for different installation conditions. Therefore, the required current ratings for the different circuits are

$$I_{\text{Ampacity}} = 1.25 I_{\text{Load}} \quad \text{distribution and load (branch) circuit}^{21} \tag{5.30a}$$

$$I_{\text{Ampacity}} = 1.25 I_{\text{RectSystem}} \quad \text{battery circuit} \tag{5.30b}$$

$$I_{\text{Ampacity}} = 1.25 I_{\text{RectChassis}} \quad \text{rectifier circuit} \tag{5.30c}$$

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[21] A *branch circuit* consists of circuit conductors between the final overcurrent protection device and the load equipment.

where $I_{\text{Current rating}}$ = conductor current rating (A)
I_{Load} = load current (A)
$I_{\text{RectSystem}}$ = maximum current from rectifier system (A) [depending on system design, this usually is the ultimate rectifier system current (I_{RSU})]
$I_{\text{RectChassis}}$ = maximum current from an individual rectifier chassis or rectifier shelf assembly (A)

Example 5.23 A standalone rectifier is rated 50 A at 48 V and has 10% overload capability. Determine the output conductor current rating.

Solution The maximum available current from this rectifier is 50 × 1.1 = 55 A. Therefore, the required current rating is

$$I_{\text{Ampacity}} = 1.25 I_{\text{RectChassis}} = 1.25 \times 55 \text{ A} = 69 \text{ A}$$

Example 5.24 A modular rectifier shelf holds four 3.0-kW rectifiers and the rectifiers have no overload capability. The lowest operating voltage of the rectifiers is 42.0 V. Determine the output conductor current rating.

Solution The maximum available current from each rectifier is 3000 kW ÷ 42.0 V = 71.4 A, and the maximum available shelf current is 4 × 71.4 A = 286 A. Therefore, the required current rating is

$$I_{\text{Ampacity}} = 1.25 I_{\text{RectShelf}} = 1.25 \times 286 \text{ A} = 358 \text{ A}$$

The dc current ratings for different wire configurations and installation conditions (Fig. 5.36) are derived in the following subsections, including

- Wires in free air (separated from other wires by at least their diameter) in a single layer
- Two bundled wires (two wires touching each other) in free air in a single layer
- Wires with no separation and laid flat in single layer, stacked in multiple layers, or randomly laid
- Wires bundled in a rounded configuration in free air in a single layer

Many telecommunications power circuits use parallel wires to meet current rating and voltage drop requirements. The current rating of parallel wires is the algebraic sum of individual wire current ratings, or

$$I_p = \sum_{1}^{n} I_I n_p \tag{5.31}$$

where I_p = parallel current rating (A)
I_I = current rating of individual wires for the specified physical configuration (A)
n_p = number of parallel wires

When determining the current rating of parallel wires, it is necessary to know the physical configuration. For example, if the parallel wires are installed in free air, then the table for

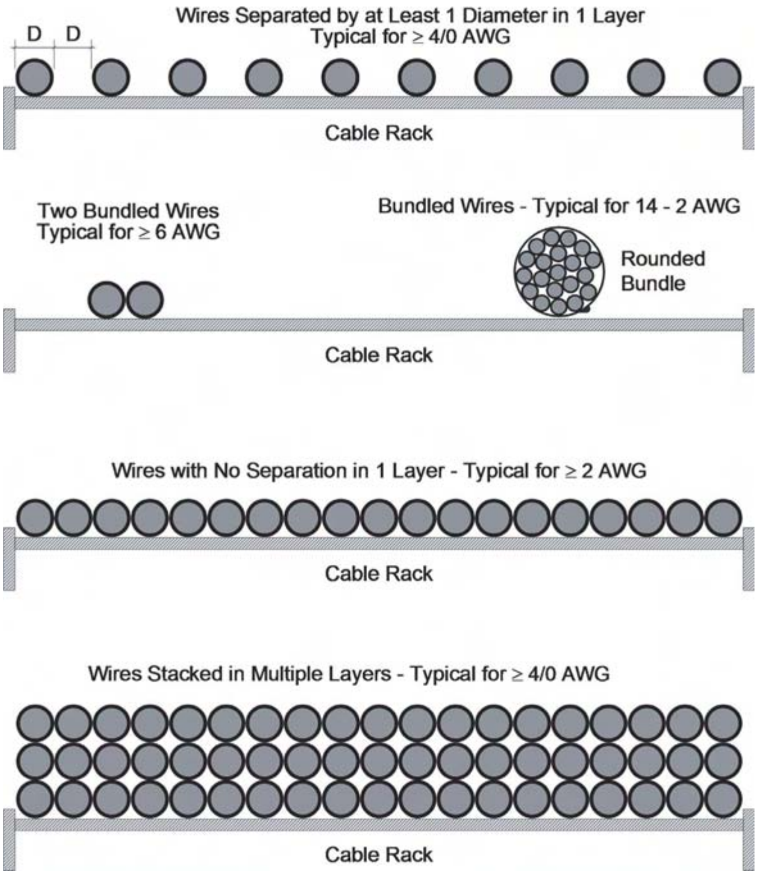

Fig. 5.36 Common cable rack installation conditions. In single- or multiple-layer installations, the wire layers do not always extend across the entire width of the cable rack. Wire sizes shown in each configuration are common and are not meant to limit the sizes actually used in the field.

free air current rating would be used, and if the wires are bundled, the current rating tables for bundled configurations would be used. Parallel wires always are the same size.

In all configurations discussed in this section, the current ratings are for wires on ladder-type cable racks commonly found in telecommunications facilities, and the installation conditions are such that the heat convected and radiated from the wires is freely dissipated (i.e., there are no heat flow restrictions). This generally means there are no cable racks or other obstructions above or below that can block the heat flow, and external heat sources (such as lighting fixtures) are sufficiently separated from the cable racks that they have no effect on wire temperatures. For purposes of consistent treatment, the current ratings in this section are developed from basic heat flow and energy balance principles and methods accepted in the electrical industries (U.S. and international).

Current ratings under specified conditions are derived by determining the heat generated in a wire from resistive losses. For a single wire in free air, the heat flows by conduction from the copper conductor through the insulation to its surface. The heat is then dissipated through radiation and convection to the ambient air. The conductor in the wire is operated at its maximum specified temperature, such as 75°C (167°F) or 90°C (194°F).

For purposes of calculation, the ambient is assumed to be 30°C (86°F), and factors are provided to compensate for other ambient temperatures.

The insulation outside surface temperature will be somewhat lower than the copper conductor temperature and somewhat higher than the ambient temperature. One of the steps in calculating current rating is determining the temperature rise of the insulation surface with respect to the ambient. Depending on the installation conditions, the temperature rise above ambient varies from around 35°C to 52°C for common power wires used in telecommunications.

Where wires are close together, bundled or layered, each wire influences the temperature rise of the other wires. This complicates the calculations and it is necessary to make simplifying assumptions. Specific simplifying assumptions are described in each subsection but, in all cases, it is assumed that:

- Wires are installed on horizontal cable racks.
- No heat is conducted from the wires to the cable rack.
- No air movement takes place around the cable racks except as caused by natural convection (there is no forced air movement).
- Wires are Class B (concentric coarse strand) and Class I (bunch or rope fine strand) constructions with conventional insulation or insulation and outer jacket (no shielding or armoring).
- The thermal resistance of insulation and jackets is the same.
- The thermal resistance of the copper conductor is so small compared to other thermal resistances (insulation, jackets, air) that it can be neglected.
- Where more than one wire is involved, all wires are assumed to be the same size and to carry the same current.
- Wires are single conductors and are not cabled into multiple conductor cables under a common sheath or common jacket.

In load equipment that uses an isolated return (see Section 5.9.2), the feed and return conductors of a given circuit will carry the same current but in opposite directions. In older systems with equipment that uses an integrated return, the return conductors may carry less current than the feed conductors (the steel infrastructure and frame ground conductors carry some if not most of the return current). However, regardless of the type of return used, a conservative design will assume that currents are equal in the feed and return conductors.

The ac ampacities used in the electrical industries are traceable to work published in 1957 by Neher and McGrath [31] in the American Institute of Electrical Engineers (AIEE) *Transactions*.[22] Both IEEE Standard 835, IEEE Standard Power Cable Ampacity Tables [32], and NFPA 70, National Electrical Code (NEC) [29], ampacity tables refer to [31]; however, the ampacity values in these documents are for ac at 60 Hz and, as such, are not directly usable in dc circuits. The ac ampacities include skin effects and proximity effects and losses due to alternating current that do not apply to direct currents.

Because there must be thermal equilibrium between the heat generated inside the wires and the heat dissipated by the wires, the wire currents may be determined by solving the

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[22] The AIEE merged with the Institute of Radio Engineers (IRE) in 1963 to form the Institute of Electrical and Electronics Engineers (IEEE).

heat transfer equations for a given maximum conductor temperature and ambient temperature. The phrase *wire mass* is used to indicate stacked, layered, or bundled wires with no intentional separation.

To allow easy cross reference to current engineering references on power cables [33–36], the equations in this section are based on length dimensions in meters. Since almost all wire catalogs and data sheets from manufacturers in the United States still use dimensions in inches and feet, the necessary conversion factors are:

To convert length in meters to inches, multiply by 39.37 in./m

To convert length in inches to meters, multiply by 0.0254 m/in.

To convert length in meters to feet, multiply by 3.281 m/ft

To convert length in feet to meters, multiply by 0.3048 ft/m

Other common length units, such as millimeter and centimeter can be used if caution is exercised in their application. Thermal coefficients, such as thermal resistivity and heat transfer coefficients, must be in compatible units, and care must be taken with temperatures. Where a temperature difference (such as a temperature rise) is used in a calculation, the temperatures may be in Kelvin (K) or Celsius (°C) as long as both are the same units. The subscript in the equations indicates where temperatures must be in Kelvin (e.g., T_{sK}). Note that a temperature in Celsius (°C) is converted to absolute temperature in Kelvin (K) by adding 273.15 (i.e., K = °C + 273.15).

The heat generated per unit length in a single wire or group of wires is

$$W_w = nI_w^2 R_w \tag{5.32}$$

where W_w = heat dissipated per unit length by the wire (W/m)
I_w = dc current in the wire (A)
R_w = dc resistance per unit length of the wire (Ω/m)
n = number of wires in a bundle or layered configuration
= 1 for single wire
> 1 for bundled or layered configurations

To convert R_w from ohms/meter to ohms/feet, multiply by 0.3048 m/ft

To convert R_w from ohms/feet to ohms/meter, multiply by 3.281 ft/m

For thermal equilibrium, the heat generated by resistive losses in the wire must equal the heat dissipated by convection and radiation, or

$$W_w = W_{\text{conv}} + W_{\text{rad}} \tag{5.33}$$

where W_{conv} = heat dissipated by convection (W/m)
W_{rad} = heat dissipated by radiation (W/m)

The temperature rise from ambient to the surface of a hot wire or wire bundle is proportional to the heat dissipated by convection and radiation. The concept is analogous to voltage drop across a resistance due to current flow through the resistance. In the case of heat flow, the temperature difference (or thermal potential difference) across a thermal resistance is due to the heat flow through the resistance. The relationship for heat flow is

$$T_{\max} - T_a = (W_{\text{conv}} + W_{\text{rad}})(TR_{\text{Total}}) \tag{5.34}$$

where $T_{\max}$ = maximum allowed temperature (K)
T_a = ambient temperature (K)
TR_{Total} = Total thermal resistance from the hottest location to ambient air (m-K/W)

The thermal resistance is a measure of how a material or medium resists heat flow. Nonconducting materials in a wire, such as the insulation and jacket (if any) and the air surrounding the wire, resist heat flow away from the conductor. The following subsections provide analysis of the thermal resistances for the various physical wire configurations. The current ratings are then found by iterative calculations using a programmable calculator or a personal computer running a math analysis program. Example code is provided in Appendix B.

Wires in Free Air Individual wires installed on ladder-type cable racks can be considered to be in free air if they are separated by a distance ≥ wire outside diameter. The heat in the conductor due to resistive losses flows to the inside surface of the insulation, through the insulation to the outside surface, and then to the ambient air. The thermal resistance of the copper conductor is very small compared to the insulation. The temperature rise from the conductor to the ambient air is

$$T_{\max} - T_a = W_w(\text{TR}_{\text{ins}} + \text{TR}_{\text{sa}}) \tag{5.35}$$

where $T_{\max}$ = maximum allowed temperature (K)
T_a = ambient temperature (K)
TR_{ins} = thermal resistance of the insulation (m-K/W)
TR_{sa} = thermal resistance from the surface to ambient air (m-K/W)

The thermal resistance of the cylindrical insulation shell is given by [33]

$$\text{TR}_{\text{ins}} = \frac{\rho_{\text{ins}}}{2\pi} \ln\left(1 + \frac{2t_{\text{ins}}}{D_c}\right) \tag{5.36}$$

where ρ_{ins} = thermal resistivity of insulation (m-K/W) (typically 3.5 to 5.0 m-K/W for thermoset, thermoplastic, and rubberlike insulation materials)[23]
t_{ins} = insulation thickness (m)
D_c = conductor diameter (m)

The external thermal resistance of the air surrounding the insulation surface is given by [33]

$$\text{TR}_{\text{sa}} = \frac{1}{\pi D_e h_{\text{cr}} (T_s - T_a)^{1/4}} \tag{5.37}$$

where D_e = external or outside diameter of the wire (m)
h_{cr} = heat transfer coefficient ($\text{W/m}^2\text{-K}^{5/4}$)

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[23] Thermoset is a plastic material that undergoes a nonreversible chemical reaction when it is cured by heat (or pressure) and cannot be melted by subsequent heating. A thermoplastic material hardens when cooled but will soften when reheated.

$T_s - T_a$ = temperature rise of wire surface above ambient (K)
T_s = temperature at conductor surface (K)
T_a = ambient air temperature (K)

The heat transfer coefficient, h_{cr}, in Eq. (5.37) includes the effects of both convection and radiation. For a wire in free air, the heat transfer coefficient may be found from [33]

$$h_{\mathrm{cr}} = \left(\frac{Z}{(D_e)^g} + E \right) \tag{5.38}$$

where $Z = 0.21$
$g = 0.60$
$E = 3.94$

The temperature rise of the surface with respect to the ambient air, $(T_s - T_a)$, can be calculated from the following iterative process (see also Appendix B):

1. Define the coefficient K_A from

$$K_A = \pi D_e h_{\mathrm{cr}}(\mathrm{TR}_{\mathrm{ins}}) \tag{5.39}$$

2. Substitute K_A from step 1 in

$$(T_s - T_a)_{n+1} = \frac{T_{\max} - T_a}{1 + K_A (T_s - T_a)_n^{1/4}} \tag{5.40}$$

3. Start the iteration by substituting a convenient value for $(T_s - T_a)_n$ and calculate a value for $(T_s - T_a)_{n+1}$
4. Use this as a new value for $(T_s - T_a)_n$ and recalculate step 2
5. Repeat step 4 until the absolute value of the difference between $(T_s - T_a)_{n+1}$ and $(T_s - T_a)_n \leq 0.001$.

Example 5.25 Find the surface temperature of a jacketed 4/0 AWG wire operated at a maximum temperature of 90°C and an ambient temperature of 30°C. Assume the thermal resistivity of the insulation is 5.0 m-K/W.

Solution The following dimensions apply to jacketed 4/0 AWG wire (from Table 5.15):

Conductor diameter, $D_c = 0.528$ in. $= 0.528$ in. $\times$ 0.0254 m/in. $= 0.01341$ m
Insulation thickness, $t =$ is 0.125 in. $= 0.125$ in. $\times$ 0.0254 m/in. $= 0.003175$ m
Wire outside diameter, $D_e = 0.778$ in. $= 0.778$ in. $\times$ 0.0254 m/in. $= 0.01976$ m

The calculated heat transfer coefficient is

$$h_{\mathrm{cr}} = \frac{0.21}{(0.01976)^{0.6}} + 3.94 = 6.1517 \ \mathrm{W/m^2\text{-}K^{5/4}}$$

The calculated value of $\mathrm{TR}_{\mathrm{ins}}$ is

$$\mathrm{TR}_{\mathrm{ins}} = \frac{5.0}{2\pi}\ln\left(1 + \frac{2 \times 0.003175}{0.01341}\right) = 0.3085\ \text{m-K/W}$$

The calculated value of K_A in step 1 is

$$K_A = \pi \times 0.01976 \times 6.1517 \times 0.3085 = 0.1178$$

Starting with an insulation temperature rise $(T_s - T_a)_n = 30$ K, and substituting K_A in step 2 gives

$$(T_s - T_a)_{n+1} = \frac{363.15 - 303.15}{1 + 0.1178 \times 30^{1/4}} = 47.03\ \text{K}$$

Substituting this value for $(T_s - T_a)_n$ gives

$$(T_s - T_a)_{n+1} = \frac{363.15 - 303.15}{1 + 0.1178 \times 47.03^{1/4}} = 45.85\ \text{K}$$

Continuing with the iteration until the difference between the results is ≤ 0.001 yields a surface temperature rise of 45.92 K above ambient (since this is a temperature rise, it is the same as a rise of 45.92°C). The results of this calculation indicate the temperature profile; that is, the conductor temperature is 90°C, the outer insulation surface is (30 + 45.92 =) 75.92°C, and the ambient air temperature is 30°C.

Once the surface temperature is found using the above technique, the external thermal resistance, $\mathrm{TR}_{\mathrm{sa}}$, is found from Eq. (5.37), and the insulation thermal resistance, $\mathrm{TR}_{\mathrm{ins}}$, is found from Eq. (5.36). The current rating is then calculated by combining Eq. (5.32) and Eq. (5.35) and solving for the current, or

$$I_w = \sqrt{\frac{T_{\max} - T_a}{R_w(\mathrm{TR}_{\mathrm{ins}} + \mathrm{TR}_{\mathrm{sa}})}} \tag{5.41}$$

Example 5.26 Determine the current rating of the jacketed 4/0 AWG wire in Example 5.25.

Solution The following information is known:

$$T_{\max} = 90°\text{C } (363.15\ \text{K})$$

$$T_a = 30°\text{C } (303.15\ \text{K})$$

$$\mathrm{TR}_{\mathrm{ins}} = 0.3085\ \text{m-K/W}$$

The dc resistance from Table 5.13 for 4/0 AWG wire is 0.0000500 Ω/ft at 20°C. This value must be converted to resistance in ohms/meter at 90°C. To convert from ohms/feet to ohms/meter, multiply by 3.281, gving 0.0001641 Ω/meter at 20°C. To find the resistance at 90°C, use the conversion method described in Chapter 2, or

$$R_{\mathrm{dc}}(90) = R_{\mathrm{dc}}(20)[1 + 0.00393(90 - 20)] = 0.0001641[1 + 0.00393(90 - 20)]$$

$$= 0.0002093\ \Omega/\text{m at } 90°\text{C}$$

The thermal resistance from the wire surface to the ambient air is

$$\mathrm{TR}_{\mathrm{sa}} = \frac{1}{\pi \times 0.01976 \times 6.1517(45.92)^{1/4}} = 1.0059 \text{ m-K/W}$$

Substituting the known values in Eq. (5.39) gives

$$I_{\mathrm{dc}} = \sqrt{\frac{363.15 - 303.15}{0.0002093(0.3085 + 1.0059)}} = 467 \text{ A}$$

The foregoing procedures are used to develop the current ratings for single unjacketed and jacketed wires in free air [Table 5.16(a)].

In some design problems, it is necessary to refer to the NEC for ampacity data. However, to be useful for dc, the ac ampacities in the NEC must be converted to dc current ratings by multiplying factors that account for skin effect and proximity effect. The factors are calculated from

$$F_{\mathrm{SP}} = \sqrt{\frac{R_{\mathrm{ac}}}{R_{\mathrm{dc}}}} \tag{5.42}$$

where F_{SP} = skin effect/proximity effect multiplying factor
R_{ac} = ac resistance per unit length (Ω/m)
R_{dc} = dc resistance per unit length (Ω/m)

Values for R_{ac} and R_{dc} or their ratios may be found in [30] and [37]. The factors for adjusting ac to dc current ratings (F_{SP}) and calculation results are shown in Table 5.16(b). It should be noted that the dc current ratings in Table 5.16(b), as derived from NEC tables, and the factors shown are lower than the calculated current ratings in Table 5.16(a). The differences arise because the NEC ac ampacities were determined from [31] using different assumptions than in the foregoing calculations and then adjusted for dc. Where it is necessary to observe NEC requirements, the lower values should be used.

Two Bundled Wires Where two wires are bundled together (with lacing twine or cable ties) with no separation between the two but separated from other wires by at least their diameter, the heat dissipated by one wire is influenced by the other wire, and it is necessary to reduce the current ratings from their free air values. The reduction is reflected in the heat transfer coefficient of the bundled configuration. The combined heat transfer coefficient (in W/m^2-K$^{5/4}$) includes the effects of convection and radiation and is of the familiar form

$$h_{\mathrm{cr}} = \frac{Z}{(D_e)^g} + E \tag{5.43}$$

where [33] $Z = 0.29$
$g = 0.50$
$E = 2.35$

The procedures in the previous subsection for single wires in free air are used to develop the current ratings for the two-wire bundle but with the new heat transfer coefficient [Table 5.16(c)]. These current ratings should be used only on two bundled wires if it can be ensured that other wires will not be bundled to them in future projects. If not, the current ratings for rounded wire bundles or layered wires, as appropriate, should be used instead.

Wires with No Separation in One or More Layers Generally, when wires are operated at or less than 25% load factor (actual load current divided by rated free air current rating), resistive losses and self-heating are negligible and the wires can be installed in multiple layers with reduced or no spacing. At higher load factors, the self-heating is higher and the current ratings must be reduced or the installation conditions must be changed to compensate. The heat dissipation can be improved by increasing the wire spacing, installing fewer wires on the cable rack, derating their current rating, or a combination. Where these changes are not practical, it is necessary to use current ratings based on a wire mass as developed in this subsection.

The analytical methods for calculating cable tray (cable rack) ac current ratings were proposed by Stolpe [38] in 1970. Stolpe's method did not take into account load diversity (i.e., variation in the loading of the wires of different circuits). Harshe and Black [39] proposed an improved thermal model in 1994. These methods were incorporated in ampacity tables in ANSI/ICEA P-54-440, Ampacity of Cables Installed in Cable Trays [40].[24] Leake [41] proposed further modifications in 1996. The following discussion uses these heat flow models.

The analysis of heat flow on a cable rack is simplified by assuming the heat flow is out the top and bottom of the wire mass, and there is no heat flow out the sides of the wire mass (i.e., the heat flow is one dimensional).

A convenient representation of the heat flow parameters is shown in Figure 5.37. As current flows through a wire, it generates heat because of resistive losses. The heat flows by conduction through the conductors and insulations to the surface of the overall wire mass and then flows from the surface by convection and radiation to the surrounding air.

By limiting the wire currents to those determined by solving the heat transfer equations for a given maximum wire mass temperature and a given ambient temperature, the wire

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[24] ICEA—Insulated Cable Engineers Association; this document also is known as NEMA (National Electrical Manufacturers Association) WC 51.

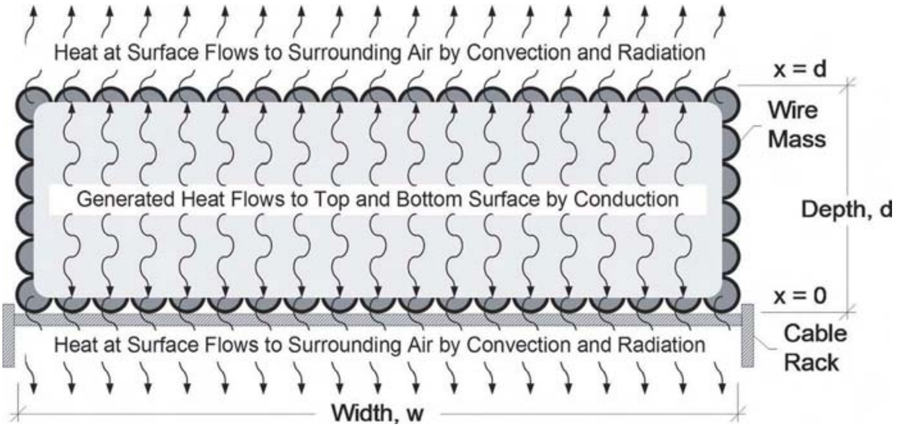

Fig. 5.37 One-dimensional heat flow diagram. The illustration shows a cross section of the wire mass; neat stacking of the wires is not a requirement for this analysis. Heat is assumed to flow to the top and bottom surfaces only and not through the sides (a conservative assumption).

mass will reach thermal equilibrium and the hottest wire will not exceed its maximum specified temperature. In principle, the wires can be any combination of sizes and can be neatly stacked and laced or randomly laid in the cable rack.

The heat generated in any single wire is

$$W_w = I_w^2 R_w \tag{5.44}$$

where W_w = heat dissipated per unit length by the wire (W/m)
I_w = current in the wire (A)
R_w = dc resistance per unit length of the wire (Ω/m)

The total heat generated by all wires is

$$W_{\text{wm}} = I_{c1}^2 R_{c1} + I_{c2}^2 R_{c2} + \cdots + I_{cn}^2 R_{cn} = \sum_1^n I_n^2 R_n \tag{5.45}$$

where W_{wm} is the total heat per unit length and the subscripts on the right side indicate the individual currents and resistances. This representation allows different or the same currents in the wires.

The total heat generated in the wire mass must equal the heat dissipated at its top and bottom surfaces by convection and radiation, or

$$W_{\text{wm}} = W_{\text{conv}} + W_{\text{rad}} \tag{5.46}$$

where W_{conv} = heat dissipated by convection (W/m)
W_{rad} = heat dissipated by radiation (W/m)

The wire mass is assumed to generate heat uniformly throughout its cross section. Assuming no heat flows out the sides and equal amounts flow out the top and bottom of the wire mass, the temperature at a point, *x*, between the top and bottom of the wire mass is (Fig. 5.37)[25]

$$T(x) = \frac{W_{\text{wm}}\rho_{\text{eff}}}{A_{\text{wm}} \times 2} x^2 + \frac{W_{\text{wm}}\rho_{\text{eff}}}{A_{\text{wm}} \times 2} dx + T_s = \frac{W_{\text{wm}}\rho_{\text{eff}}}{A_{\text{wm}} \times 2}(dx - x^2) + T_s \tag{5.47}$$

where $T(x)$ = temperature at distance *x* between the top and bottom of the wire mass (K)
W_{wm} = total heat per unit length generated in the wire mass (W/m)
A_{wm} = cross-sectional area of the wire mass in which the heat is generated (m^2)
ρ_{eff} = effective thermal resistivity of the wire mass including conductors, insulations, and air in the interstices (m-K/W)
d = depth of wire mass (m)
T_s = surface temperature of cable mass (K)

The cross-sectional area of the wire mass is

$$A_{\text{wm}} = wd \tag{5.48}$$

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[25] For derivation, see, for example, [42, 43].

where A_{wm} = total cross-sectional area (m^2)
w = width of the wire mass (m)
d = apparent depth of the wire mass (m)

Substituting Eq. (5.48) in Eq. (5.47) and rearranging gives

$$T(x) - T_s = \frac{W_{\mathrm{wm}}\rho_{\mathrm{eff}}}{2wd}(dx - x^2) \tag{5.49}$$

To find the location of maximum temperature in the cable mass, Eq. (5.49) is differentiated with respect to x and the result set equal to zero

$$\frac{\partial T(x)}{\partial x} = \frac{W_{\mathrm{wm}}\rho_{\mathrm{eff}}}{2wd}(d - 2x) = 0 \tag{5.50}$$

Solving for x gives $x = d/2$ for the location of maximum temperature, which is the centerline of the cable mass, as would be expected.

The maximum temperature rise is found by substituting $x = d/2$ in Eq. (5.49), or

$$T_{\max} - T_s = \frac{W_{\mathrm{wm}}\,\rho_{\mathrm{eff}}}{2wd}\left(\frac{d^2}{2} - \frac{d^2}{4}\right) = \frac{W_{\mathrm{wm}}\,\rho_{\mathrm{eff}}}{2wd}\,\frac{d^2}{4} = \frac{W_{\mathrm{wm}}\,\rho_{\mathrm{eff}}d}{8w} \tag{5.51}$$

The heat transferred by convection is

$$W_{\mathrm{conv}} = h_{\mathrm{conv}}(T_s - T_a)A_s \tag{5.52}$$

where W_{conv} = heat transferred per unit length by convection from the wire mass (W/m)
h_{conv} = convection heat transfer coefficient from the overall wire mass to the surrounding air ($\mathrm{W/m^2}$-K)
T_s = temperature of the cable mass surface (K)
T_a = ambient temperature (K)
A_s = total surface area per unit length of the top and bottom of the wire mass surface ($\mathrm{m^2/m}$)
= 2 × width × length $\mathrm{m^2/m}$

In Eq. (5.52), the heat transfer coefficient only includes the effects of convection and has different units than the heat transfer coefficient in the previous two subsections. The convection heat transfer coefficient, h_{conv} (in $\mathrm{W/m^2}$-K), may be calculated from [41]

$$h_{\mathrm{conv}} = 0.101(T_s - T_a)^{1/4} \tag{5.53}$$

Alternately, a fixed value of 2.4 $\mathrm{W/m^2}$-K (0.223 $\mathrm{W/ft^2}$-K) may be used (as in ANSI/ICEA P-54-440 [40]).

The heat transferred by radiation is

$$W_{\mathrm{rad}} = \frac{\sigma A_s \varepsilon (T_{s\mathrm{K}}^4 - T_{a\mathrm{K}}^4)}{l} \tag{5.54}$$

where W_{rad} = heat transferred per unit length by radiation from the cable mass (W/m)

σ = Stefan–Boltzmann constant
= 5.67×10^{-8} W/m^2-K^4 (5.27×10^{-9} W/ft^2-K^4)
ε = thermal emissivity coefficient of the cable mass surface
= 0.8 (based on field measurements)
$T_{s\mathrm{K}}$ = absolute average cable mass surface temperature (K)
$T_{a\mathrm{K}}$ = absolute ambient temperature (K)

The total heat transferred from the wire mass surface to the surrounding air is

$$W_{\mathrm{sa}} = W_{\mathrm{conv}} + W_{\mathrm{rad}} \tag{5.55}$$

and

$$W_{\mathrm{sa}} = h_{\mathrm{conv}}(T_s - T_a)A_s + \sigma A_s \varepsilon (T_{s\mathrm{K}}^4 - T_{a\mathrm{K}}^4) \tag{5.56}$$

where W_{sa} is the total heat transferred per unit length from the wire mass surface to the surrounding air (W/m).

For thermal equilibrium, the heat transferred from the surface to the surrounding air, W_{sa}, must equal the heat generated in the wire mass, or

$$W_{\mathrm{sa}} = W_{\mathrm{wm}} \tag{5.57}$$

The heat flow equations are solved by setting the ambient temperature and the maximum temperature of the wire mass and then calculating the allowable heat generated per unit length (W/m). The calculated heat generated then is divided by the cross-sectional area of the wire mass to determine the allowable heat flux (heat per unit volume in W/m^2-m). The allowable heat flux applies to any wire or cross section in the wire mass. Since the cross-sectional area of each wire size is known, the allowable heat generated per unit length by each wire size can be found and the allowable current rating then can be calculated. Procedures are provided later in this subsection.

In some installations, the wires may be randomly laid in a cable rack rather than neatly layered or stacked. For this situation, the concept of an apparent, or calculated, wire mass depth is used. The apparent depth equals the sum of all the wire cross-sectional areas divided by the width, or

$$d_{\mathrm{app}} = \frac{F_{\mathrm{pack}}}{w} \sum_{1}^{n} n_i D_i^2 \tag{5.58}$$

where d_{app} = apparent wire mass depth (m)
F_{pack} = wire packing factor
w = width of wire mass (m)
D_i = outside diameter of each wire (m)
n_i = number of wires of each diameter

The wire packing factor takes into account the interstices between the wires ($F_{\mathrm{pack}} = \pi/4 = 0.786$) or ignores them ($F_{\mathrm{pack}} = 1.0$). With the latter value the wire cross sections are taken as squares with side length equal to the wire diameter and is the value used in ANSI/ICEA P-54-440 [40] to develop ac ampacities for wires and cables in cable trays.

Where $F_{\mathrm{pack}} = 1.0$, the apparent depth is

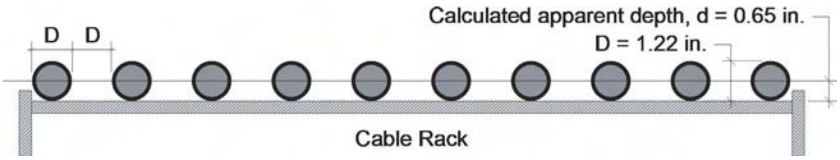

Fig. 5.38 Example where apparent cable rack fill depth (*d*) is < wire diameter (*D*).

$$d_{\text{app}} = \frac{n_1 D_1^2 + n_2 D_2^2 + \cdots + n_n D_n^2}{w} \tag{5.59}$$

Example 5.27 Determine the apparent depth of 10 unjacketed 750-kcmil wires in one layer and separated by one diameter each in a 24-in. cable rack (Fig. 5.38).

Solution The usable cable rack width in this example is 23 in. Since the units are in inches, the calculations will be made without converting to another unit system. The nominal wire outside diameter is 1.22 in., and the apparent depth is

$$d_{\text{app}} = \frac{10(1.22)^2}{23} = 0.65 \text{ in.}$$

In this example, the apparent cable rack fill depth is less than the diameter of the wires.

Example 5.28 Determine the apparent wire depth of thirty-six 750-kcmil wires in three layers of 12 each with no spacing between wires on an 18-in. cable rack (Fig. 5.39).

Solution The actual width of the wire layers is 12 × 1.22 in. = 14.64 in. The apparent depth is

$$d_{\text{app}} = \frac{36(1.22)^2}{14.64} = 3.66 \text{ in.}$$

It should not be surprising that, in this example with neatly stacked layers, the apparent depth is the same as the physical depth of the three layers (3 × 1.22 in. = 3.66 in.).

In terms of the apparent depth, the maximum temperature rise within the cable mass is

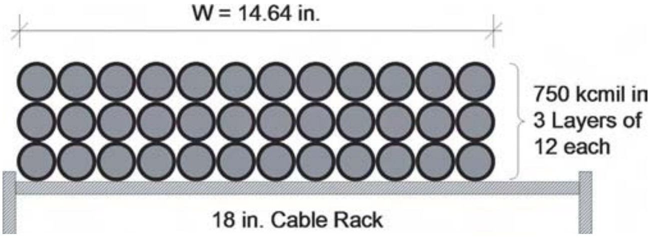

Fig. 5.39 Example of thirty-six 750-kcmil wires in three layers.

$$T_{\mathrm{max}} - T_s = \frac{W_{\mathrm{max}}\rho_{\mathrm{eff}}d_{\mathrm{app}}}{8w} \tag{5.60}$$

where W_{max} = maximum heat dissipated by cable mass per unit length (W/m)
T_{max} = maximum temperature within the cable mass (K)
T_s = average temperature at the surface of the cable mass (K)
w = width of the cable mass (m), usually assumed to be cable tray width less 0.0254 m (1 in.)
ρ_{eff} = effective thermal resistivity of the cable mass (m-K/W)
d_{app} = apparent depth of the cable mass (m)

The maximum allowable heat flux in the wire mass is

$$q_w = \frac{W_{\mathrm{max}}}{A_{\mathrm{wm}}} \tag{5.61}$$

where q_w = heat flux (W/m^2/m)
W_{max} = maximum allowable heat generated per unit length by the wire mass (W/m)
A_{wm} = cross-sectional area of wire mass in terms of apparent depth (m^2)

The allowable heat generated in any wire is

$$W_w = q_w A_w \tag{5.62}$$

where W_w = allowable heat generated per unit length in an individual wire (W/m)
A_w = apparent cross-sectional area of wire (m^2)

and

$$A_w = D_w^2 \tag{5.63}$$

where D_w it the outside diameter of insulated wire (in meters).

The current rating of a given wire size is found from

$$I_w = \sqrt{\frac{W_w}{R_w}} \tag{5.64}$$

where I_w = allowable current rating of an individual wire (A)
W_w = allowable heat generated per unit length in the wire (W/m)
R_w = dc resistance per unit length at maximum allowed wire temperature (Ω/m)

The following is a set of iterative procedures that may be used to determine the current rating of various wire sizes (see also Appendix B):

1. Determine the apparent wire mass depth from Eq. (5.59).
2. Set the required values for the ambient temperature (e.g., 30°C) and maximum wire temperature (e.g., 75°C or 90°C).
3. Assume W_{wm} is initially zero.

4. Set a temporary variable, W_{temp}, equal to W_{wm}.
5. Calculate the wire mass surface temperature T_s from Eq. (5.60). The first iteration will yield a surface temperature equal to the maximum wire temperature used in step 2.
6. Calculate the convection heat transfer coefficient h_{conv} from Eq. (5.53).
7. Substitute the values in Eq. (5.56) and solve for the heat dissipated from the surface W_{sa}.
8. Find the difference between W_{temp} in step 4 and W_{sa} in step 7.
9. If the absolute value of the difference is > 0.001, increase W_{wm} by one-half the difference and repeat steps 4 through 9; if the difference is ≤ 0.001, the heat generated W_{wm} and surface temperature T_s are from steps 4 and 5, respectively.
10. Determine the heat flux, q_w (in W/m^2-m) from Eq. (5.61) by dividing W_{wm} by the cross-sectional area of the wire mass from Eq. (5.48).
11. Determine the allowable heat generation, W_w, of a given wire size from Eq. (5.62) by multiplying the heat flux, q_w, from step 10 by the apparent cross-sectional area of the wire A_w from Eq. (5.63).
12. Determine the allowable current for the given wire size from Eq. (5.64).

The foregoing techniques are used to calculate the current ratings of unjacketed and jacketed 1/C wires in cable racks [Table 5.16(d)] using the following parameters:

• Cable rack width (w)	= 24 in. (0.6096 m)
• Surface emissivity of cable mass (ε)	= 0.8
• Cable mass temperature ($T_{\max}$)	= 75 and 90°C
• Ambient temperature (T_a)	= 30°C
• Thermal resistivity of wire mass(ρ_{eff})[26]	= 4.0 m-K/W (13.12 ft-K/W)[27]
• Apparent cable rack fill depth (d_{app})	= 0.0254 to 0.1016 m (1 to 4 in.)

Examination of the tables reveals that a few of the calculated cable rack current ratings for large wires and shallow depths exceed the free air current ratings. To be conservative, the table current ratings should be reduced to the free air current ratings to minimize the possibility of hot spots in the cable layer.

The current ratings are based on the wire diameters shown in the tables. For wire of the same gauge and construction but slightly different outside diameter, the current rating can be determined from [40]

$$I_x = I_{\text{Table}} \frac{D_x}{D_{\text{Table}}} \tag{5.65}$$

where I_x = current rating of wire with different diameter (A)
I_{Table} = current rating from Table 5.16(d) (A)
D_x = outer diameter of wire (same dimension units as D_{Table})
D_{Table} = outer diameter of wire from table (same dimension units as D_x)

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[26] A constant overall thermal resistivity is used, which is consistent with [40]; however, in practice, the thermal resistivity is slightly lower for large wires and slightly higher for small wires but the overall effect is small. For a detailed discussion of thermal resistivity as applied to power cables, see [34, 36].

[27] Value from [40].

Table 5.21 Allowable Heat Flux (watts/unit cross-sectional area/unit length) for 30°C Ambient Temperature and 75°C and 90°C Maximum Wire Temperatures[a]

Apparent Cable Rack Fill Depth (in.)	Allowable Heat Flux, 75°C Maximum (W/in.^{2}/ft)	Allowable Heat Flux, 90°C Maximum (W/in.^{2}/ft)
0.5	11.185	15.809
1	4.996	6.997
1.5	3.016	4.195
2	2.070	2.864
2.5	1.527	2.105
3	1.182	1.624
3.5	0.946	1.296
4	0.777	1.062

[a] To convert from W/in.^{2}/ft to W/m^2/m, multiply by 1.966×10^{-4}.
To convert from W/m^2/m to W/in.^{2}/ft, multiply by 5.085×10^{3}.

The calculated allowable heat fluxes for various apparent cable rack fill depths are given in Table 5.21. These values can be used to calculate the allowable current ratings for wire diameters and resistances different from the current rating table values.

Example 5.29 Unjacketed 1/C 750-kcmil wires are installed in a 24-in. cable rack to an apparent cable rack fill depth of 4 in. Assume all wires are equally loaded. Confirm the current rating at 90°C given in Table 5.16(d).

Solution The following information is taken from Table 5.13 and Table 5.15 for 750-kcmil wire and from Table 5.21 for 4-in. cable rack fill depth:

- dc resistance = 0.01798 Ω/1000 ft
- Conductor diameter = 0.998 in.
- Insulation thickness = 0.110 in.
- Wire outside diameter = 0.998 + 2 × 0.110 = 1.22 in.
- Effective cross-sectional area (D^2) = 1.488 in.^{2}
- Allowable heat flux = 1.062 W/in.^{2}/ft

The allowable heat generation is 1.488 in.^{2} × 1.062 W/in.^{2}/ft = 1.580 W/ft; therefore,

$$I_w = \sqrt{\frac{W_w}{R_w}} = \sqrt{\frac{1.580}{0.01798 \times 10^{-3}}} = 296 \text{ A}$$

which agrees with the table value (except for small rounding error).

The foregoing current rating calculations are based on equal loading of all wires. If some of the wires are lightly loaded, the heat generated by them will contribute less to the overall temperature rise of the wire mass, and it is possible to operate the other wires at a heavier loading. Such a condition can be described by a diversity factor, which, for the purposes of this discussion, is the ratio of heat generated by the actual re-

Table 5.22 Current Rating Factors for Various Diversities and Cable Rack Fill Depths

Diversity Factor	Current Rating Multiplying Factor						
	Cable Rack Fill Depth						
	1 in.	1.5 in.	2 in.	2.5 in.	3 in.	3.5 in.	4 in.
1.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.9	1.04	1.04	1.03	1.03	1.03	1.03	1.03
0.8	1.09	1.08	1.07	1.07	1.06	1.06	1.05
0.7	1.14	1.13	1.11	1.10	1.10	1.09	1.08
0.6	1.20	1.18	1.16	1.15	1.14	1.13	1.12
0.5	1.28	1.24	1.22	1.20	1.18	1.17	1.16
0.4	1.37	1.32	1.28	1.26	1.23	1.21	1.20
0.3	1.49	1.41	1.36	1.32	1.29	1.27	1.25
0.2	1.64	1.53	1.46	1.41	1.36	1.33	1.31
0.1	1.87	1.70	1.59	1.51	1.46	1.41	1.37

sistive losses in the wires to the heat generated when all wires are operated at their maximum ratings, or

$$F_{\mathrm{Div}} = \frac{W_{\mathrm{res}}}{W_{\mathrm{max}}} \tag{5.66}$$

where W_{res} = estimated heat dissipation based on actual resistive losses (W/ft)
W_{max} = maximum allowable heat dissipation of the entire cable mass (W/ft)

Diversity factors and corresponding current rating multiplying factors are given in Table 5.22. Care should be taken when using low diversity factors in single-layer or shallow arrangements to avoid overloading individual wires and causing hot spots.

The conductors in many telecommunications power circuits are oversized to meet voltage drop requirements and their actual current loading is a fraction of their current rating. For example, say 4/0 AWG wires are used in a 200-A circuit (as determined by the overcurrent protection) to limit voltage drop. The free air current rating of jacketed 4/0 AWG wire at 75°C is 404 A (from Table 5.19), so the load factor is 200 A/404 A = 0.50, or 50%. In many situations, the equipment manufacturer may require an overcurrent device that is sized 150 to 200% of the continuous load to prevent false tripping. Ignoring voltage drop for the moment, the wire used in such a circuit would be sized for the overcurrent protection and would have a load factor of 67 to 50%. The basic circuit design rules in this book are based on a load factor no higher than 80%. Where the load factor of a circuit is 25% or less, the heat generated by that circuit can be ignored in the current rating calculations.

Heavy loading and high load factors should be avoided in initial installations. Subsequent system expansion invariably will use existing cable racks and new wires probably will be installed on top of or adjacent to existing wires. If this is done without consideration of the original design, the current ratings of the existing lower layer possibly could be decreased below the current they were originally designed to carry.

Example 5.30 Forty unjacketed 1/C 750-kcmil wires are uniformly stacked in an 18-in. cable rack with 26 wires loaded to 215 A each and 14 wires loaded to 350 A each. Determine the current rating of the wires at 90°C.

Solution The unit area for unjacketed 1/C 750-kcmil wire is 1.488 in.^{2} and the total area of all wires is 40 × 1.488 in.^{2} = 59.5 in.^{2}. Assuming the full width of the cable rack (less 1 in.) is used, the apparent cable depth is 59.5 in.^{2} ÷ 17 in. = 3.5 in. The basic current rating of 750-kcmil wire in a cable mass with calculated depth of 3.5 in. is taken from the nearest depth value in Table 5.16(d).2 (3.5 in.), or 317 A. The maximum allowable heat flux for 3.5-in. fill depth from Table 5.21 is 1.296 W/in.^{2}/ft and the total allowable heat generation is W_{wm} = 1.296 W/in.^{2}/ft × 59.5 in.^{2} = 77.1 W/ft. With the current loading given, the actual heat generated is (0.01798 Ω ÷ 1000 ft) × (350 A)^2 = 2.203 W/ft for each heavily loaded wire and (0.01798 Ω ÷ 1000 ft) × (215 A)^2 = 0.831 W/ft for each lightly loaded wire. The total heat generated based on this current loading is (26 × 0.831 W/ft) + (14 × 2.203 W/ft) = 52.4 W/ft. The diversity factor is (52.4 W/ft) ÷ (77.1 W/ft) = 0.7 (rounded). Table 5.23 summarizes the calculations so far.

From Table 5.22, the current rating factor is 1.09 for 3.5-in. cable rack fill depth and 0.7 diversity factor. This factor is applied to the current rating from Table 5.16(d).2, or 1.09 × 317 A = 346 A. Therefore, with diversity taken into account, the current rating of the heavily loaded wires is slightly less than their actual loading.

Wires in Rounded Bundles Where a group of wires is bundled together for management purposes on cable racks, the heat is transferred in the same ways as described in the previous subsection. For purposes of calculating the current ratings of wires in a rounded bundle, all wires are assumed to be the same size and construction (either all jacketed or all unjacketed) and to carry the same current. The bundled configuration includes air gaps between the wires, or interstices. Although in practice the bundle may have an irregular shape, it is assumed to be circular for the analysis that follows. All wire bundles in telecommunications circuits contain an even number of wires (each circuit in the bundle consists of paired feed and return wires). The wires are assumed to be laid straight with no crossovers. The analytical development below generally follows [44].[28]

The maximum temperature rise from the bundle surface to the center, in terms of the overall thermal resistance of the wire bundle, is

$$T_{\max} - T_s = W_w(\text{TR}_b) \tag{5.67}$$

where $T_{\max}$ = maximum temperature at the wire bundle center (K)
T_s = temperature at the surface of the wire bundle (K)
W_w = heat generated per unit length in the wire bundle (W/m)
TR_b = thermal resistance of wire bundle (m-K/W)

Assuming the heat is generated uniformly throughout the wire bundle, the radial temperature distribution of a cylindrical heat source is given by [42]

$$T(r) = \frac{W_w \rho_{\text{eff}}}{4\pi}\left(1 - \frac{r^2}{r_{\text{eb}}^2}\right) + T_s \tag{5.68}$$

where ρ_{eff} = effective thermal resistivity of the wire bundle including the conductors, insulations, and air gaps (m-K/W)

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[28] In [44], a wire located in the bundle center is assumed to be the hottest and the ampacity calculation includes the effects of this conductor and its insulation. However, because bundles consisting of even numbers of wires do not necessarily have a center conductor, this effect is ignored in this subsection.

Table 5.23 Example Loading with Three Layers of 750-kcmil Wire on 18-in. Cable Rack

Wire Size	Quantity	Unit Area (in.^{2})	Total Area (in.^{2})	Load Current (A)	Unit Heat Generated (W/ft)	Total Heat Generated (W/ft)
750 kcmil	26	1.488	38.7	215	0.831	21.6
750 kcmil	14	1.488	<u>20.8</u>	350	2.203	<u>30.8</u>
Total	40		59.5			52.4

Apparent depth (in.) = Total area ÷ 18 in. = 3.3 Diversity factor = $\frac{52.4}{77.1} = 0.7$

= 4.0 m-K/W (13.12 ft-K/W)
r_{eb} = wire bundle outside radius (m)
= $D_{\text{eb}}/2$ (m)

The maximum temperature occurs at the center where $r = 0$ [this may be confirmed by differentiating Eq. (5.68) with respect to r, setting the result equal to zero and solving for r]. Substituting $r = 0$ gives the maximum temperature rise with respect to the bundle surface, or

$$T_{\max} - T_s = W_w \frac{\rho_{\text{eff}}}{4\pi} \tag{5.69}$$

Therefore, the thermal resistance of the wire bundle is

$$\text{TR}_b = \frac{\rho_{\text{eff}}}{4\pi} \tag{5.70}$$

The total cross-sectional areas of wire insulations, copper conductors, and air gaps influence the effective thermal resistivity of the wire bundle. For calculation purposes, it is considered to be the same as described in the previous subsection for wires with no separation in one or more layers.

The temperature rise of the wire bundle surface over the ambient air is

$$T_s - T_a = W_b(\text{TR}_{\text{sa}}) \tag{5.71}$$

where W_b is the heat generated per unit length of wire bundle (W/m).

The thermal resistance of the air surrounding the wire bundle surface is similar to that previously given for a cylindrical surface, or

$$\text{TR}_{\text{sa}} = \frac{1}{\pi D_{\text{eb}} h_{\text{cr}} (T_s - T_a)^{1/4}} \tag{5.72}$$

where TR_{sa} = thermal resistance from the bundle surface to the surrounding air (m-K/W)
D_{eb} = diameter of the wire bundle (m)
h_{cr} = combined heat transfer coefficient including convection and radiation (W/m^2-K$^{5/4}$)
$T_s - T_a$ = temperature rise of wire surface above ambient (K)
T_s = temperature at conductor surface (K)
T_a = ambient air temperature (K)

The combined heat transfer coefficient for a circular bundle of wires in free air, h_{cr}, in W/m^2-K$^{5/4}$, is similar to the coefficient for a single wire, or

$$h_{\mathrm{cr}} = \frac{Z}{(D_{\mathrm{eb}})^g} + E \tag{5.73}$$

where $Z = 0.21$
$g = 0.60$
$E = 3.94$

Substituting Eq. (5.72) in Eq. (5.71) gives

$$T_s - T_a = W_b \frac{1}{\pi D_{\mathrm{eb}} h_{\mathrm{cr}} (T_s - T_a)^{1/4}} \tag{5.74}$$

Combining terms gives

$$(T_s - T_a)^{5/4} = \frac{W_b}{\pi D_{\mathrm{eb}} h_{\mathrm{cr}}} \tag{5.75}$$

and solving for the temperature difference gives

$$T_s - T_a = \frac{W_b^{4/5}}{(\pi D_{\mathrm{eb}} h_{\mathrm{cr}})^{4/5}} = W_b \frac{1}{(\pi D_{\mathrm{eb}} h_{\mathrm{cr}} W_b^{1/4})^{4/5}} \tag{5.76}$$

Therefore,

$$\mathrm{TR}_{\mathrm{sa}} = \frac{1}{(\pi D_{\mathrm{eb}} h_{\mathrm{cr}} W_b^{1/4})^{4/5}} \tag{5.77}$$

To calculate the wire bundle diameter, D_{eb}, it is assumed that the bundle cross-sectional area is the sum of the cross-sectional areas of the individual wires with a packing factor of 1.0 (to be consistent with [40]). Therefore,

$$A_b = \pi \frac{D_{\mathrm{eb}}^2}{4} = n D_w^2 \tag{5.78}$$

where A_b = cross-sectional area of wire bundle (m^2)
D_w = outside diameter of insulated wire (m)
n = number of wires in bundle

and

$$D_{\mathrm{eb}} = 2 \sqrt{\frac{n}{\pi}}\, D_w \tag{5.79}$$

The total temperature rise from the ambient air to the center of the wire bundle (assuming the heat is generated uniformly throughout the bundle) is

$$T_{\max} - T_a = W_b(\mathrm{TR}_T) \tag{5.80}$$

where

$$\mathrm{TR}_T = \mathrm{TR}_b + \mathrm{TR}_{\mathrm{sa}} \tag{5.81}$$

Substituting Eq. (5.70) and Eq. (5.77) in Eq. (5.81) and then substituting the result in Eq. (5.80) gives

$$T_{\max} - T_a = W_b\left[\frac{\rho_{\mathrm{eff}}}{4\pi} + \frac{1}{(\pi D_{\mathrm{eb}} h_{\mathrm{cr}} W_b^{1/4})^{4/5}}\right] \tag{5.82}$$

The maximum allowable heat flux in the wire bundle is

$$q_w = \frac{W_b}{A_b} \tag{5.83}$$

where q_w = heat flux per unit length (W/m^2-m)
W_b = maximum allowable heat generated per unit length in the wire bundle (W/m)
A_b = cross-sectional area of wire bundle (m^2)

Since the heat flux is the same in any cross section within the bundle, the allowable heat generated per unit length in any individual wire is

$$W_w = q_w A_w \tag{5.84}$$

where W_w = allowable heat generated per unit length in an individual wire (W/m)
A_w = apparent cross-sectional area of wire (m^2)

and

$$A_w = D_w^2 \tag{5.85}$$

where D_w it the outside diameter of insulated wire (meters).

The current rating of a given wire size is found from

$$I_w = \sqrt{\frac{W_w}{R_w}} \tag{5.86}$$

where I_w = allowable current rating of an individual wire (A)
W_w = allowable heat generated per unit length in the wire (W/m)
R_w = dc resistance per unit length at maximum allowed wire temperature (Ω/m)

The wire current rating in the bundled configuration can be calculated as follows (these procedures are similar to those described in the previous subsection):

1. Determine the wire bundle equivalent diameter from Eq. (5.79).
2. Calculate the combined heat transfer coefficient h_{cr} from Eq. (5.73).
3. Determine the required values for the ambient temperature (for example, 30°C) and maximum wire temperature (e.g., 75 or 90°C).
4. Define a temporary variable, W_{temp}, and set it to a small positive value (but not zero).

5. Set W_b equal to W_{temp}.
6. Using W_b from step 5, calculate a new value for W_{temp} from

$$W_{\text{temp}} = \frac{T_{\max} - T_a}{\dfrac{\rho_{\text{eff}}}{4\pi} + \dfrac{1}{(\pi D_{\text{eb}} h_{\text{cr}} W_b^{1/4})^{4/5}}}$$

7. Find the difference between W_{temp} in step 6 and W_b in step 5.
8. If the absolute value of the difference is > 0.001, increase W_{temp} by one-half the difference and repeat steps 5 through 8; if the difference is ≤ 0.001, the heat generated, W_b (in W/m), is from step 5.
9. Determine the heat flux, q_w (in W/m^2/m), from Eq. (5.83) by dividing W_b by the cross-sectional area of the wire bundle A_b.
10. Determine the allowable heat generated, W_w, in a given wire size from Eq. (5.84) by multiplying the heat flux, q_w, from step 9 by the apparent cross-sectional area of the wire A_w from Eq. (5.85).
11. Determine the allowable current rating for the given wire size from Eq. (5.86).

Example 5.31 Find the current rating of eight bundled 2 AWG unjacketed wires if the allowable insulation temperature is 90°C and the ambient temperature is 30°C.

Solution

Step 1 The outside diameter of unjacketed 2 AWG wire is 0.412 in. (see Table 5.15). Therefore,

$$D_{\text{eb}} = 2\left(\sqrt{\frac{8}{\pi}}\right)0.412 = 1.31 \text{ in.} = 0.03327 \text{ m}$$

Step 2 The combined heat transfer coefficient is

$$h_{\text{cr}} = \left[\frac{Z}{(D_{\text{eb}})^g} + E\right] = \left(\frac{0.21}{0.03327^{0.6}} + 3.94\right) = 5.558 \text{ W/m}^2\text{-K}^{5/4}$$

Step 3 The temperature variables are $T_{\max} = 90°\text{C}$ (363.15 K) and $T_a = 30°\text{C}$ (303.15 K).

Step 4 Initial $W_{\text{temp}} = 30$ W/m.

Step 5 $W_b = W_{\text{temp}} = 30$ W/m.

Step 6 New

$$W_{\text{temp}} = \frac{T_{\max} - T_a}{\dfrac{\rho_{\text{eff}}}{4\pi} + \dfrac{1}{(\pi D_{\text{eb}} h_{\text{cr}} W_b^{1/4})^{4/5}}} = \frac{363.15 - 303.15}{\dfrac{4.0}{4\pi} + \dfrac{1}{(\pi \times 0.03327 \times 5.558 \times 30^{0.25})^{0.8}}}$$

$$= 54.52366 \text{ W/m}$$

Step 7 $W_{\text{temp}} - W_b = 54.52366 - 30 = 24.523666$.

Step 8 Since 24.523666 > 0.001,

$$W_{\text{temp}} = \frac{24.523666}{2} + 54.523666 = 66.785499 \text{ W/m}$$

At this point, steps 5 through 8 are repeated until the difference between W_b and W_{temp} is ≤ 0.001, which occurs when W_b is close to 60.055.

Step 9 The area of the wire bundle and heat flux are

$$A_b = \pi\left(\frac{D_{\text{eb}}^2}{4}\right) = \pi\left(\frac{0.03327^2}{4}\right) = 0.000869 \text{ m}^2$$

$$q_w = \frac{W_b}{A_b} = \frac{60.055}{0.000869} = 69{,}079.9 \text{ W/m}^2\text{-m}$$

Step 10 The wire cross-sectional area is

$$A_w = D_w^2 = \left(\frac{0.412 \times 0.3048}{12}\right)^2 = 0.0001095 \text{ m}^2$$

The heat generated in the wire is

$$W_w = q_w A_w = 69{,}079 \times 0.0001095 = 7.565 \text{ W/m}$$

Step 11 The dc resistance of 2 AWG copper wire at 90°C (from Table 5.13) is 0.20274 Ω/1000 ft, or 0.00066519 Ω/m.

The allowable current rating is

$$I_w = \sqrt{\frac{W_w}{R_w}} = \sqrt{\frac{7.565}{0.00066519}} = 106.6 \text{ A}$$

The foregoing techniques are used to calculate the current ratings of unjacketed and jacketed wire bundles in cable racks [Table 5.16(e)] using the following parameters:[29]

- Maximum wire temperature ($T_{\max}$) = 75 and 90°C (348.15 and 363.15 K)
- Ambient temperature (T_a) = 30°C (303.15 K)
- Thermal resistivity of wire bundle (ρ_{eff}) = 4.0 m-K/W (13.12 ft-K/W)

Ambient Temperature Correction To determine temperature correction factors when the wire configurations are operated at ambient temperatures other than 30°C, it is necessary to briefly analyze how the ambient temperature affects heat dissipation of a given wire configuration. The basic relationship between temperature rise, heat generated, and thermal resistance is

$$T_{\max} - T_a = W_{\text{conf}}(\text{TR}_T) = I^2 nR(\text{TR}_T) \tag{5.87}$$

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[29] The current rating found in Example 5.31 differs slightly (by 0.6 A) from the value given in Table 5.16(e).3 due to rounding errors in the manual solution shown.

where $T_{\max}$ = maximum wire temperature (K)
T_a = ambient temperature (K)
W_{conf} = heat generated per unit length in the wire configuration (W/m)
T_{RT} = total thermal resistance of wire configuration (m-K/W)
n = number of wires in the configuration
I = current carried by each wire (A)
R = dc resistance per unit length of wire (Ω/m)

The ratio of current rating at one ambient temperature (T_2) to the current rating at another ambient temperature (T_1) is

$$\frac{I_{T_2}}{I_{T_1}} = \sqrt{\frac{(T_{\max} - T_2)R_1(\text{TR}_{T1})}{(T_{\max} - T_1)R_2(\text{TR}_{T_2})}} \tag{5.88}$$

The resistance at one temperature is related to the resistance at another temperature by

$$R_2 = R_1[1 + \alpha_1(T_2 - T_1)] \tag{5.89}$$

where α_1 is the temperature coefficient of resistance for copper at temperature T_1 (Ω/°C). By substitution

$$\frac{I_{T_2}}{I_{T_1}} = \sqrt{\frac{(T_{\max} - T_2)R_1(\text{TR}_{T_1})}{(T_{\max} - T_1)R_1[1 + \alpha_1(T_2 - T_1)](\text{TR}_{T_2})}} \tag{5.90}$$

Temperature rise has subsidiary effects on the thermal resistances and can be ignored in this analysis. Therefore, assuming no change in thermal resistances over the temperatures of interest

$$\frac{I_{T_2}}{I_{T_1}} = \sqrt{\frac{T_{\max} - T_2}{(T_{\max} - T_1)[1 + \alpha_1(T_2 - T_1)]}} \tag{5.91}$$

Ambient temperature correction factors for the current ratings in Table 5.16(a) through Table 5.16(e) are developed by substituting the following values in Eq. (5.91):

$T_{\max}$ = 75 or 90°C
T_1 = 30°C
T_2 = new ambient temperature (°C)
α_1 = 0.00378 Ω/K at 30°C

Table 5.24 shows the resulting correction factors.

Example 5.32 Four 500-kcmil unjacketed wires are installed in a single layer on a cable rack and are separated from each other by a distance equal to their diameter. The wire insulation and terminations are rated 90°C, and the ambient temperature is 40°C. Determine the wire current rating.

Solution The wires are in free air. From Table 5.16(a) for 500 kcmil unjacketed wire,

Table 5.24 Ambient Temperature Correction Factors[a]

Ambient Temperature (T_2) (1)	75°C Current Rating (2)	90°C Current Rating (3)
21–25°C (70–77°F)	1.06	1.05
26–30°C (78–86°F)	1.00	1.00
31–35°C (87–95°F)	0.93	0.95
36–40°C (96–104°F)	0.87	0.90
41–45°C (105–113°F)	0.79	0.84
46–50°C (114–122°F)	0.72	0.79
51–55°C (123–131°F)	0.64	0.73
56–60°C (132–140°F)	0.55	0.67
61–65°C (141–149°F)	0.44	0.61
66–70°C (150–158°F)	0.31	0.54
71–75°C (159–167°F)	—	0.46
76–80°C (168–176°F)	—	0.37

[a] For ambient temperatures from 21–80°C (70–176°F), multiply the current ratings in Table 5.16(a) through Table 5.16(e) by the factors given in the table.

the current rating at 30°C is 834 A. From Table 5.24 for 90°C wire temperature and 40°C ambient temperature, the correction factor is 0.9. Therefore, the current rating of the 500-kcmil wire in free air at 40°C ambient temperature is (834 A × 0.9 =) 751 A.

Parallel Wires The current rating of parallel wires is the algebraic sum of individual wire current ratings, where the individual wire current ratings depend on the installation conditions. For example, if the paralleled wires all are in free air, then the free air current rating would apply; if the paralleled wires are in a rounded bundle with other wires, the current rating for each wire in the bundle would apply. The current rating of parallel busbars is treated differently and is discussed in the next subsection.

$$I_p = \sum_{1}^{N} I_I = I_I N_{\text{Cond}} \tag{5.92}$$

where I_p = parallel current rating (A)
I_I = current rating of individual wire (A)
N_{Cond} = number of parallel wires

Example 5.33 Each side of a circuit consists of four jacketed 3/0 AWG wires in parallel (i.e., four parallel wires in the feed side and four parallel wires in the return side). These wires are neatly stacked in a 12-in. cable rack (effective width 11 in.) with 12 other jacketed 3/0 AWG wires. Determine the current rating at 75°C of the individual wires and the parallel combination.

Solution The diameter of jacketed 3/0 AWG wire is 0.470 + 2 × 0.080 = 0.630 in. There are a total of 20 wires and the apparent depth of the wire mass is

$$d_{\text{app}} = \frac{nD_i^2}{w} = \frac{20 \times 0.630}{11} = 0.722 \text{ in., rounded to 1 in.}$$

From Table 5.16(d).1 for jacketed 3/0 AWG and 1-in. depth, the current rating of each wire is 161 A. The total current rating of four wires in parallel is 4 × 161 A = 644 A.

Rigid Busbar Current Ratings Since most busbar installations use bare, uninsulated busbar, they do not have the same thermal limitations as insulated wire. Nevertheless, the temperature rise for busbar system design normally is limited to 30°C above an ambient of 40°C (70°C busbar temperature). Also, the current rating of parallel busbars does not follow a simple linear relationship; that is, the current rating of N parallel bars is not N times the current rating of a single bar. For example, the multiplication factor for four bars is not 4.0 but is 3.2.

The proximity and emissivity of the parallel busbars determines how much heat they dissipate for a given temperature rise above ambient. Outer bars obstruct convected and radiated heat from the inner bars. Also, the current density in the bars is distorted by the magnetic field interactions due to their close proximity (proximity effect). Emissivity is the ratio of the radiation emitted by a surface to the radiation emitted by a blackbody at the same temperature. A busbar with a higher emissivity can radiate more heat and subsequently has a higher current rating. For example, for a 30°C rise, the current rating of a 1/4 in. × 4 in. copper bar with 0.15 emissivity is approximately 1100 A, but if the emissivity is increased to 0.4, the current rating is increased to 1400 A. Surface coatings and treatments may be applied to copper busbars to increase or decrease their emissivity. For example, the emissivity may be increased by applying a flat or a matt black finish. Table 5.25 compares the emissivity for various busbar surface conditions, and Fig. 5.40 shows its effects on the current rating of single and parallel busbars.

The busbar current ratings shown in Table 5.17 for single bars are based on ac ampacity data from the Copper Development Association, Inc. (CDA) [45], adjusted to dc current rating as follows:

$$I_{\text{dc}} = I_{\text{ac}}\sqrt{S} \tag{5.93}$$

where I_{dc} = dc current rating (A)
I_{ac} = ac ampacity (A), data from CDA, Inc., at www.copper.org
S = skin effect ratio at 60 Hz, data from CDA, Inc., at www.copper.org

The busbar current ratings in Table 5.18 apply to parallel bar combinations and are based on the single bar current ratings from Table 5.17 multiplied by the factors from Table 5.26. The mechanical design of busbar arrangements must account for the changes in length that occur as the bars expand and contract with temperature changes. If not compensated for in the mechanical design, the expansion and contraction can lead to stress and damage to the busbar supporting structure and joints and splices and even to the busbars themselves. The change in length is

Table 5.25 Copper Busbar Surface Emissivity Comparison

Busbar Surface Condition	Emissivity
Bright metal	0.1
Partially oxidized	0.3
Heavily oxidized	0.7
Dull nonmetallic paint	0.9

Source: Data from [44].

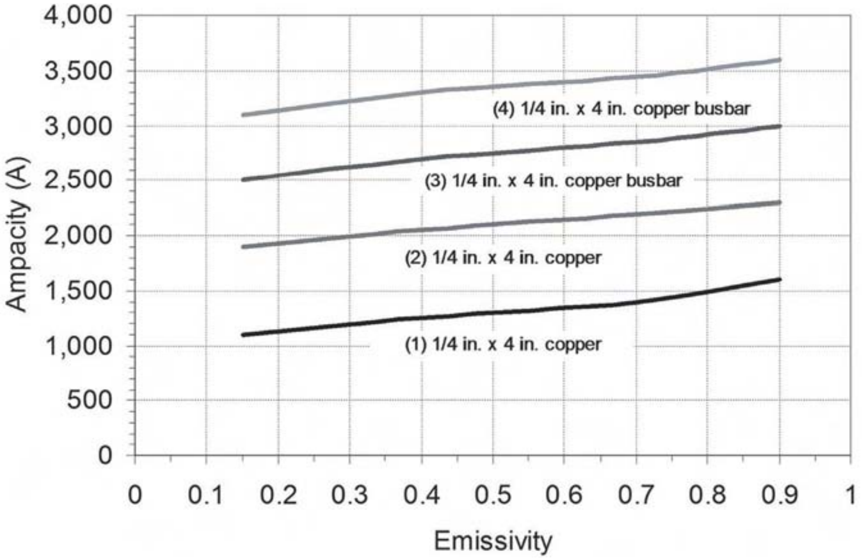

Fig. 5.40 Effects of emissivity on single and multiple parallel busbar current rating. (Data from Storm Copper Components Company.)

$$\Delta L_T = L_{T0}\alpha_{T0}(T - T_0) \tag{5.94}$$

where ΔL_T = length change

L_{T0} = length at base temperature T_0

α_{T0} = coefficient of linear expansion (approximately 17.3 × 10^{-6}/°C or 9.61 × 10^{-6}/°F over the range of ordinary engineering work)

For example, a 100-ft section of copper busbar will expand in length by 0.052 ft, or 0.62 in., if the busbar temperature rises 30°C.

Table 5.26 Current Rating Multiplying Factors for Parallel Copper Busbar Spaced Equal to Their Thickness

Number of Parallel Bars	Multiplication Factor
2	1.8
3	2.5
4	3.2
5	3.9
6	4.4
7	5.0[a]
8	5.5
9	6.0[a]
10	6.5
11	6.9[a]
12	7.3[a]

[a] Values are interpolated or extrapolated using second-order polynomial trend line analysis.

Source: Basic data from [45].

To minimize stress on the busbar and its supports, expansion joints or flexible sections should be used on straight runs greater than approximately 30 ft. Flexible sections also are used where overhead horizontal busbar runs connect with vertical busbars to equipment below. The joints may use laminated thin copper strips or leaves, braided copper conductors, or Z-bent sections (Fig. 5.41). The expansion joints and flexible sections must have the same total current rating as the busbars.

5.8.1.7 Conductor Terminations and Taps For extraordinarily long runs between the batteries and the charge and discharge buses, wire sizes and quantities may be larger than can be conveniently terminated at either end. In such cases, the larger wires can be tapped with smaller pigtails to make the actual bus connections. Another method is to terminate the larger wires on a nearby collector or termination busbar and then run short, smaller wire to the final termination. The pigtails must have adequate current rating and, if kept short, their voltage drop will have negligible contribution. For seismic installations, the collector bars provide a convenient point to transition from busbar or coarse-strand (Class B) wire to flexible (Class I) wire for termination at the battery or bus to prevent strain on the terminations during a seismic event.

5.8.1.8 Fault Currents The battery system contributes more current during a fault than any other component. The only other source of significant fault current is the rectifier system, but, depending on the location of the fault, rectifier currents generally are an order of magnitude smaller than battery fault currents.

Figure 5.42 shows typical short-circuit current magnitudes available at the terminals of telecommunications batteries. Variations can be expected for different brands and for models within a brand. As a rule of thumb, a battery can supply a fault current in amperes

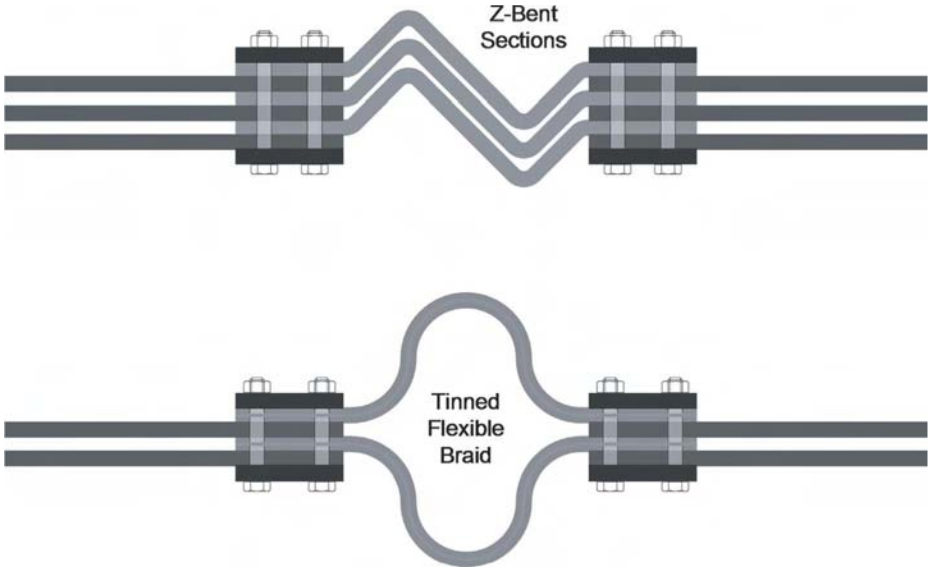

Fig. 5.41 Copper busbar expansion joints (edge-on views).

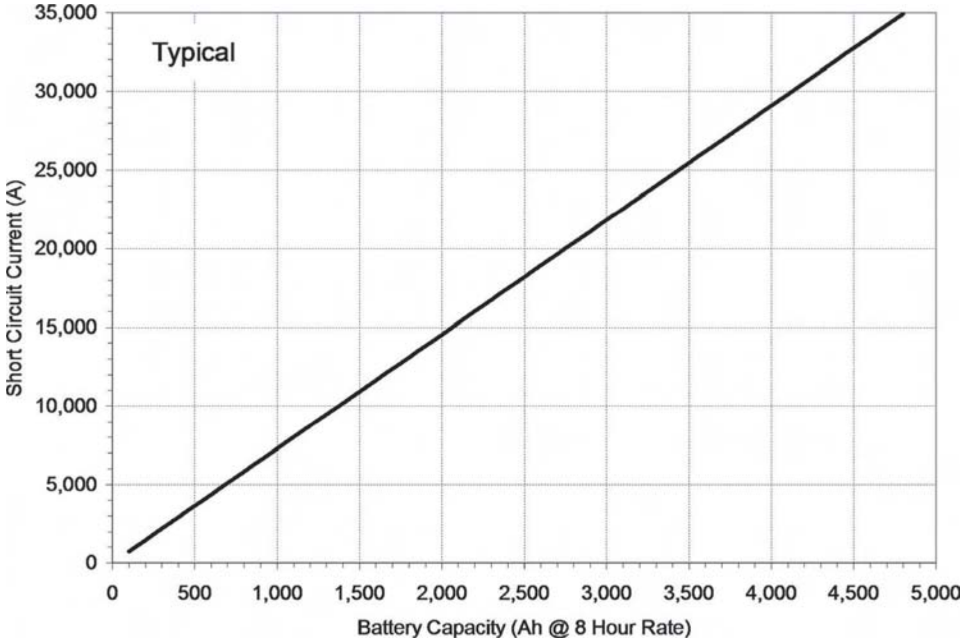

Fig. 5.42 Battery short-circuit current vs. battery capacity.

approximately equal to 10× the 1- or 2-min rating to 1.75 V/cell. Since such short time ratings are not always available on data sheets for telecommunications batteries, another useful rule of thumb is 7.5× the ampere-hour rating of the battery (at its 8-h rate). Battery manufacturers may also provide the maximum short-circuit current for a particular battery type.

Where a battery system consists of more than one string, each string contributes fault current on an additive basis. For example, if three identical strings are connected in parallel and each string can supply 2000-A fault current, the total fault current is 6000 A. The equivalent resistance of batteries in parallel is calculated the same as conductor resistances in parallel. For example, three identical strings, each with 0.06-Ω equivalent resistance, have a parallel resistance of 0.02 Ω.

The highest fault current occurs at the cell or battery terminals. The resistance of the fault reduces the fault current, and if the fault occurs some distance from the battery, the circuit conductor resistances significantly reduce the available fault current at the fault location. Also, intervening circuit components, such as overcurrent protective devices, introduce additional resistance that will reduce fault current levels. Of these, the circuit conductor resistances usually have the largest effect. For worst-case calculations, the fault resistance is assumed to be 0 Ω.

Circuit inductance and capacitance affect fault rise time but they do not affect steady-state dc fault currents. If it is necessary to analyze fault rise time, circuit capacitance can be ignored. The inductance of two parallel conductors is

$$L = 10^{-7}\left(1 + 4 \ln \frac{d}{r}\right) l \text{ henries} \tag{5.95}$$

where L = inductance per unit length (H)
d = distance between centers of the two conductors (m)
r = radii of the two conductors (assumed to be the same) (m)
l = conductor length (m)

The fault current as a function of time is

$$i(t) = I_0 + \frac{V}{R}(1 - e^{-Rt/L}) \text{ A} \tag{5.96}$$

where I_0 = circuit current at the instant of fault initiation (A)
V = source voltage (V)
R = circuit resistance (Ω)
t = time (s)
L = circuit inductance (H)

The ratio L/R is the circuit time constant, denoted by the symbol τ. When $\tau = t$ (i.e., the ratio $L/R = t$), the current will change by ($1 - e^{-1}$ =) 63.2% from its steady-state value.

Example 5.34 Determine the resistance, inductance, and time constant for two bundled parallel insulated 4/0 AWG conductors (nominal inner diameter 0.53 in. and outer diameter 0.70 in.) that are shorted 20 m from their source (assume the source has infinite amperage capability). If the initial current is 100 A and voltage is 50 V, plot the fault current versus time until the current reaches its steady-state value.

Solution From Table 5.13 for 4/0 AWG at 30°C, the unit resistance is $R = 0.00005197$ Ω)/ft, and the total resistance is $R = 0.00005197 \times 20 \times 2 \times 3.281 = 6.82 \times 10^{-3}$ Ω. From the information given

$$d = 0.7 \text{ in. } (0.0178 \text{ m})$$

$$r = 0.53/2 \text{ in.} = 0.265 \text{ in. } (0.00673 \text{ m})$$

and

$$L = 10^{-7}\left(1 + 4 \ln \frac{d}{r}\right)l = 10^{-7}\left(1 + 4 \ln \frac{0.0178}{0.00673}\right)20 = 9.77 \times 10^{-6} \text{ H}$$

The time constant is

$$\tau = \frac{L}{R} = \frac{9.77 \times 10^{-6}}{6.82 \times 10^{-3}} = 1.43 \times 10^{-3} \text{ s} = 1.43 \text{ ms}$$

The fault current plot is shown in Fig. 5.43. The steady-state fault current in this example is

$$I_{SS} = \frac{V}{R} = \frac{50}{6.82 \times 10^{-3}} = 7331 \text{ A}$$

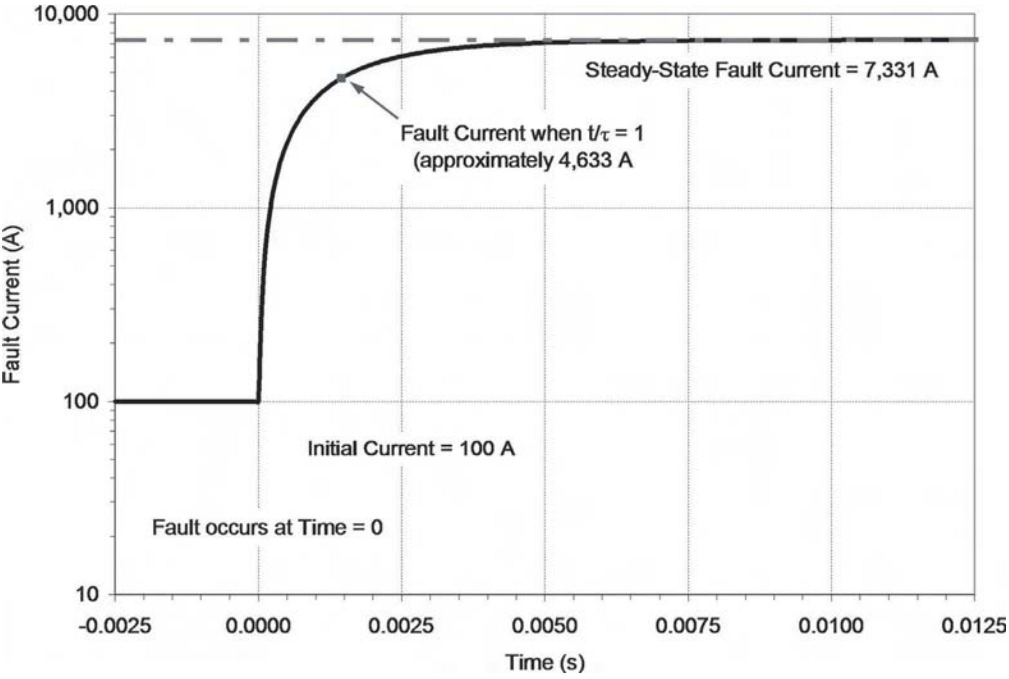

Fig. 5.43 Plot of fault current vs. time for Example 5.34.

When $t/\tau = 1$, the fault current has increased from its initial value of 100 A to 63.2% of its final steady-state value, or 4,633 A.

For steady-state fault analysis, only the circuit resistance is relevant. An equivalent circuit of a typical system is shown in Figure 5.44.

There are two basic types of faults—line-to-line and line-to-ground. A line-to-line fault includes both the feed and return conductors in the path from the fault to the current source (battery or rectifiers). A line-to-ground fault includes the ungrounded feed conductors from the fault to the current source, but only those return conductors from the current source to the point where they are bonded to ground. The remainder of the return fault path usually is not known in any detail, particularly in a common bonding network (CBN).

The dc power system design and installation directly affects the fault risk and the fault current magnitude. Figure 5.45 shows four fault scenarios for a typical dc power system.

Referring to Figure 5.45, any conductive object, such as a tool, may cause fault 1, shorting the current-carrying negative and positive buses (line-to-line fault). For purposes of analysis, the short circuit can occur anywhere along a parallel path consisting of the bus conductors, across rectifier output terminals and battery terminals, and distribution equipment and hardware.

Fault 2 is similar to fault 1 but the short occurs between the negative bus in a –48-V system (or positive bus in a +24-V system) and the equipment and frame grounds (line-to-ground fault). Such a fault has a higher probability of occurring than other scenarios because of the many opportunities for inadvertent grounding. This type of fault frequently is

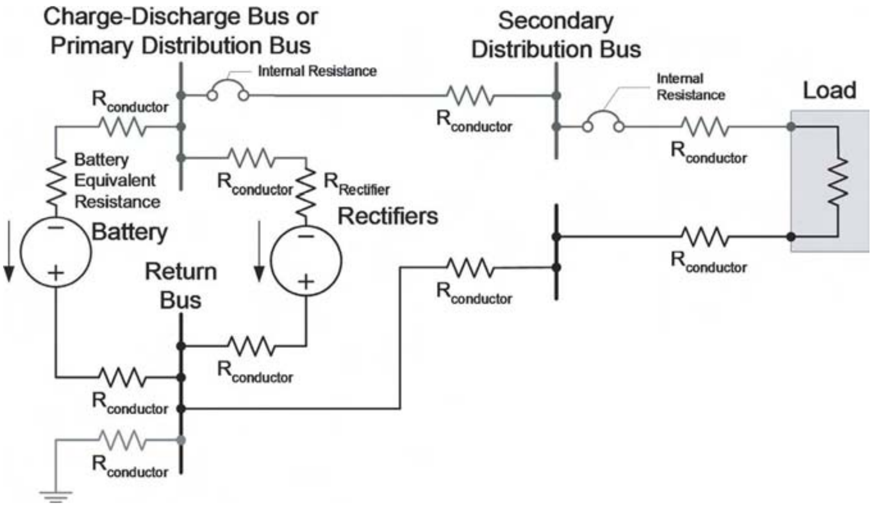

Fig. 5.44 The dc power system equivalent circuit (positive grounded system).

seen during cable mining operations, where old cables are being removed and the removal process damages the insulation of in-service cables. If an overcurrent protection device is installed at the battery, it would clear faults 1 and 2.

Fault 3 occurs between the load side of the primary or secondary distribution protection device and the return bus (line–line). Fault 4 occurs between the load side of the primary or secondary distribution device and the equipment and frame grounds (line–ground). Faults 3 and 4 differ from 1 and 2 in that overcurrent protection devices in the primary or secondary distribution circuits (depending on the fault location) should clear faults 3 and 4. The primary and secondary overcurrent devices are normally coordi-

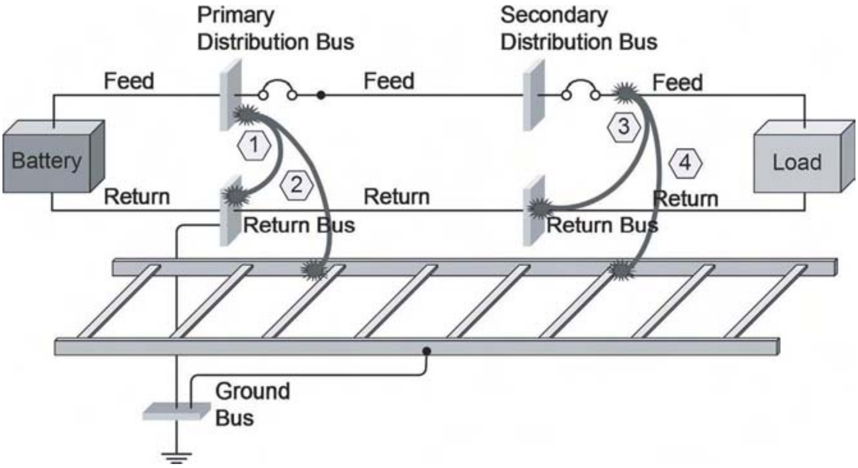

Fig. 5.45 Typical fault scenarios.

nated so they clear a fault with the minimum disturbance to system loads (i.e., they disconnect the minimum amount of equipment necessary to remove the fault from the system). The overcurrent devices and the distribution conductors feeding the loads are located close to each other and there are many opportunities for inadvertent short circuits during installation or removal.

Example 5.35 Calculate the fault current resulting from the fault shown in Figure 5.46. Assume the available fault current at the terminals of a 200-Ah, 48-V (24-cell) battery is 2000 A, the circuit conductor resistance from the battery to the powerboard is 0.013 Ω (equivalent to a total of 50 ft of 4 AWG conductor), the circuit conductor resistance from the powerboard bus to a line-to-line fault is 0.0105 Ω (equivalent to a total of 40 ft of 4 AWG wire), and the fault resistance is zero.

Solution By definition, a line-to-line fault is a short circuit between the feed and return leads and ground circuit resistances are not involved. The equivalent resistance of the battery is 48 V/2000 A, or 0.024 Ω. The total resistance to the fault is the battery equivalent resistance (0.024 Ω) plus the battery feed and return circuit conductor resistance (0.013 Ω) plus the distribution feed and return circuit conductor resistance (0.0105 Ω) plus the fault resistance (0 Ω), or 0.0475 Ω. The fault current will be 48 V/0.0475 Ω = 1010 A, a 50% reduction from the current available at the battery terminals.

The foregoing example assumes a line-to-line fault. In this case, the circuit conductor resistances include both the feed and return conductors between the battery and the fault. If the fault occurs line-to-ground, the fault return path and its resistance are not well defined. The return path includes the parallel resistance of all conductive components from the fault to the point where the battery circuit is bonded to ground. Since the battery circuit normally is not bonded to ground at the battery itself, the battery circuit conductor resistances (both feed and return) usually are included in the fault path. The fault path also can include cable supporting and equipment frame infrastructure, conductive building components, and equipment grounding conductors and will depend on the type of bonding network involved [common bonding network (CBN) or isolated bonding network

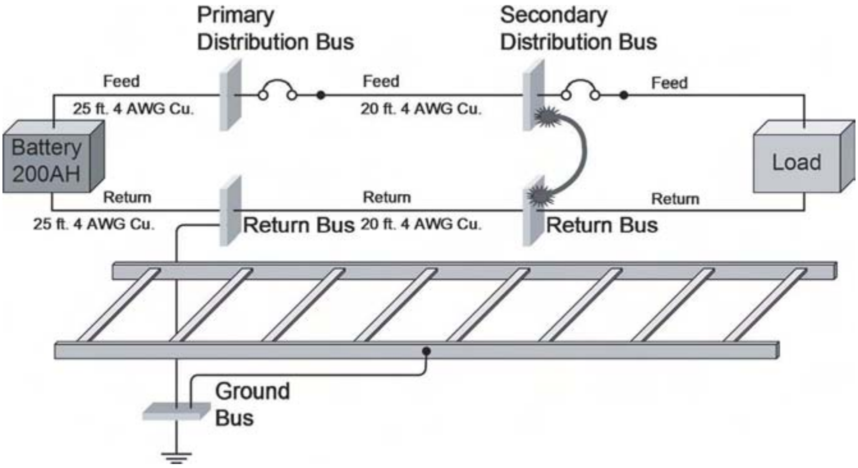

Fig. 5.46 Example 5.28 line-to-line fault.

(IBN)].[30] For worst-case calculations, the return path resistance is assumed to be 0 Ω, and that is the value to be used in calculations when more accurate information is not available.

Example 5.36 Calculate the fault current resulting from the fault shown in Figure 5.47. Assume the same conditions as the previous example except that the fault is line-to-ground.

Solution In this case, the circuit conductor resistance from the fault to the powerboard bus is 0.0053 Ω (equivalent to 20 ft of 4 AWG wire), the battery circuit resistance is 0.013 Ω (as before), and the fault resistance is zero. The resistance of the grounded metallic components, including all connections to the ground bus, is assumed to be zero (worst-case). The equivalent resistance of the battery is 0.024 Ω (as before), and the total resistance to the fault in this case is 0.0423 Ω. The ground fault current is 48 V/0.0423 Ω = 1,136 A, a 12% increase compared to the example line-to-line fault.

5.8.1.9 *Short-Circuit Heating of Conductors* Calculations of the conductor temperature rise during a short circuit normally assume that all the heat generated is absorbed by the conductor and none is lost by convection and radiation as would be for a conductor under continuous load. The temperature rise depends on the specific heat of the copper conductor material and its mass. Specific heat is the amount of heat energy per unit mass required to raise the temperature by one degree Celsius. The specific heat of copper increases as its temperature increases, and at normal ambient temperatures it is about 385 J/kg-K (0.092 Btu/lb-°F) and at 300°C is about 410 J/kg-K (0.098 Btu/lb-°F). The energy required to raise the temperature over small ranges is approximately

$$J = sm\,\Delta T \text{ joules}$$

where s = specific heat of copper (385 J/kg-K at normal ambient temperatures)
m = mass (kg)
ΔT = temperature increase (K)

Example 5.37 Determine the energy required to raise a 50-ft piece of 2 AWG copper conductor by 40°C from a normal ambient temperature. If the temperature is raised this amount over a 10-s period and none of the heat is radiated or convected away from the conductor, determine the current in the conductor.

Solution The equivalent diameter of a 2 AWG conductor is 0.292 in., or 7.42 mm, and the length is 50 ft, or 15,240 mm. The cross-sectional area is $\pi(d^2/4) = 43.2\ \text{mm}^2$, and the volume is $43.2\ \text{mm}^2 \times 15{,}240\ \text{mm} = 658{,}428\ \text{mm}^3$, or $0.000658\ \text{m}^3$. The density of copper is $8230\ \text{kg/m}^3$, so the mass of the conductor in question is $0.000658\ \text{m}^3 \times 8230\ \text{kg/m}^3$, or 5.42 kg (about 12 lb).

Assuming that the specific heat is constant over the temperature range, the energy is approximately 385 J/kg-K × 5.42 kg × 40°C = 83,450 J. Since 1 J = 1 Ws, the energy in electrical units is 83,450 Ws, or 23.2 Wh. The power required to raise the temperature

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[30] See Chapter 1 for a brief discussion and [46, 47] for a detailed discussion of common and isolated bonding networks.

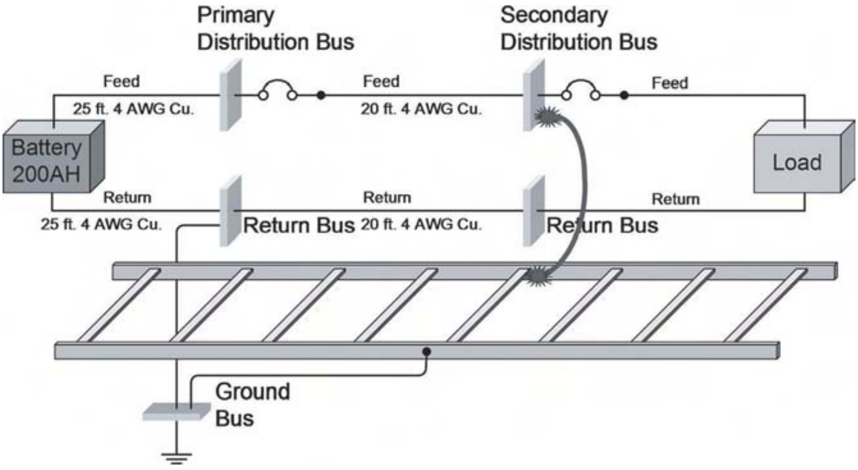

Fig. 5.47 Example 5.29 line-to-ground fault.

40°C over a 10-s period is 83,450 Ws ÷ 10 s = 8345 W. The power is dissipated in the conductor resistance and is given by $P = I^2R$.

The resistance of 2 AWG at 30°C is 0.00016525 Ω/ft and the total conductor resistance is 50 ft × 0.00016525 Ω/ft = 0.00826 Ω. Assuming it is constant over the temperature range of interest (it actually increases by about 16%), the current is approximately

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{8345}{0.00826}} = 1005 \text{ A}$$

The foregoing concepts of specific heat and the assumptions concerning heat radiation and dissipation can be generalized. The time required for the temperature to rise during a fault is approximately [45]

$$t = 0.051\left(\frac{A}{I}\right)^2 \left(\sqrt{1 + 0.0076\ \Delta T} - 1\right) \text{ s} \tag{5.97}$$

where t = maximum short-circuit time (s)
A = conductor cross-section area (mm^2) (to convert CM to mm^2, multiply CM by 0.000507)
I = Current (kA = A/1000)
ΔT = temperature increase (°C)

Example 5.38 Check the previous example using Eq. (5.97).

Solution The conductor cross-sectional area and current were found to be 43.2 mm^2 and 1005 A, respectively. For a 40°C temperature rise

$$t = 0.051\left(\frac{43.2}{1.005}\right)^2 \left(\sqrt{1 + 0.0076 \times 40} - 1\right) = 13.4 \text{ s}$$

The 30% difference indicates the approximate nature of this analysis.

If the allowable temperature rise is $\theta = 300°\mathrm{C}$, which is the maximum allowable for copper busbar under fault conditions, then Eq. (5.97) can be simplified to

$$t = 41.4 \times 10^{-3}\left(\frac{A}{I}\right)^2 \text{ s} \tag{5.98}$$

The value of t obtained from the above equation always should be greater than the required short-circuit withstand time. The withstand time typically is less than 1 s for circuits with overcurrent protection but can be several minutes for large battery circuits with no overcurrent device. Where $A/I > 4$, the rate of temperature rise is approximately [45]

$$\theta = 5.2 \times 10^{-3}\left(\frac{I}{A}\right)^2 \text{ °C/s} \tag{5.99}$$

Example 5.39 Determine rise time to 300°C in a 4/0 AWG copper conductor if the current is 6000 A.

Solution The cross-sectional area of a 4/0 AWG conductor is 211,600 CM, or 107.3 mm^2. The rise time to 300°C is approximately

$$t = 4.14 \times 10^{-2}\left(\frac{107.3}{6}\right)^2 = 13.2 \text{ s}$$

5.8.1.10 Selective Coordination of Overcurrent Protective Devices

Three methods have been used to perform selective coordination analysis in power systems:

- Overlaying printed delay characteristic curves on a light table and hand plotting on log–log paper
- Using computer software to display the curves and select overcurrent devices
- For fuses, using published selectivity ratios

No computer software is available for low-voltage fuses or circuit breakers used in telecommunications applications, nor are published fuse selectivity ratios available. This leaves hand plotting as the only alternative.

Selective coordination analysis requires published delay characteristic curves for dc. The ac delay characteristic curves cannot be used for devices that are rated both ac and dc without first verifying with the manufacturer. Also, delay characteristic curves normally represent average conditions and do not show the minimum/maximum time values for any given current amplitude. This means that, absent specific information from the device manufacturer, a number of assumptions have to be made.

The following discussion covers fuse–fuse coordination, circuit breaker–circuit breaker coordination, and fuse–circuit breaker coordination.

Fuse–Fuse Coordination For a given type of fuse (TPL, TPS, or TPN), selective coordination generally can be achieved by using a 2 : 1 ratio in their current ratings. For example, a 400-A TPL fuse generally will coordinate properly with a 200-A TPL fuse, and a

70-A TPS fuse generally will coordinate properly with a 35-A TPS fuse. The same can be said about coordination between TPL and TPS fuse types (a 100-A TPL fuse will coordinate with a 50-A TPS fuse; see Fig. 5.48).

Circuit Breaker–Circuit Breaker Coordination As mentioned in Chapter 3, DC Power System Components, circuit breakers with the delay 52 curve are most common in telecommunications, and that curve will be used here. Because of the trip time variations for any given current value, two circuit breakers with even a high ratio of current ratings will not coordinate for all fault currents. For example, as seen in Figure 5.49, a 50-A circuit breaker does not coordinate for any fault currents with a 100-A circuit breaker because the delay curves overlap. The same 50-A circuit breaker will barely coordinate with a 200-A circuit breaker at 250 A (the lower trip curve for the 200-A circuit breaker brushes against the upper trip curve for the 50-A circuit breaker at 250 A), but for currents above 350 A, the curves for the two breakers overlap.

Fuse–Circuit Breaker Coordination Fuses do not coordinate with delay 52 circuit breakers unless the current ratios are > 4, and even then the delay curves can overlap at high current levels (Fig. 5.50).

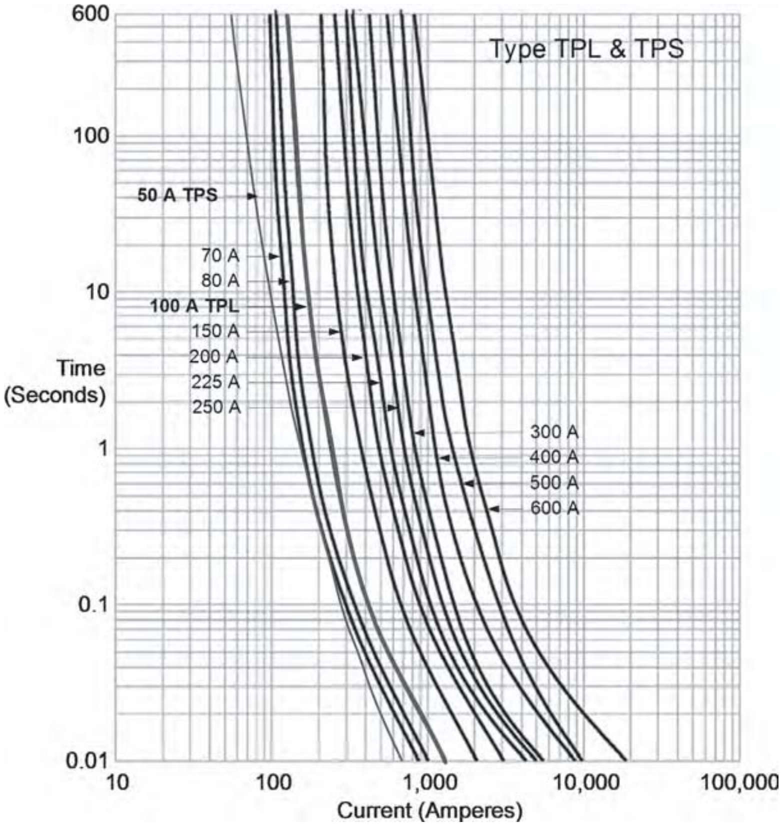

Fig. 5.48 Fuse–fuse coordination (100-A TPL and 50-A TPS).

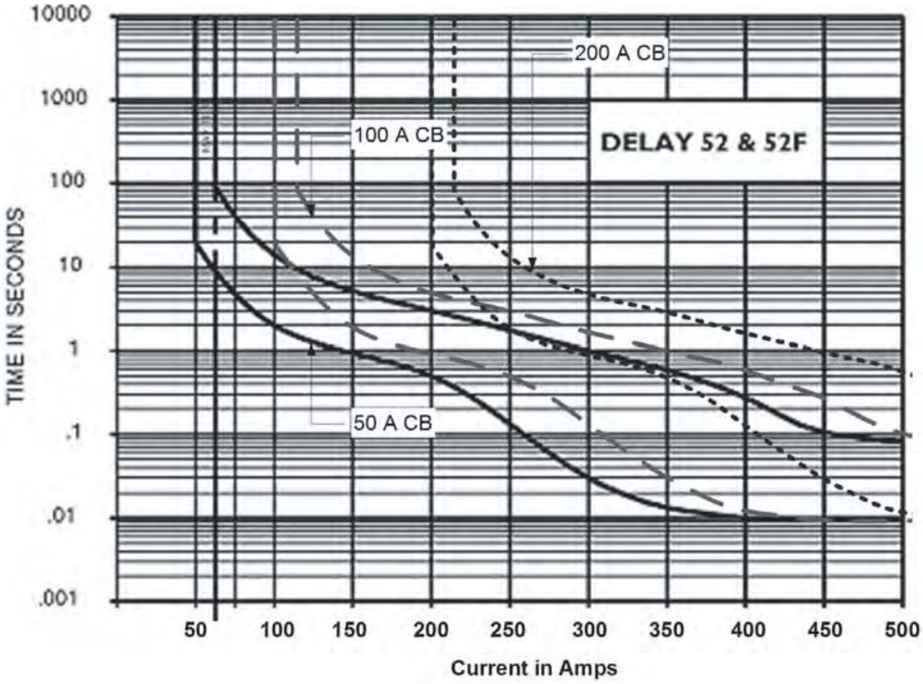

Fig. 5.49 Circuit breaker–circuit breaker coordination (200, 100, and 50 A delay 52).

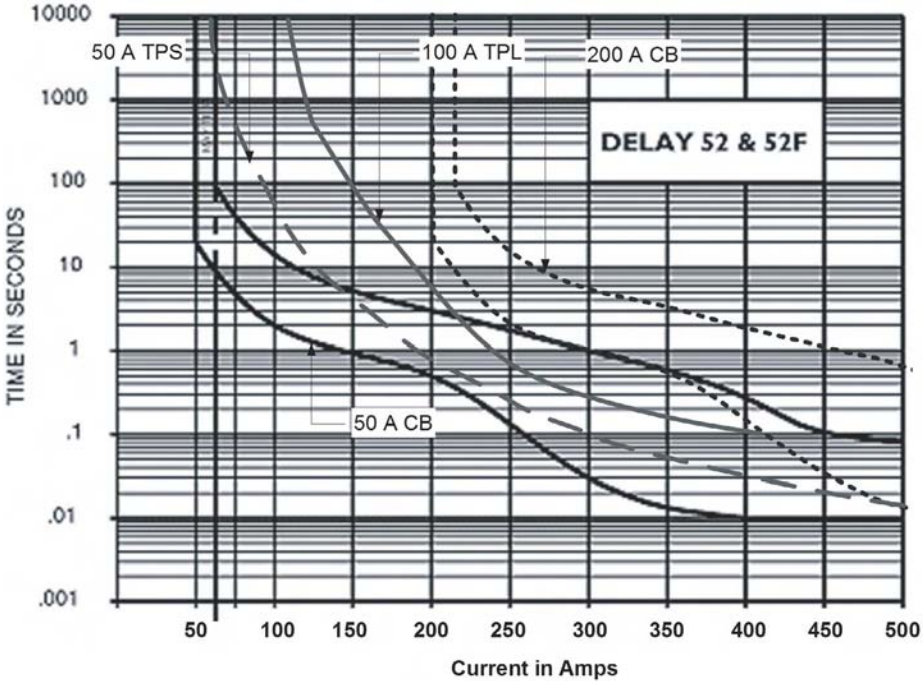

Fig. 5.50 Fuse–circuit breaker coordination (200 A delay 52 circuit breaker, 100-A TPL fuse, and 50-A TPS fuse).

5.8.2 Circuit Design Procedures

The circuit design procedures described in this section take into account the foregoing discussions on wire and busbar conductors. Each circuit is designed with its specific requirements in mind. The basic steps are to independently determine:

- Conductor size needed to meet voltage drop requirements
- Conductor size needed to meet current rating requirements

The conductor size selected for that circuit is the larger of the two. Other circuit design considerations include selecting wire or rigid busbar and determining conductor termination requirements and routing. Some additional considerations are required for battery circuits, and these are described in the next section.

Manufacturers usually recommend the overcurrent device rating for circuits feeding their equipment. Where the manufacturer does not recommend a circuit rating but does provide load amperage or wattage ratings, the overcurrent device is chosen to avoid false tripping. Generally, the rating is 150 to 200% of the maximum load current. In some cases, the manufacturer may specify that the overcurrent device not exceed a certain rating, thus providing a boundary of ratings that must be observed. The conductor current rating must be at least as high as the overcurrent device rating.

The voltage drop used to size circuit conductors is the segment voltage drop. Each segment must be coordinated with the voltage drop in the other segments so that the end-end circuit does not exceed maximum total voltage drop (Fig. 5.51).

5.8.2.1 Circuit Design Summary The following steps allow systematic circuit design:

Rectifier and Distribution Circuits (Table 5.27):

1. List the normal and peak load currents for each circuit in columns (2) and (3), respectively. Normal currents are for reference and are at normal system operating voltage. Peak load currents are used to size conductors and are at an average discharge voltage somewhat less than normal operating voltage. See Section 5.1.4.2.
2. Indicate the design voltage drop for each circuit in column (4). The voltage drop in any given circuit segment depends on how the total voltage drop from battery terminals to load equipment terminals is allocated. See Section 5.8.1.5.
3. Calculate the minimum wire size that meets the peak current rating requirement for each circuit and list in column (5). Wire current rating = 1.25 × column (3). See Section 5.8.1.6.
4. Calculate the minimum wire size that meets the voltage drop requirement for each circuit and list in column (6).
5. Select the larger of the two wire sizes for each circuit and indicate in column (7).
6. Indicate the circuit breaker or fuse rating for each circuit in column (8). Standard fuse and circuit breaker sizes are tabulated in Tables 5.28 and 5.29. Check that the fuse or circuit breaker panel will accept the size in question.

Battery Circuits (see also Section 5.8.3) (Table 5.30):

1. Indicate the maximum battery circuit current in column (2). The maximum battery circuit current occurs during battery recharge after a discharge and equals the max-

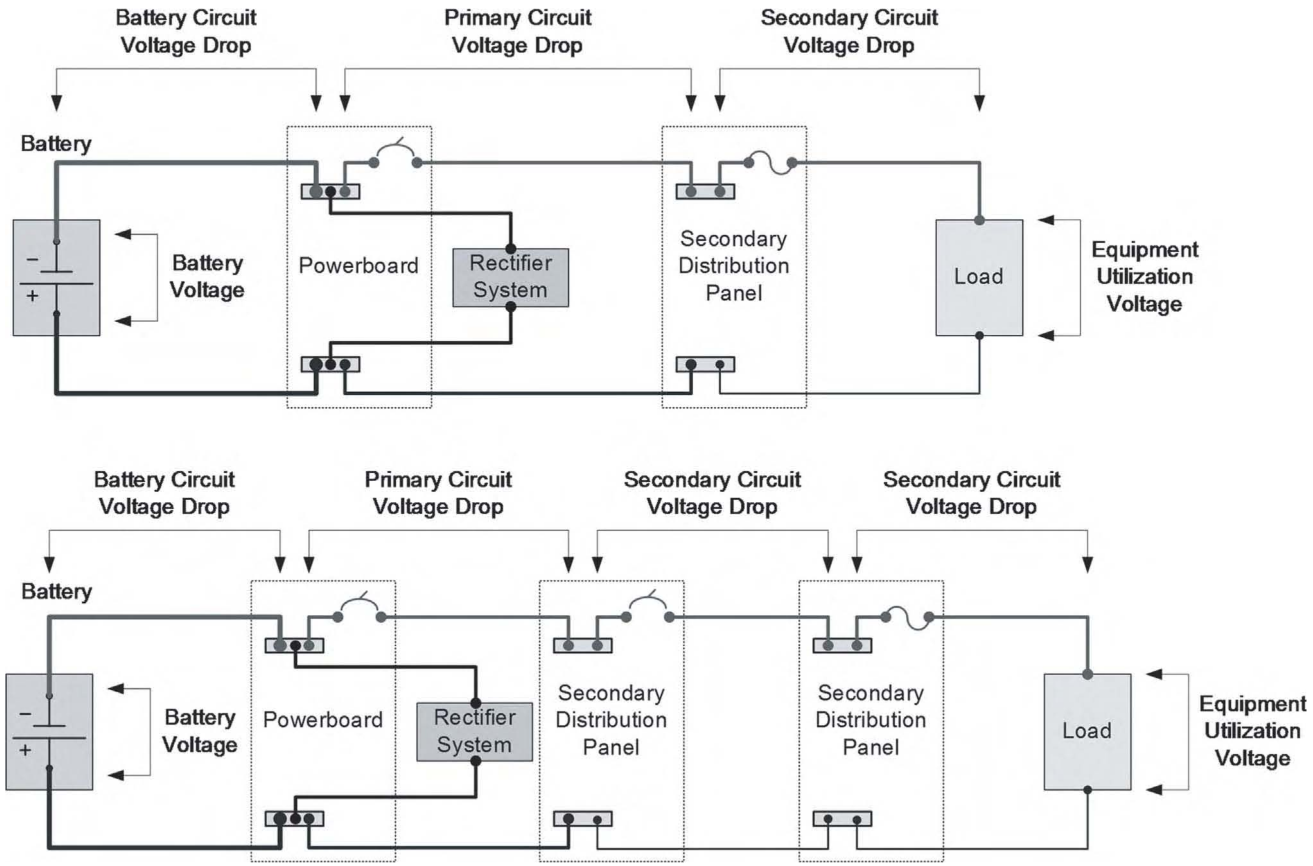

Fig. 5.51 Segment voltage drops. The total voltage drop of all segments must not exceed the total specified for the system operating voltage.

Table 5.27 Distribution Circuits

Circuit Number (1)	Normal Load Current (A) (2)	Peak Load Current (A) (3)	Design Voltage Drop (V) (4)	Minimum Wire Size		Selected Wire Size (7)	Fuse or Circuit Breaker Size (A) (8)
				Current (5)	Voltage Drop (6)		
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
Totals							

Table 5.28 Standard Alarm Indicating Fuse Ratings

Rating (A) GMT	Color	Rating (A) Type 70	Color
18/100	Yellow	1/10	Gray & white
1/4	Violet	15/100	Red & white
3/8	White & gray	18/100	Yellow
1/2	Red	2/10	Black
65/100	Black	1/4	Violet or violet & white
3/4	Brown	1/2	Red
1	Gray	3/4	Brown
$1\frac{1}{3}$	White	1	Pink
$1\frac{1}{2}$	White & yellow	$1\frac{1}{3}$	White
2	Orange	2	Orange
3	Blue	3	Blue
$3\frac{1}{2}$	White & blue	$3\frac{1}{2}$	Black & white
4	White & brown	5	Green & black
5	Green	6	Green & white
$7\frac{1}{2}$	Black & white	8	Brown & white
10	Red & white	10	Violet & yellow
12[a]	Yellow & green		
15[a]	Red & blue		
4AB (125 V and 250 V)[b]		**TPL**	
1, 2, 3, 5, 8, 10, 15, 20, 25, 30 A		70, 100, 150, 200, 225, 250, 300, 400, 500, 600 A	
TPN			
1, 3, 5, 6, 10, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 110, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500, 600 A			
TPS			
1, 2, 3, 5, 6, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70 A			

[a] Do not use unless fuse holder is rated 15 A.

[b] Use in existing fuse panels only; do not use 4AG glass cartridge fuses.

Table 5.29 dc Circuit Breaker Ratings (Typical for Telecommunications Applications)[a]

1	20	50	125	300	700
3	25	60	150	350	800
5	30	70	175	400	1000
7.5	35	80	200	450	1200
10	40	90	225	500	1600
15	45	100	250	600	2000

[a] Not all sizes may be available from a given manufacturer, and sizes not listed may be available from some manufacturers.

imum rectifier system current. The battery will draw the maximum rectifier current until its voltage increases and its current acceptance decreases. Also, the low-voltage disconnect, if equipped, will engage, reconnecting the load, when the bus voltage increases to the LVD reconnect threshold. At this point, the rectifier system current may again increase to its maximum value. In any case, the maximum rectifier system current determines the current rating of the battery circuit conductors.

2. Indicate the design voltage drop for the battery circuit in column (3). This is the maximum allowable voltage drop in the battery circuit segment during discharge. See Section 5.8.1.5.
3. Calculate the minimum wire size that meets the current rating requirement for each battery string. Under maintenance conditions, any battery string may be subjected to the maximum rectifier system current; therefore, no current sharing by the battery strings is assumed. Indicate this wire size in column (4). Wire current rating = 1.25 × column (2). See Section 5.8.1.6.
4. Calculate the minimum wire size that meets the voltage drop requirement for each battery circuit and list in column (5).
5. Select the larger of the two wire sizes for each battery string and indicate in column (6). If the conductor lengths are the same to all battery strings, all circuits would use the same conductor size and have the same voltage drop. However, battery strings may be different distances and different conductor sizes may be needed in practice.
6. Calculate the actual voltage drop in each battery string circuit based on the selected conductor size in column (6). If the voltage drops do not match within 5%, increase conductor sizes or adjust conductor lengths to match. Recheck voltage drops.

Table 5.30 Battery Circuits

			Minimum Wire Size			
String Number (1)	Battery Current (A) (2)	Design Voltage Drop (V) (3)	Current rating (4)	Voltage Drop (5)	Selected Wire Size (6)	Battery Circuit Connection Method and Rating (A) (7)
1						
2						
3						
4						
5						

7. Indicate the battery connection method in column (7) for reference (see Section 5.8.3.1).

5.8.3 Battery Circuits

In addition to the design steps just described for distribution circuits, battery circuits require several other considerations, which are described in the following sections.

5.8.3.1 Battery Connection Methods A number of methods are available for terminating and connecting battery circuits. The method chosen for any particular application depends on a number of factors. There is no single best method.

Current can flow in either direction in a battery circuit depending on whether the battery is charging or discharging. The bi-directional characteristic complicates the circuit design in terms of overcurrent protection and service reliability. In general, there are two competing objectives in battery circuit design:

- Minimize the possibility of human injury and building and equipment damage during battery circuit electrical faults.
- Minimize battery service interruptions.

A battery circuit consists of a connection device at or close to the battery terminals, circuit conductors, and another connection device at the powerboard or battery charge bus (Fig. 5.52). The connection device can be a simple bolted direct connection (rigid busbar with Z-bent section or fine-strand wire with terminal connector lugs) or can include a switch or an overcurrent protection device. A switch or overcurrent protection device, if used, can be connected to only the ungrounded conductors in the circuit, using a one-pole device, or both the ungrounded and grounded conductors, using a two-pole device. Where a one-pole device is used, the grounded return circuit conductors (positive polarity on –48-Vdc systems and negative polarity on +24-Vdc systems) use a bolted direct connection at both ends.

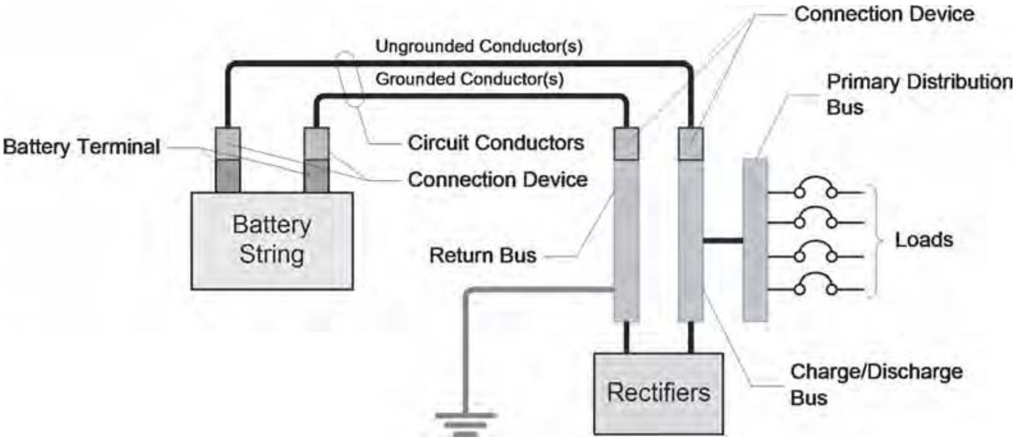

Fig. 5.52 Battery circuit connections.

Table 5.31 shows various devices and whether they provide overload protection, short-circuit protection, and disconnection and whether they are subject to false tripping and have remote disconnection capability. Although shown in the table, fuses seldom are used because of the need for isolation switches and the time involved in replacing them (compared to resetting a circuit breaker). However, current-limiting fuses may be required as part of a circuit breaker or switch assembly where high fault currents exceed the circuit breaker interrupt rating or switch withstand rating.

Remotely controlled disconnects are used to trip a circuit breaker or molded case switch from a remote location, typically at the entrance to the battery room or at the powerboard. Local fire codes may require a remote disconnect or the local fire marshal may request it be installed. Circuit breakers and switches are available that are specifically designed for battery circuit applications, and they can be ordered with other features such as remote position indication and remote reset and for mounting on the battery rack or wall.[31]

The battery circuit can carry current in two directions—from the battery during discharge or from the powerboard charge bus during recharge (Fig. 5.53). It is difficult to design reliable bi-directional overcurrent protection on such a circuit, especially when the currents in the two directions can be significantly asymmetric. It is for this reason that overcurrent protection seldom is used on battery circuits unless electrical codes or other engineering considerations require it. If used, the overcurrent protection device or devices must be rated for operation with bi-directional currents.

Where multiple battery strings are used, each string should be equipped with a dedicated disconnect switch so an individual string may be isolated during maintenance. An installation with a single battery string may or may not have a disconnect switch, and the disconnect may or may not have overcurrent protection capabilities.

Figure 5.54(a) shows two possible bus and overcurrent protection configurations with one-pole overcurrent protection at the battery end of the circuit and disconnect switches at the bus end. Figure 5.54(b) shows similar battery configurations with one-pole disconnect switches at the battery end and direct connection at the bus end. Figure 5.54(c) shows configurations with two-pole circuit breakers and two-pole disconnect switches, respectively.

5.8.3.2 Battery Disconnect Switches and Circuit Breakers

Battery disconnect switches generally are found in three forms—enclosed knife switch, also known as a safety switch, fused contactor [Fig. 5.55(a)] and molded case switch [Fig. 5.55(b)]. The latter looks similar to a molded case circuit breaker, which also may be used as a battery disconnect [Fig. 5.55(c)]. The knife switch and molded case switch, by definition, do not have a built-in *overload* trip mechanism. However, unlike the enclosed knife switch, the molded case switch may be equipped with an *instantaneous* trip mechanism (and called an instantaneous trip circuit breaker). The instantaneous trip mechanism monitors the load current and opens during a short circuit but not during an overload.[32] The enclosed fuse contactor is a large relay that uses a fuse to limit fault currents.

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[31] See, for example, Airpax Power Protection Products of Cambridge, MD, Electric Equipment & Engineering Company of Denver, CO, and Cutler-Hammer of Moon Township, PA.

[32] Note that a molded case thermal circuit breaker has an overload sensing mechanism that monitors the thermal energy passing through it and opens when the rated current is exceeded for the period of time specified by its time–current or delay characteristic curve. See Chapter 3, DC Power System Components.

Table 5.31 Battery Connection Devices

Device	Overload	Short Circuit	Disconnect	Potential False Tripping	Remote Disconnect
Direct connection	No	No	No	No	No
Circuit breaker without shunt trip	Yes	Yes	Yes	Yes	No
Circuit breaker with shunt trip	Yes	Yes	Yes	Yes	Yes
Fuse without switch	Yes	Yes	No	Yes	No
Fuse with switch	Yes	Yes	Yes	Yes	No
Enclosed knife switch	No	No	Yes	No	No
Molded case switch without instantaneous current trip	No	No	Yes	No	No
Molded case switch with instantaneous current trip	No	Yes	Yes	No	No
Molded case switch with shunt trip	No	Yes	Yes	No[a]	Yes

[a] A molded case switch with shunt trip is subject to *inadvertent* or *accidental* tripping (caused by a failure in the trip circuitry or human error).

A disconnect switch normally is located adjacent to or on the battery string. It must be able to carry (withstand) the available fault current, but it is not required to interrupt the fault current unless the switch could open during a fault. Three parameters are used to specify a disconnect switch:

- Voltage rating
- Nominal operating current rating
- Withstand current rating.

Switches used in 24- and 48-Vdc telecommunications systems are rated 60-Vdc class or

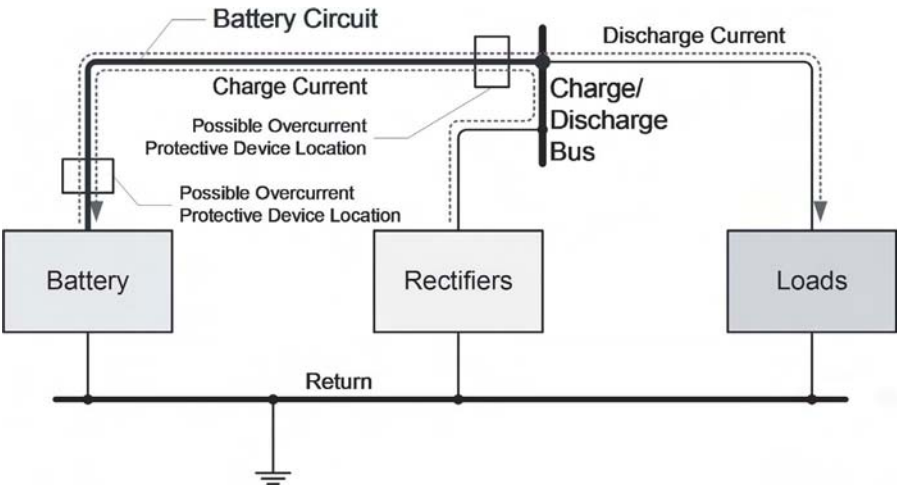


Fig. 5.53 Battery circuit current directions.

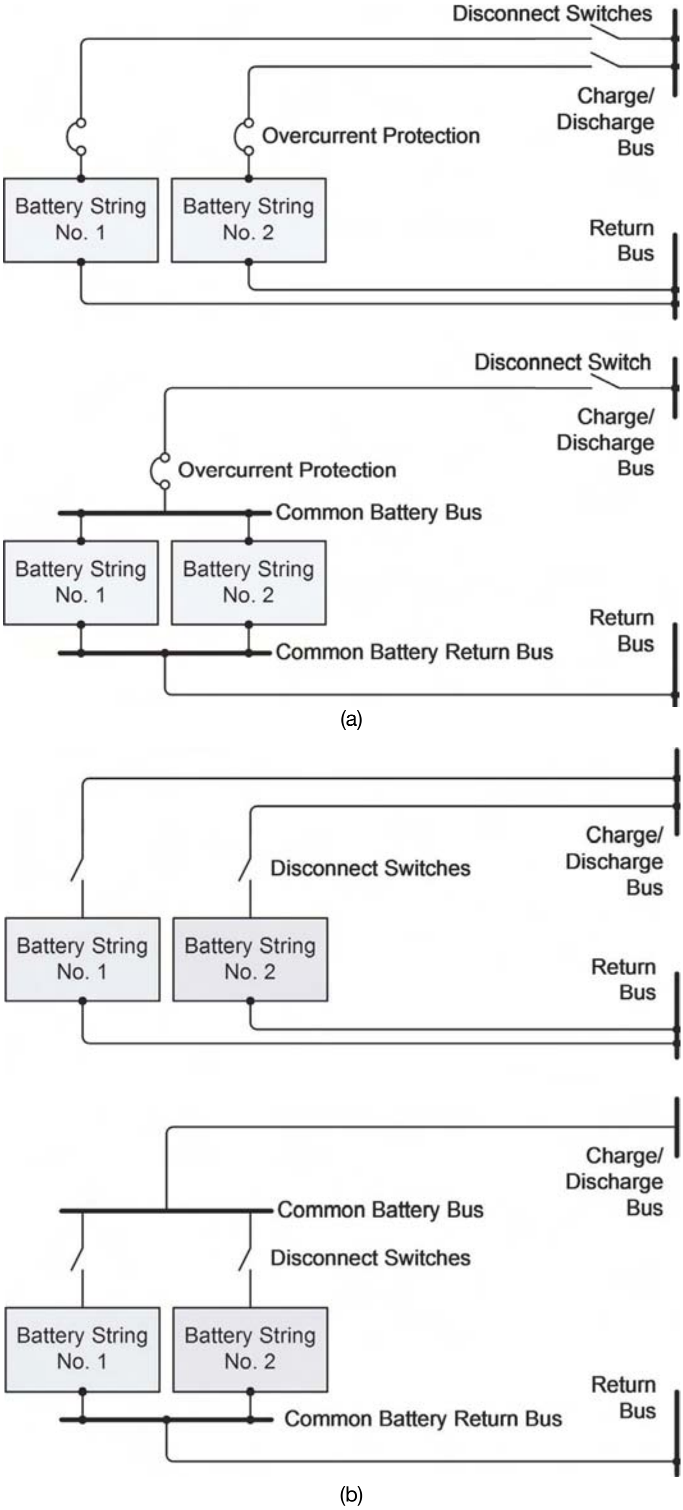
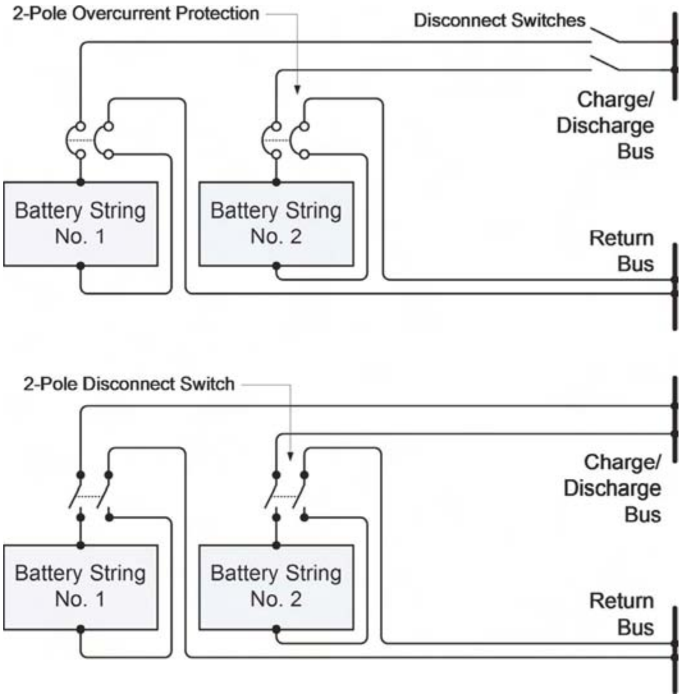


Fig. 5.54 (a) One-pole overcurrent protection at battery. (*Upper*) One circuit breaker for each battery string; (*lower*) one circuit breaker for entire battery system (not recommended). (b) One-pole disconnect switches at battery. (*Upper*) One disconnect switch for each battery string; (*lower*) collector bar with one disconnect for each battery string.



(c)

Fig. 5.54 (c) Two-pole circuit breakers and two-pole disconnect switches at battery. (*Upper*) Two-pole circuit breaker for each battery string; (*lower*) two-pole disconnect switch for each battery string.

higher. Operating current rating will depend on the required currents during battery discharge and recharge. The withstand current rating will depend on the short-circuit currents available from the battery system. The withstand current is the current the device will carry and remain operable without damage (however, a device subjected to its rated withstand current probably will require replacement and, in fact, such replacement may be recommended by the device manufacturer).

A circuit breaker is similar to a molded case switch, but the circuit breaker also includes an overload trip mechanism. A similar set of parameters is used to specify a circuit breaker:

- Voltage rating
- Nominal operating current rating
- Interrupt rating

The voltage and operating current ratings are the same as described for the switch. The interrupt rating is similar to the withstand current rating, but in this case it is the current the device can interrupt during a fault (a circuit breaker must be able to safely interrupt a fault in progress, whereas a switch is not expected to interrupt a fault in progress).

The interrupt rating is the highest current the device can interrupt without damaging the device or its surrounding structure or injuring people. When the device tries to interrupt a higher-than-rated current, the device may (1) successfully interrupt the current, (2) weld closed, (3) open without extinguishing the arc, or (4) open but not be able to dissipate the arc energy. The first is the goal of a successful design while the latter three are unacceptable and are safety risks.

5.8.3.3 Battery Connection Device Selection and Sizing

The selection of a battery connection device should account for the following factors:

- Probability of a fault occurring
- Costs of the connection device
- Consequences of a fault
- System availability requirements
- Battery current under normal discharge conditions
- Rectifier charging current
- Fault current magnitude
- Coordination with downstream protection devices

The probability of a short or failure in the battery circuit is lower where circuit conductors are not very long and are not exposed to physical damage (such as when they are enclosed in conduit) and are insulated or covered at their terminations. The risk is higher on long runs and where terminations and conductors are exposed.

An overcurrent protection device at the battery should be considered in the following situations:

- Probability of a fault occurring is high.
- The costs or adverse operational and safety consequences resulting from an uncleared fault are high.
- The consequences of false tripping are not significantly adverse.
- NEC requirements apply to the installation.
- The facility is unattended in a remote location or may require a long response time.

An overcurrent protection device normally is not used in the following situations:

- Risk of a fault occurring is low, such as in most central office environments.
- The consequences of false tripping are significantly adverse.
- Circuit equipment and installation costs are an overriding consideration.
- Circuit conductors and terminations are protected from accidental short circuits under all operating and maintenance conditions.

If the connection device consists of a switch, with or without overcurrent protection, it should be capable of remote position indication through a contact closure. Some circuit breaker types provide an indication only when tripped open due to an overload and not when manually opened. While this feature eliminates alarms when the switch needs to be manually opened, it does not guard against problems with the switch being opened and then forgotten.

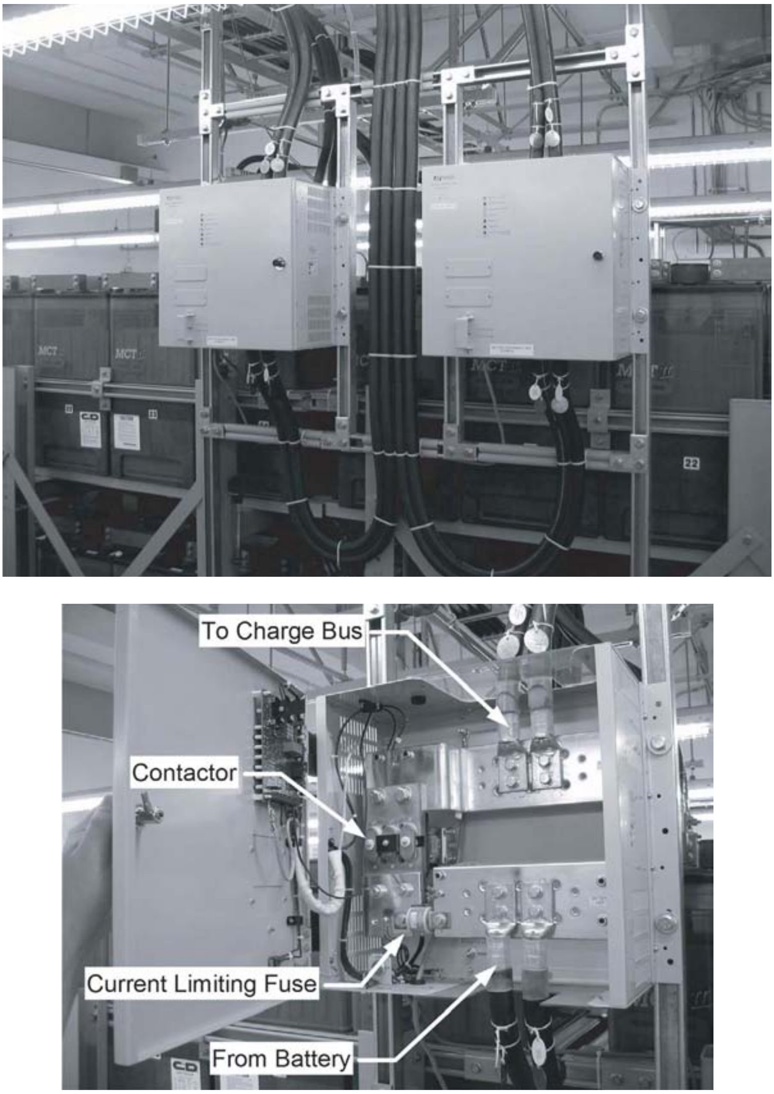
One of the basic requirements of electrical circuit design is that conductors be protected from overcurrent and that the overcurrent protection device be located at the current source. In most central office applications, to which the National Electrical Code (NEC) does not apply, the battery connection device does not include overcurrent protection. Historically, there have been few catastrophic (although not zero) failures in properly designed and maintained battery circuits in central office environments. However, battery circuit overcurrent protection is required in applications covered by the NEC.

The 2005 edition of the NEC [29] Article 90.2(B) lists installations *not* covered by the NEC Par. 90.2(B)(4): “Installations of communications equipment under the exclusive control of communications utilities located outdoors or in building spaces used exclusively for such installations.” An example of such an installation is a network operator’s central office. Battery installations in all other facilities are covered by article 480 of the 2005 edition of the NEC. Article 480.3 says “Wiring and equipment supplied from storage batteries shall be subject to the requirements of this *Code* applying to wiring and equipment operating at the same voltage, unless otherwise permitted by 480.4.” Article 480.4 applies only to starting and ignition batteries for “prime movers” such as engines. Article 240.4 applies to protection of conductors and states that “Conductors . . . shall be protected against overcurrent in accordance with their current ratings specified in 310.15, unless otherwise permitted or required in 240.4(A) through (G).” The cited paragraphs, 240.4(A) through 240.4(G), do *not* apply to telecommunications applications.

Protection of battery circuits is discussed in additional detail in [48]. Overcurrent protection devices in battery circuits are subject to false tripping and almost always reduce overall system availability. A battery circuit overcurrent protective device that has tripped open may go undetected until an ac service outage occurs that affects the rectifiers. Therefore, if an overcurrent device is used in a battery circuit, it should have a trip indicator and contacts that can be connected to an alarm indicating and reporting system.

The minimum current rating of the battery connection device and battery circuit conductors is determined by the worst-case battery current. If the system is equipped with a low-voltage disconnect, the worst-case battery charge current occurs when the battery is fully discharged and ac power is restored after an outage but before the low-voltage disconnect reconnects the load. In this situation battery current acceptance is highest and rectifiers provide the maximum possible current to the battery (the rectifiers operate in their current-limiting mode because a discharged battery looks like a short circuit to the rectifiers). The total rectifier current will depend on the number and rating of the rectifiers. When calculating charging currents, it is necessary to take into account the maximum possible rectifier capacity including the installation of rectifiers to fill initially unused slots in modular rectifier shelves and the addition of rectifier shelves as the load grows. Note that the worst-case battery charge current always is higher than the worst-case discharge current because the rectifiers must have extra capacity, as much as or higher than 50 to 100%, to simultaneously recharge the batteries and power the loads.

Where the system is not equipped with a low-voltage disconnect, the rectifier system provides current to both the dead battery and load equipment. However, since most modern load equipment uses switch-mode power supplies, the equipment load will be small during the initial charging stage (when bus voltage is below the threshold for the power

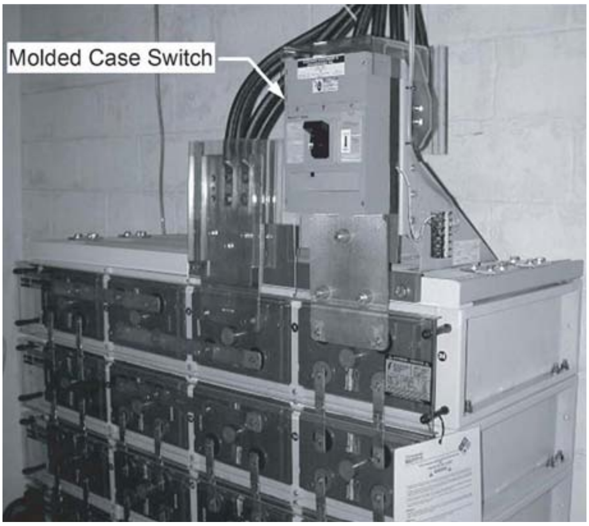


(a)

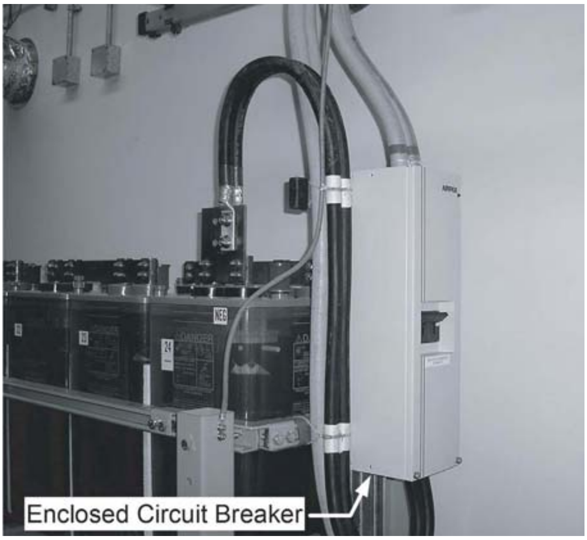
Fig. 5.55 Battery disconnect devices: (a) enclosed battery disconnect contactor mounted on channel strut on the side of a battery rack (*upper*); cabinet door open showing components (*lower*). (Photos courtesy of Argus Technologies.)

supplies), and the battery system will accept almost all rectifier current as described in the previous paragraph. The load current will increase as equipment power supplies are activated. The initial conditions dictate that battery circuits carry the maximum available rectifier system current.

All rectifiers used in telecommunication applications have integral output circuit breakers, and the fault current from the rectifiers will be limited to the overload capability of the rectifier output circuits or the circuit breaker rating, whichever is smallest. There-



(b)



(c)

Fig. 5.55 Battery disconnect devices: (b) Molded case switch. (Photo courtesy of Electric Equipment & Engineering Company.) (c) Enclosed circuit breaker.

fore, an external circuit breaker is not normally used in the battery circuit at the discharge bus.

The currents described above are significantly higher than normal battery circuit operating currents. During normal conditions the battery circuit carries only float current. The float current depends on the battery technology and capacity rating but is in the few milliamperes to few hundred milliamperes range per 100-Ah battery capacity. Float current increases with battery age but never approaches charge or discharge current magnitudes.

If an overcurrent protection device is used in the battery circuit, the protection device rating usually is at least 150 to 200% of the worst-case charge current (total rectifier current capacity at current limit). Where overload protection is avoided because of the potential for false tripping, a short-circuit protection device (instantaneous trip circuit breaker) may be desirable to protect against short-circuit currents.

Example 5.40 Determine the battery overcurrent device rating for the circuit in Figure 5.56 and the following conditions:

- Equipment load = 40 A (worst case)
- Modular rectifier system = (2) online 50-A rectifiers [total capacity of (4) 50-A rectifiers]
- Battery capacity 200 Ah
- Battery reserve time = 4 h

Solution The 200-Ah battery used in this example can deliver 46 A at 77°F (25°C) for 4 h. From Figure 5.42 the short-circuit current available from a 200-Ah battery is approximately 1500 A. The configuration provides $N + 1$ rectifier redundancy such that if one rectifier fails, the other can carry the load plus provide some charging current to the battery. Because the rectifier system is modular, it will be easy to add two more rectifiers for a nominal output current capability of 200 A.

Because a battery overcurrent device is used in this example, it is oversized by 150% to prevent false tripping. The maximum current in the battery circuit during recharge will be 200 A (assuming the rectifiers are adjusted to limit output current to 50 A). Therefore, the minimum current rating for the battery circuit protection device in this example would be 300 A (1.5 × 200 A). In this case, the required rating is a standard size, but if the calculated rating is not a standard size, the rating must be increased to the next larger standard size. In this example, the device must be able to interrupt a fault current of at least 1500 A, and the conductors between the battery and the charge bus must be rated at least 300 A.

Good design practice (and NEC requirements, where applicable) requires that conductor current rating be increased to at least 125% of the continuous current and that temperature and other correction factors be applied when determining conductor size. If an oversized protection device is used to prevent false tripping, the conductors must be oversized to match the protection device rating.

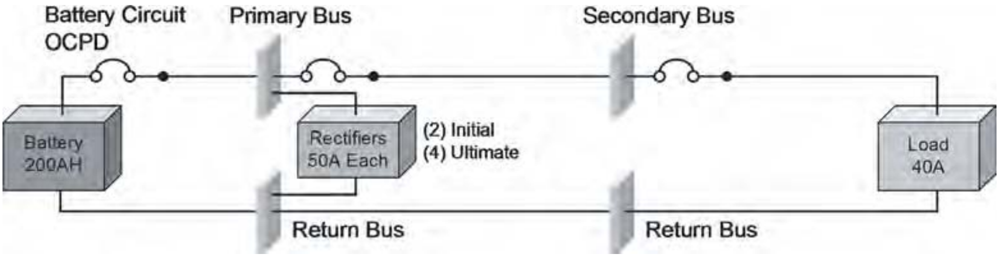


Fig. 5.56 Circuit for Example 5.33.

All devices in the battery circuit must be able to safely carry fault current. They must have the mechanical strength to withstand electromagnetic reaction forces during a fault as well as have the electrical and temperature ratings to withstand the fault current levels.

The choice between a one-pole and two-pole battery disconnection device is based on the operational and maintenance requirements. If it is desirable to simply provide a means to isolate the ungrounded circuit from the battery for cell replacement or capacity testing, a one-pole device is sufficient. However, if it is desirable to completely isolate both battery terminals so that insulation resistance measurements may be made between the battery terminals and ground, a two-pole device is required.

5.8.3.4 Battery Overcurrent Protection Device Characteristics and Coordination Typical ratings for devices used in battery circuits are 200, 400, 600, 1200, 1600 and 2000 A (other values are available). If a battery circuit has overcurrent devices at each end, it usually is impossible to predict which one will open when there is a fault in the battery circuit (i.e., a fault somewhere between the protection device at the battery and the protection device at the discharge bus). Similarly, with parallel battery strings and an overcurrent protection device on each string, it is almost impossible to ensure coordinated operation.

In addition to the coordination issue, an operational problem exists with overcurrent protection (circuit breakers) on parallel battery strings. If one of the battery strings is taken offline for maintenance and allowed to self-discharge or is discharged for any other reason, large currents will flow into the battery string when its circuit breaker is closed. This may cause the circuit breaker to immediately trip or it may trip later from the high charge currents. Such a problem can be eliminated if the offline battery string is precharged to the same potential as the online strings prior to closing the circuit. Chapter 6, System Installation and Maintenance, describes a simple precharge technique.

Example 5.41 A system consists of three battery strings. Either one main disconnect switch or three switches (one for each battery string) are to be installed. Determine the switch ratings for both scenarios for the circuit in Figure 5.57 and the following conditions:

- Initial and ultimate equipment load = 170 A (worst case)
- Initial rectifier system = (1) rectifier shelf with (4) online 50-A rectifiers
- Ultimate rectifier system = (2) rectifier shelves with (8) online 50-A rectifiers
- Initial and ultimate battery = (3) strings at 680-Ah capacity each

Solution Single main disconnect switch—The dc power system is designed to meet initial and ultimate requirements. Two rectifier shelves are installed but only (4) rectifiers are initially equipped. Three battery strings are initially installed to meet the reserve requirement. Each 680-Ah battery string can deliver 85 A at 77°F (25°C) for 8 h. From Figure 5.42, the short-circuit current available from each battery string is approximately 5000 A. The maximum charging current available to the battery is initially 200 A (4 × 50 A) but ultimately 400 A (8 × 50 A).

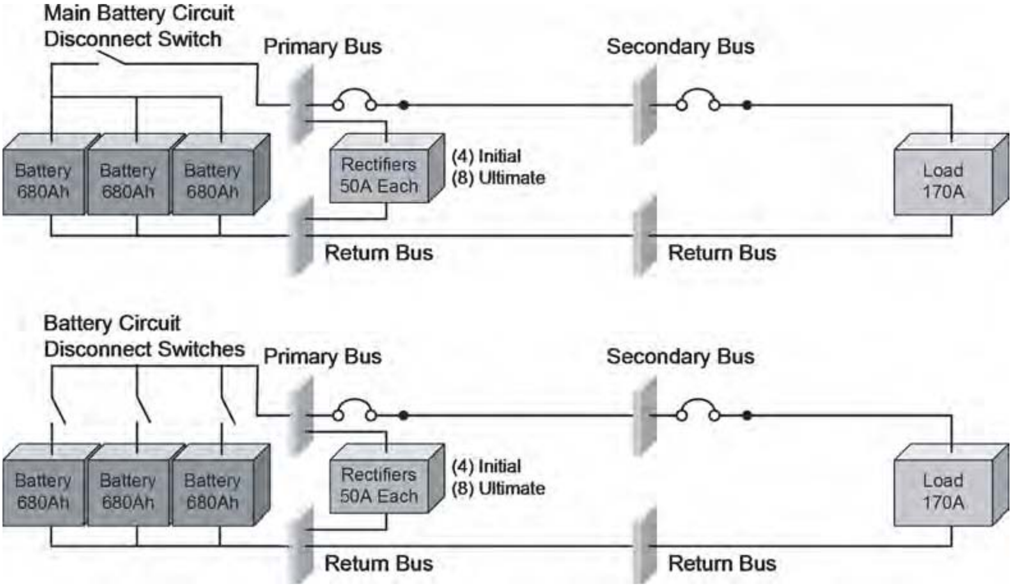


Fig. 5.57 Circuit for Example 5.41, showing one main battery disconnect switch (*upper drawing*) or three individual switches (one for each string, *lower drawing*).

A suitable main battery circuit disconnect switch would have a minimum current rating of 400 A and a short-circuit current withstand rating greater than 15,000 A (three times the fault current available from an individual battery string).

Individual Battery Disconnect Switches—If a battery disconnect device is to be used on each of the three battery strings, each one would require the same minimum current rating (400 A) as a single main device because of the possibility of two batteries being offline (disconnected for maintenance). If the online battery became discharged, it would initially sink the full rectifier system current. An individual disconnect device on each battery string will have to carry the fault current available from the other battery strings or just the string associated with it (depending on the location of the fault). All conductors between each battery and the charge bus must be rated 400 A minimum.

5.8.3.5 Parallel Strings

Conductors connecting different battery strings to the discharge bus should be balanced by sizing the conductors for equal resistance (and therefore equal voltage drop) between the battery terminals and the bus. If they are unbalanced, the string with the least voltage drop to the bus will provide more than its share of current during each discharge and thus will have a shorter life and shorter reserve time than the other battery strings.

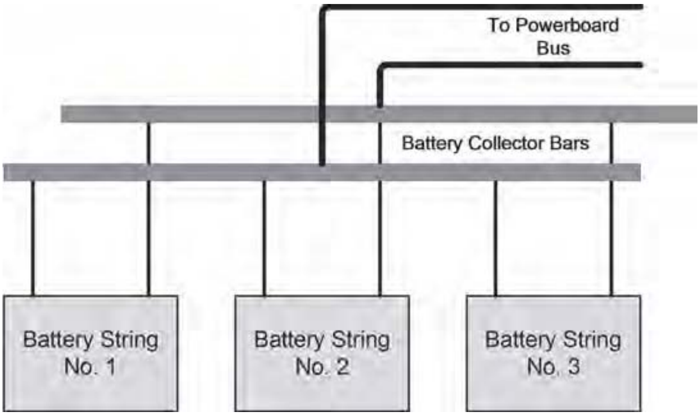
To minimize and balance the voltage drop to parallel battery strings, the largest practical conductor size should be used for the most distant battery string. The conductor sizes for the strings nearer to the discharge bus are then selected so the voltage drop in each is approximately equal to that of the most distant string.

- If the same size conductors are used to connect each parallel string, the conductors should be the same length (within 5%).

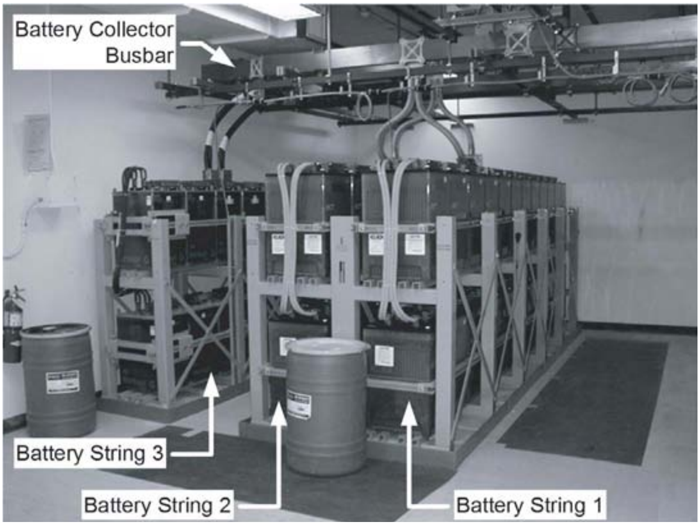
- The resistances of the battery circuits should be the same (within 5%). Different conductor sizes may be used to achieve this requirement (note: in the case of parallel conductors on a given battery string, all parallel conductors must be the same size).

Since conductors are available only in limited and discrete sizes, it normally is not possible to make the voltage drops exactly the same in all runs. Conductors also must meet current rating requirements regardless of voltage drop requirements.

Rather than use individual runs from each battery to the charge/discharge bus, collector bars may be used near the battery strings [Figs. 5.58(a) and 5.58(b)]. With this arrangement, it is easier to control the conductor length and resistance of the individual



(a)



(b)

Fig. 5.58 (a) Battery circuit collector bar schematic and (b) battery circuit collector bar application. Note spill containment kit near each battery rack. (Photo courtesy of Schultz Brothers Electric Company.)

battery circuits. Generally, the drop circuits from the battery collector bars have the same current rating as the main run to the powerboard charge bus; however, for the wiring from the battery terminal to the battery collector busbar, it is common practice to use 4/0 AWG Class I (fine-strand) power wire as a basic size on battery strings up to around 1800-Ah and 350-kcmil Class I wire on larger battery strings. See Table 5.32.

5.8.4 Power Cable Supporting Structure

5.8.4.1 Structural Considerations The cable racks and their attachments to the building must support the weight of the power wires. Cable racks look like steel ladders and sometimes are called ladder racks (Fig. 5.59). They may be run horizontally or vertically. The normal length of a cable rack section is 9 ft 8.5 in. Cable racks vary from 5 to 24 in. wide, although sizes outside this range will be encountered in the field or found in manufacturers' catalogs. Cable racks wider than 24 in. are equipped with additional reinforcement on the first and every other rung or cross member. Bar-type cable racks, with cross members welded to the top of the stringers, generally are not used.

The stringers, or rectangular side rails, can be tubular (hollow) or solid steel. Solid steel stringers are stronger and should be used in all applications except where cable loads are small and site logistics (shipping and handling) require light-weight materials. For example, a 12-in. section of tubular steel cable rack weighs 23 lb (10.4 kg) while the same size in solid steel weighs 61 lb (27.7 kg). Cable racks generally are supported at 5-ft intervals, although 4-ft intervals may be used where extra support is required, and 6-ft intervals may be used where site physical and dimensional constraints require them. Two stringer dimensions are available—$\frac{3}{8}$ in. × 1.5 in. and $\frac{3}{8}$ in. × 2 in.; the 2 in. is used in most applications, especially where structural strength is of concern. Many small installations use 1.5 in. The choice sometimes is dictated by logistics. Table 5.33 shows the weights for various stringer configurations.

In small central offices, it is common to install only one cable rack tier that is shared by both signal and power cables. In larger central offices, two or three tiers usually are installed, one or two for power wires and another for signal cables, although the latter sometimes may be used to carry secondary distribution wires for short distances (Fig. 5.60).

Cable rack structural design can be handled by calculations or by simply limiting the wire weight or cable *pileup* height. Either way the goal is to limit the deflection (sag) in the loaded cable rack while providing a factor of safety against overloading.

The cable rack stringers essentially are two uniformly loaded, rectangular beams supported at intervals (Fig. 5.61). A simple analysis assumes that the stringer length is equal

Table 5.32 Battery Circuit Wiring from the Battery Terminal to Battery Collector Busbar—Common Practice

	Battery Circuit Conductors	
Battery String Capacity (Ah at 8 h Rate)	Quantity in Parallel	Conductor Size (AWG or kcmil)
< 450	1	4/0
450–900	2	4/0
900–1,800	4	4/0
> 1,800	4	350

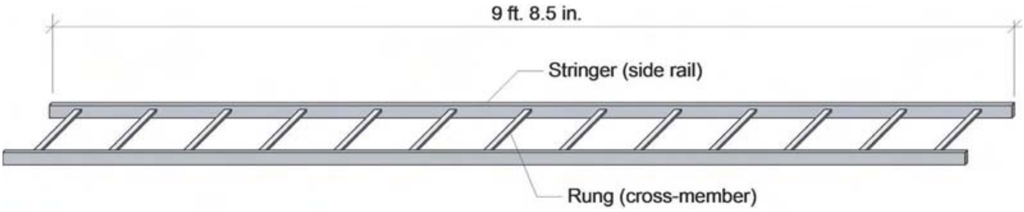


Fig. 5.59 Cable rack section.

Table 5.33 Cable Rack Weights (Painted)[a]

Cable Rack Width (in.)	1.5-in. Tubular Stringer Weight (lb)	1.5-in. Solid Stringer Weight (lb)	2-in. Tubular Stringer Weight (lb)	2-in. Solid Stringer Weight (lb)
5	16.0	39.1	16.5	51.4
6	17.0	40.0	17.5	52.5
9	20.0	42.0	20.5	58.0
10	21.0	42.5	21.5	59.0
11	22.0	44.0	22.5	60.0
12	22.5	45.0	23.0	61.0
15	23.0	45.8	23.5	62.5
18	25.0	48.1	25.5	64.0
20	27.0	55.0	27.5	68.0
21	27.5	56.0	28.0	70.0
24	29.0	58.0	29.5	74.0
25	30.0	63.0	30.5	75.0
27	32.0	65.0	32.5	78.0
30	35.0	68.0	35.5	80.0
36	40.0	70.0	40.5	92.0

[a] To convert to kilograms, divide weight in pounds by 2.2.

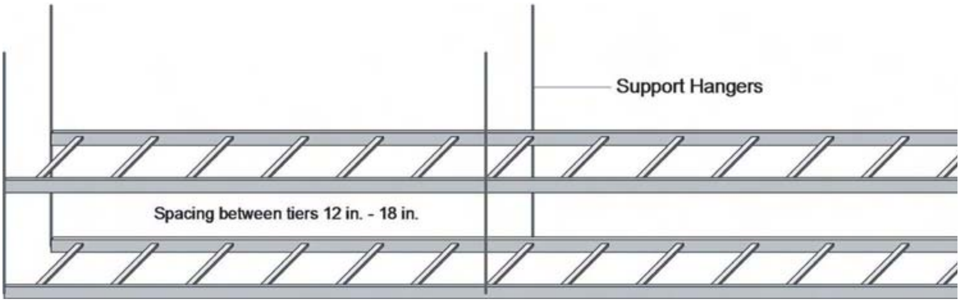


Fig. 5.60 Two-tier cable racks.

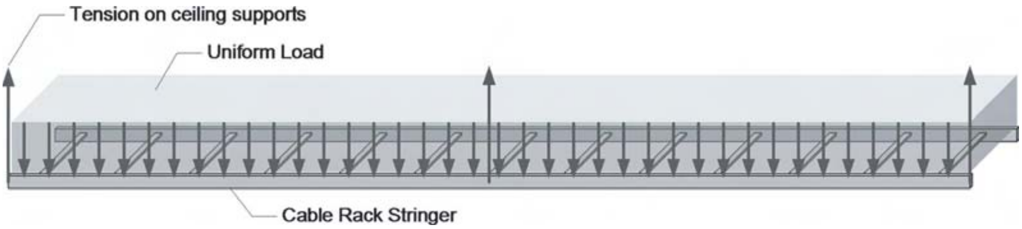


Fig. 5.61 Free-body diagram of showing loads on one of two stringers.

to the support interval (e.g., 48, 60, or 72 in.) and that the cross members transmit the load uniformly to the stringers. The deflection of a simple rectangular beam with a uniform load is

$$\Delta d = \frac{5WL^3}{384EI_M} \text{ in.} \tag{5.100}$$

where Δd = deflection (in.)
W = total uniform weight (lb)
E = modulus of elasticity (29×10^6 lb/in.^{2} for mild steel)[33]
I_M = moment of inertial (in.^{4})
L = distance between supports (in.)

The moment of inertia, I_M, for a solid rectangular shape with the long side vertical is[34]

$$I_M = \frac{bh^3}{12} \text{ in.}^4 \tag{5.101}$$

where b = width of the base of the stringer (typically 0.375 in.)
h = height of the stringer (typically 1.5 or 2 in.)

For a stringer that is 0.375 × 2 in., the moment of inertia is 0.25 in.^{4}. There are two stringers in a cable rack and both share a common centroidal axis. Therefore, the total moment of inertia for the two stringers is twice that for a single stringer, or 0.5 in.^{4}.

The above deflection equation can be used for narrow cable racks (12 in. or less) where the load can be assumed to be the same on the two stringers. This is not necessarily true for wider racks where the load could be asymmetric.

Generally, the maximum loaded deflection is limited to 1/360 of the span length between supports. Table 5.34 shows the deflections for the typical support intervals. It is necessary to calculate the failure load (1) to make sure that the weights do not cause higher deflections and (2) to determine safe loads, which include a safety factor. The maximum allowable bending moment can be determined from

$$M_{\text{Max}} = F_Y S \tag{5.102}$$

---

[33] The modulus of elasticity is a measure of a material's stiffness.

[34] The moment of inertia is a measure of a body's resistance to angular acceleration.

Table 5.34 Cable Rack Deflections

Support Interval	Deflection = 1/360 × Interval
48 in.	0.13 in.
60 in.	0.17 in.
72 in.	0.20 in.

where M_{Max} = maximum moment (lb-in.)
F_Y = yield point (35×10^3 lb/in.^{2} for mild steel)[35]
S = section modulus (in.^{3})[36]

The maximum moment for a uniformly loaded beam is

$$M_{\text{Max}} = \frac{W_{\text{Max}} L}{8} = \frac{w_{\text{Max}} L^2}{8} \text{ lb-in.} \tag{5.103}$$

where W_{Max} = maximum total load (lb)
w_{Max} = maximum uniform load (lb/in.)

The section modulus for a simple rectangular cross section is

$$S = \frac{bh^2}{6} \text{ in.}^3 \tag{5.104}$$

For the 0.375-in. × 2-in. stringer, $S = 0.25$ in.^{3}, and the maximum moment, $M_{\text{Max}} = 35 \times 10^3$ lb/in.$^2 \times 0.25$ in.^{3} = 8750 lb-in. It is now a simple matter to determine the maximum loading for each of the common support intervals, or spans, by rearranging Eq. (5.103), or

$$W_{\text{Max}} = M_{\text{Max}} \frac{8}{L} \tag{5.105}$$

For a 48-in. support interval (span), the calculations give a maximum total load to failure on one stringer of 1458 lb. Since this load is uniformly distributed along the full span length, the maximum uniform load to failure on one stringer of a 48-in. span is 365 lb/ft. The cable rack consists of two stringers, so the maximum loads to failure of the cable rack would be twice the individual stringer values.

The simplifying assumptions do not account for the effect of the cross members on the stringer strength nor do they account for any twisting, different mounting configurations, uncertainty in installation practices and materials, and future installations where cables may be added without detailed analysis of their effect. The calculated maximum loads to failure are never used in practice. To account for uncertainty and simplifications, the values are adjusted by a safety factor. With two stringers and a safety factor of 2.0, the maximum useful loads for the cable rack are the same as the maximum failure loads for a single stringer without any safety factor. Table 5.35 summarizes the calculated maximum

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[35] The yield point is the stress at which material deformation first increases markedly without any increase in the applied load.

[36] The section modulus is a measure of the capacity of a section to resist any bending moment that may be applied.

Table 5.35 Maximum Loads for $\frac{3}{8}$-in. 2-in. Solid Stringer Cable Rack Including Safety Factor = 2.0[a]

Support Interval (in.)	Maximum Uniform Load (lb/ft)	Maximum Total Load (lb)
48	365	1,458
60	233	1,167
72	162	972

[a] Loads include cable rack weight.

loads including a safety factor of 2.0, and Figure 5.62 shows the deflection of narrow cable racks for uniform distributed loads. It is unlikely that in any practical installation the cable rack loads would approach the maximums shown except where many layers of large power cables are installed in large central offices (Fig. 5.63).

One method of determining pileup is based on the assumption that the power wire is 750 kcmil, which has an outside diameter (including insulation) of approximately 1.35 in. (34.3 cm) and weighs approximately 2.7 lb/ft (4.0 kg/m) of length. Obviously, not all power wire is 750 kcmil but it represents a worst-case condition. For design estimating purposes the useful width on a cable rack is 1 in. less than its nominal width (0.5 in. on each side is taken up by the mounting hardware). Therefore, a 12-in. cable rack would have 11 in. of useful width. For this example, a single layer of eight 750-kcmil wires could be placed on a 12-in. cable rack (100% fill). Table 5.36 shows the allowed pileup according to common industry practice.

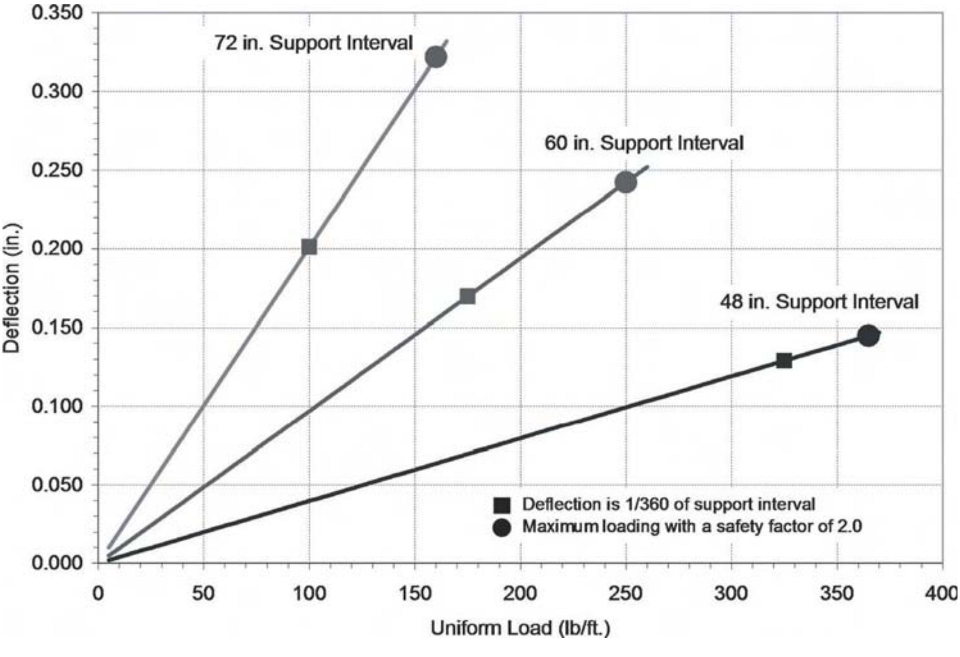

Fig. 5.62 Deflections and loads for $\frac{3}{8}$ in. × 2 in. solid stringer cable rack assuming uniform loading.

Fig. 5.63 Power cable layering in a large central office. (Photo courtesy of Schultz Brothers Electric Company.)

For 12-in. and wider cable racks, the allowed pileup is 7 in., or five layers of 750-kcmil power wire. A 12-in. cable rack could hold a total of forty 750-kcmil power wires with a weight of 40 × 2.7 lb/ft, or 108 lb/ft. This forms the basis for Table 5.37, which shows the weights on fully loaded cable racks of various dimensions. It should be noted that the allowed loads in this table are much less than the previous structural calculations indicate are possible and therefore are more conservative.

Table 5.36 Maximum Power Cable Pileup, Common Practice

	Pileup (in.)	
Cable Rack Width (in.)	60-in. Support Interval	72-in. Support Interval
5	5	5
12–20	7	6

Table 5.37 Power Cable Weight on Fully Loaded Cable Racks (Assuming 100% Fill)

	Cable Rack Support Interval			
	5 ft (60 in.)		6 ft (72 in.)	
Cable Rack Width (in.)	Uniform (lb/ft)	Total (lb)	Uniform (lb/ft)	Total (lb)
12	108	540	86.4	518
15	135	675	108	648
20	189	945	151.2	907

In one-tier installations, power and signal cables share a common cable rack; therefore, weight calculations must take into account the weight of both cable types. There are no average weights for power wire but signal cables weigh about 0.8 lb/in.^{2}/ft.

Cable rack supports, such as threaded rod and inserts, drop-in anchors, and framing channel (e.g., Unistrut framing channel), must have adequate strength for the application. For ordinary applications, detailed support analysis is normally not required. However, where cable rack loading is higher than normal, Table 5.38 can be used to determine the spacing of cable rack supports.

5.8.4.2 General Rules for Power Cable Rack Layout

1. Cable rack layouts should distribute the cable loads across the equipment area, minimize congestion, and include capacity for not only initial cables but a reasonable estimate of future cables.
2. To minimize the possibility of power cable slippage on vertical cable racks, limit continuous vertical lengths to three floors and provide a 20-ft (minimum) horizontal section every third floor (e.g., 4th, 7th, 10th, . . .). This requires that cable holes be offset by at least 20 ft (Fig. 5.64) or a horizontal loop be provided that is at least 20 ft long. Cable racks are considered continuous even if cable hole sheathing or lining interrupts the cable rack through the hole.
3. Where power cables exit the cable rack infrastructure and drop to terminations, they should not be unsupported for more than 36 in.
4. Cable racks should be placed at the front of equipment frames to accommodate rear cabled equipment.
5. Cable racks should clear building columns, walls, and other surfaces by at least 5 in.
6. A vertical clearance of at least 4 in. should be provided between the ultimate cable pileup and any obstruction for installation and removal access.
7. A minimum working space of 18 in. should be provided on at least one side of the cable rack for installation and removal access.

Table 5.38 Loads for Cable Rack Supports

Support Type	Safe Load (lb)
$\frac{5}{8}$-in.—11 threaded insert	1,200
Ceiling insert (poured in place)	1,200
$\frac{5}{8}$-in. drop-in anchor	480
$\frac{3}{8}$-in. drop-in anchor	300
$\frac{3}{8}$-in. lag screw in $\geq$ 2-in. wood	300
Embedded ceiling channel (at any single point)	2,000
Embedded ceiling channel (where two or more loads have $\leq$ 2 ft 0 in. spacing)	2,000 Total
Auxiliary framing channel (paired 2 in. × 9–16 in. × 3–16 in. steel)	
Support span (interval) $\leq$ 2 ft 0 in.	2,000
Support span (interval) 2 ft 0 in.–3 ft 0 in.	1,500
Support span (interval) 3 ft 0 in.–5 ft 0 in.	1,000
Support span (interval) 5 ft 0 in.–7 ft 0 in.	700
Support span (interval) 7 ft 0 in.–8 ft 0 in.	500

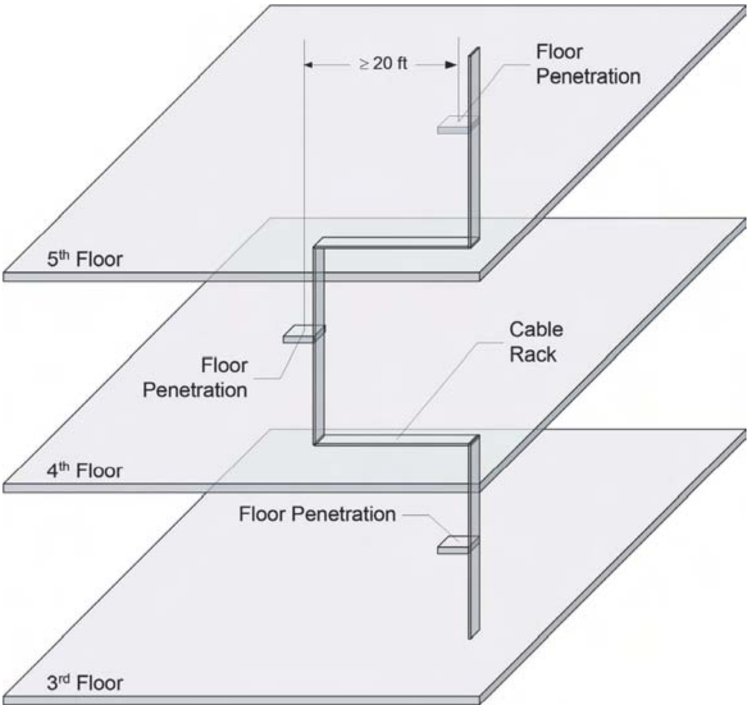

Fig. 5.64 Cable hole offset every third floor.

8. Elevation changes should be gradual, typically 45°, to avoid sharp bends in power cables (Fig. 5.65).

5.8.5 Alternating Current Circuits for Rectifier Inputs and Inverter Outputs

The ac distribution circuit design methods are beyond the scope of this book and can be found elsewhere (e.g., see [49–51]); however, basic ac ampacity and voltage drop calculations are described in this section.

The ac input circuits to rectifier systems and output circuits from inverter systems are designed the same as other ac branch circuits. The ac wiring always is contained in conduit or enclosed in wireway (Fig. 5.66) and never directly installed in cable racks (conduit

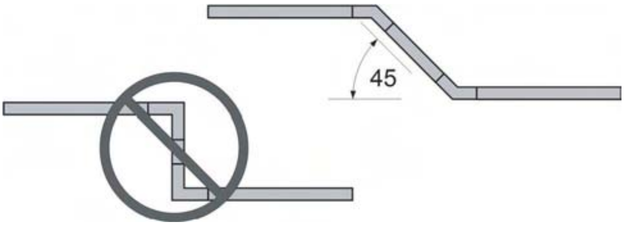

Fig. 5.65 Cable rack elevation change (side view).

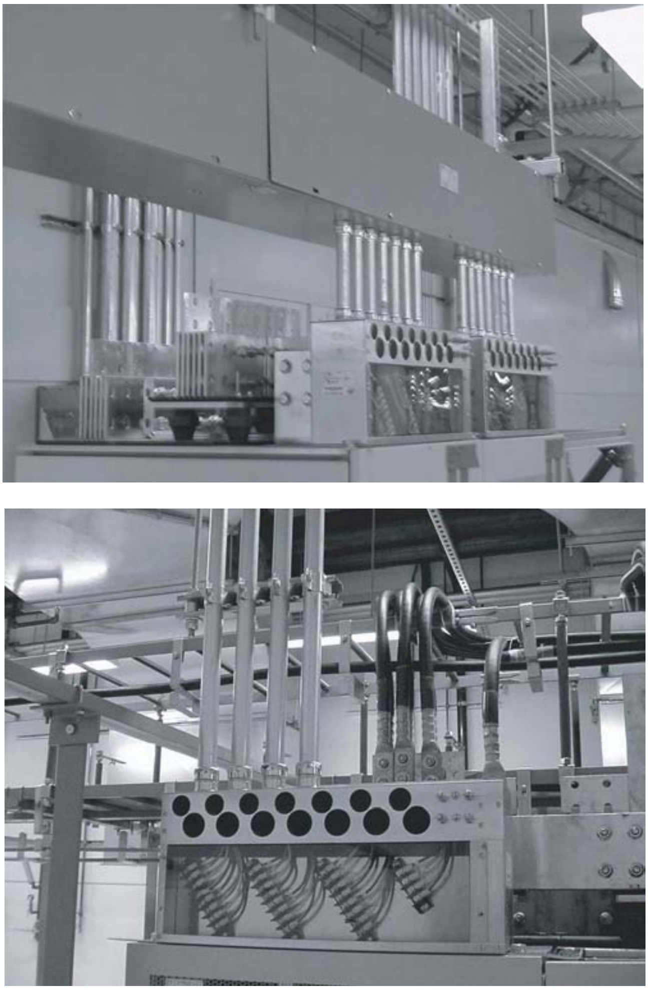

Fig. 5.66 Rectifier ac input circuit wiring in conduit and wireway. (Photos Courtesy of Power-One.)

sometimes is installed in cable rack). Except where the ac loads are located a long distance from the source, voltage drop normally is not a design issue, and the circuit is designed based on ampacity and protection requirements. If necessary, the voltage drop can be calculated as described here (refer also to Chapter 2, Electricity Review).

The ac voltage drop depends on several more factors than dc, including circuit reactance because of the operating frequency and type of conduit. Table 5.39 provides balanced three-phase, line–line voltage drop per 10,000 A-ft at 60°C (140°F) conductor temperature [the table is reasonably accurate to 75°C (167°F)] for various lagging load power factors and for both copper and aluminum wire and magnetic (steel) and nonmagnetic (aluminum or nonmetallic) conduits.

The values can be used directly for three-phase rectifiers. However, most modular switch-mode rectifiers are single-phase devices that operate line–line at nominal voltages of 208 or 240 Vac. Small rectifiers (5- to 10-A output) may operate line–neutral at 120

Vac. For single-phase line–line circuits, multiply the values in the table by 1.18, and for line–neutral circuits, multiply by 0.577. The table shows only wire sizes up to 250 kcmil, which covers most individual rectifier circuits. The voltage drops for larger wires can be found in the data source reference.

To use the ac voltage drop table for rectifier ac input circuits:

1. Determine the full-load current and power factor of the rectifier from its data sheet or as described below. For modern rectifiers, the power factor usually is around 0.9 at full load.
2. Determine the circuit distance in feet.
3. Determine the type of conduit in the circuit (magnetic or nonmagnetic).
4. Determine the wire size and material (copper or aluminum) to be used in the circuit; the wire size, at least initially, is based on the required ampacity (discussed below).
5. Divide the product of the line current and cable route distance by 10,000 (e.g., if the current is 50 A on a run of 100 ft, the product is 5000 A-ft, and the result of division

Table 5.39 Balanced Three-Phase, Line–Line Voltage Drop per 10,000 A-ft[a,b]

Load PF	Wire Size (AWG or kcmil)												
Lagging	14[c]	12[c]	10[c]	8[c]	6	4	2	1	1/0	2/0	3/0	4/0	250
Copper Conductors in Magnetic Conduit													
1.00	53	33	21	13	8.4	5.3	3.4	2.6	2.1	1.7	1.4	1.1	0.92
0.95	50	32	20	13	8.2	5.3	3.5	2.8	2.3	1.9	1.5	1.3	1.1
0.90	48	30	19	12	8.0	5.2	3.4	2.8	2.3	1.9	1.6	1.3	1.2
0.80	43	27	17	11	7.3	4.8	3.2	2.6	2.3	1.9	1.6	1.4	1.2
0.70	38	24	15	9.9	6.6	4.4	3.0	2.5	2.1	1.8	1.5	1.3	1.2
Copper Conductors in Nonmagnetic Conduit													
1.00	53	33	21	13	8.4	5.3	3.3	2.6	2.1	1.6	1.3	1.0	0.88
0.95	50	32	20	13	8.2	5.3	3.4	2.7	2.2	1.8	1.5	1.1	1.0
0.90	48	30	19	12	7.9	5.1	3.3	2.7	2.2	1.8	1.5	1.1	1.1
0.80	43	27	17	11	7.2	4.7	3.1	2.5	2.1	1.7	1.4	1.1	1.1
0.70	38	24	15	9.7	6.4	4.3	2.8	2.4	2.0	1.6	1.4	1.1	1.1
Aluminum Conductors in Magnetic Conduit													
1.00		52	33	21	13	8.4	5.2	4.2	3.3	2.6	2.1	1.7	1.4
0.95		50	32	20	13	8.2	5.3	4.2	3.4	2.7	2.3	1.8	1.6
0.90		48	30	19	12	7.9	5.1	4.1	3.4	2.7	2.3	1.9	1.6
0.80		43	27	17	11	7.3	4.7	3.9	3.2	2.6	2.2	1.8	1.6
0.70		37	24	15	10	6.5	4.3	3.6	2.9	2.4	2.1	1.7	1.6
Aluminum Conductors in Nonmagnetic Conduit													
1.00		52	33	21	13	8.4	5.2	4.2	3.3	2.6	2.1	1.7	1.4
0.95		50	32	20	13	8.2	5.2	4.2	3.4	2.7	2.2	1.8	1.5
0.90		48	30	19	12	7.9	5.0	4.1	3.3	2.6	2.2	1.8	1.5
0.80		42	27	17	11	7.2	4.6	3.8	3.1	2.5	2.1	1.7	1.5
0.70		37	24	15	9.9	6.4	4.2	3.4	2.8	2.3	1.7	1.6	1.4

[a] Data source [49].

[b] For single-phase line–line circuits, multiply by 1.18 and for one- or three-phase line-neutral circuits, multiply by 0.577.

[c] Solid conductors; all others are stranded.

by 10,000 is 0.5 (10,000 A-ft). Note: The distance used here is not total conductor length but route distance.

6. Enter the voltage drop table in the section appropriate for the conduit type, conductor size and type, and power factor. Read across to the intersection with the wire size and note the voltage drop. This is the three-phase line–line voltage drop for 10,000 A-ft.
7. Multiply the voltage drop from step 6 by the actual ampere-feet divided by 10,000 from step 5. This is the actual line–line voltage drop on a balanced three-phase circuit.
8. If the circuit is single-phase line–line (most often the case except for small rectifiers), multiply the voltage drop found in step 7 by 1.18. If the circuit is line–neutral, multiply the voltage drop found in step 7 by 0.577.

The best place to obtain rectifier input current values are from the manufacturer or data sheet. The value used in all calculations (voltage drop and ampacity) should be worst case, that is, at lowest input ac voltage, highest output dc voltage and highest dc output current. The output current must include any overload capability of the rectifier (many modern switch-mode rectifiers are rated in watts and the output current depends on the output voltage; other switch-mode and some ferroresonant rectifiers limit at 100% of nameplate rating, but many older rectifiers limit at 110%). The input current also can be calculated from the rectifier efficiency characteristics (typically 80 to 90%) using the following:

$$I_{\mathrm{acMax}} = \frac{V_{\mathrm{dcMax}} I_{\mathrm{dcMax}}}{V_{\mathrm{acMinL\text{-}L}} \mathrm{Eff(PF)}} \quad \text{A (for single-phase rectifier)} \tag{5.106}$$

$$I_{\mathrm{acMax}} = \frac{V_{\mathrm{dcMax}} I_{\mathrm{dcMax}}}{V_{\mathrm{acMinL\text{-}L}} \mathrm{Eff(PF)}\sqrt{3}} \quad \text{A (for three-phase rectifier)} \tag{5.107}$$

where I_{acMax} = maximum ac input current
V_{dcMax} = maximum dc output voltage
I_{dcMax} = maximum dc output current
$V_{\mathrm{acMinL\text{-}L}}$ = minimum ac input voltage, line–line
Eff = rectifier efficiency at full load
PF = rectifier power factor

Example 5.42 Determine the input current for a rectifier that is connected line–line to a 120/240 Vac, single-phase service. The rectifier output is rated 50 A at 56.0 Vdc but has 10% overload capability. Rectifier efficiency is 0.9 and power factor is 0.9 at full load.

Solution Because of its overload capability, the maximum rectifier output current will be 55 A. Also, the minimum ac input voltage will be 216 Vac, assuming the worst-case total voltage drop in the nominal service voltage is 10%, or 24 Vac. From Eq. (5.106), the input current is

$$I_{\mathrm{acMax}} = \frac{56.0\ \mathrm{V} \times 55\ \mathrm{A}}{216\ \mathrm{V} \times 0.9 \times 0.9} = 17.6\ \mathrm{A}$$

As noted in the above example, the nominal service voltage is not the voltage used in the calculations. The industry standard for electric power system voltage ratings is C84.1—Electric Power Systems and Equipment—Voltage Ratings (60 Hz) [52], which specifies three voltage ranges:

Range A—Service Voltage. Electric supply systems shall be so designed and operated that most service voltages will be within the limits specified for Range A. The occurrence of service voltages outside of these limits should be infrequent.

Range A—Utilization Voltage. User systems shall be so designed and operated that with service voltages within Range A limits, most utilization voltages will be within the limits specified for this range. Utilization equipment shall be designed and rated to give fully satisfactory performance throughout this range.

Range B—Service and Utilization Voltages. Range B includes voltages above and below Range A limits that necessarily result from practical design and operating conditions on supply and user systems, or both. Although such conditions are a part of practical operations, they shall be limited in extent, frequency, and duration.

The voltage ranges *A* and *B* are illustrated in Figure 5.67. Voltages ranges at the top of the figure are on a 120-V base and can be linearly scaled for other voltages (e.g., to convert to a 240-V base, multiply all values by 2 and to 208 V, multiply by 1.732). These ranges are at the bottom of the figure.

Limiting the voltage drop from the ac service equipment to the load equipment to no more than 5% is achievable in most buildings without excessively large wire. This voltage drop includes the drop from the ac service equipment to any ac subpanels and from the subpanels to the rectifiers. Use 3% maximum ac voltage drop for circuits from ac subpanels to the rectifiers unless a different value makes more sense. Table 5.40 shows max-

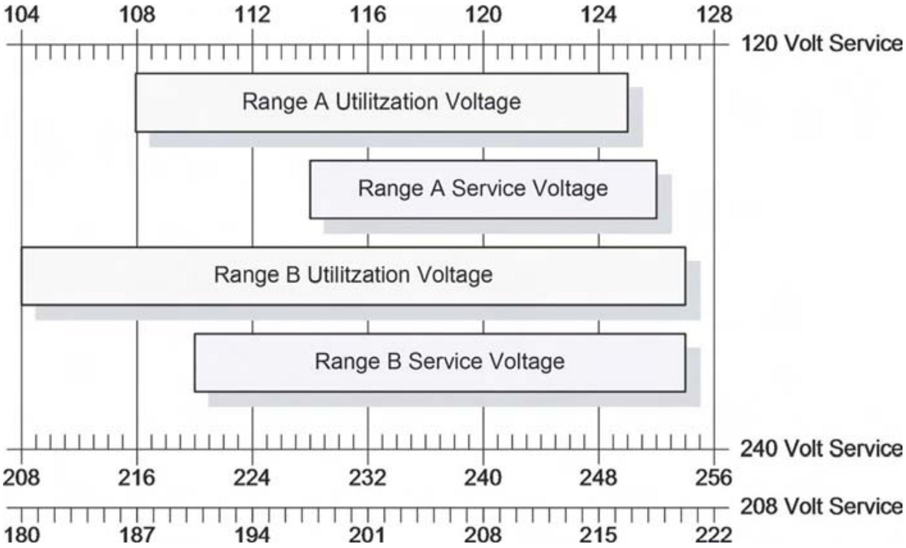

Fig. 5.67 Service and utilization voltage ranges. (Data source: ANSI C84.1 [52].)

Table 5.40 Line–Line Voltage Drops for Common Service Voltages

Service Voltage (Vac)	3% L–L Voltage Drop (Vac)	5% L–L Voltage Drop (Vac)
120/240, one-phase	7.2	12.0
208Y/120, three-phase	6.2	10.4
240/120, three-phase	7.2	12.0
480Y/120, three-phase	14.4	24.0

imum target voltage drop values at 3 and 5% for the common service voltages. One ac circuit is required for each rectifier; more than one rectifier never shares a circuit.

Example 5.43 The rectifier from the previous example is located 100 ft (cable route distance) from its ac distribution panel (also called load center) and is to be connected single-phase line–line. The circuit conductors are 10 AWG copper in PVC conduit. The service voltage is 120/240 Vac, single phase.

Solution The rectifier input current from the previous example is 17.6 A. Multiplying the current by the circuit distance and dividing by 10,000 gives 1760 A-ft/10,000, or 0.176. Assuming the rectifier power factor is 0.9, and since the conductors are in nonmagnetic conduit, the voltage drop is 19 V for a 10 AWG circuit per 10,000 A-ft. Multiplying 19 V by 0.176 gives 3.3 V for the three-phase voltage drop. Since this is a single-phase rectifier, the three-phase voltage drop is multiplied by 1.18, giving 4.0 V. Note that if the actual service voltage is at the low end of range *A* service voltage (228 V from Fig. 5.67), the actual utilization voltage would be 224 V, which is well within range *A* utilization voltage (also from Fig. 5.67).

Example 5.44 An old 24-V, 400-A, three-phase rectifier is to be recycled from warehouse storage to a site to augment an existing rectifier system because of unanticipated load growth. The rectifier is designed to provide 10% overload indefinitely, has 0.8 efficiency, and the power factor is 0.85 lagging at full load. The rectifier manual recommends an ac input conductor size of 4 AWG copper. The circuit will be connected to a 208Y/120-V load center and will use steel conduit. The circuit route distance is 150 ft. Determine the maximum ac input current and voltage drop and whether the circuit meets range *A* utilization voltage range.

Solution For purposes of calculating the rectifier input current, the maximum rectifier output voltage is assumed to be 28.0 Vdc, and the minimum input voltage is assumed to be at the bottom of range *A* service voltage, or 198 Vac. The maximum output current can be 440 Adc, including overload capability. Therefore, from Eq. (5.107), the input current is

$$I_{\text{acMax}} = \frac{28.0\ \text{V} \times 440\ \text{A}}{198\ \text{V} \times 0.8 \times 0.85\sqrt{3}} = 52.8\ \text{A}$$

Multiplying the current by the circuit distance and dividing by 10,000 gives 7920 A-ft/10,000, or 0.792. From Table 5.39 and 4 AWG copper in magnetic conduit, the voltage drop is 4.8 and 5.2 V per 10,000 A-ft for power factors of 0.8 and 0.9, respectively. Using linear interpolation, the voltage drop at a power factor of 0.85 is half-way between, or 5.0 V per 10,000 A-ft. Multiplying 5.0 V by 0.792 gives 4.0 V for the three-phase voltage drop. If the actual service voltage is 198 Vac, the actual utilization voltage would be 194 V, which is within range *A* utilization voltage shown in Fig. 5.67.

Rectifier loads are continuous so the ac input current must be multiplied by 1.25 to determine the required conductor ampacity. Table 5.41 shows the allowable ampacities for common building wire up to 250 kcmil.

Example 5.45 Confirm that the conductor size used in Example 5.44 has the required ampacity for the application. The insulation type is THW, the ambient temperature is 30°C (86°F), and there are no more than three conductors in the raceway.

Solution The required ampacity is found by multiplying the maximum rectifier input current by 1.25, or 52.8 A × 1.25 = 66 A. The allowable ampacity from Table 5.41 for 4 AWG copper under the stated conditions is 85 A, which exceeds the required ampacity. Therefore, the 4 AWG is adequate in the application.

Table 5.41 Allowable ac Ampacities for 600-V Building Wire (only commonly used insulation types and wire sizes to 250 kcmil are shown)[a]

	Temperature Rating of Conductor					
	Copper			Aluminum		
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)
Wire Size AWG or kcmil)	TW, UF	RHW, THHW, THW, THWN, XHHW, USE	RHH, THW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2	TW, UF	RHW, THHW, THW, THWN, XHHW, USE	RHH, THW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2
14	20	20	25	—	—	—
12	25	25	30	20	20	25
10	30	35	40	25	30	35
8	40	50	55	30	40	45
6	55	65	75	40	50	60
4	70	85	95	55	65	75
3	85	100	110	65	75	85
2	95	115	130	75	90	100
1	110	130	150	85	100	115
1/0	125	150	170	100	120	135
2/0	145	175	195	115	135	150
3/0	165	200	225	130	155	175
4/0	195	230	225	130	155	175
250	215	255	290	170	205	230

[a] Conditions: No more than three current-carrying conductors in raceway or cable and ambient temperature 30°C (86°F). Refer to Article 310.15 in [29] for guidance when these conditions are not met.

Source: Data from NEC Table 310.16 [29].

For the situation where there are more than three current-carrying conductors in a raceway or cable, the allowable ampacities from Table 5.41 are reduced by the factors shown in Table 5.42.

Example 5.46 Determine whether the conductors in Example 5-45 have adequate ampacity if the conduit also contains six current-carrying conductors for two other three-phase rectifiers.

Solution In this case, there are a total of nine current-carrying conductors, three from the added rectifier and six from the two existing rectifiers. From Table 5.42, the allowable conductor ampacity has to be adjusted by a factor of 0.7. For 4 AWG, the allowable ampacity under these conditions is 85 A × 0.7 = 59.5 A. Since the required ampacity is 66 A, these conductors are too small. In this case, a 3 AWG or more likely a 2 AWG conductor would be used (because 2 AWG is more readily available).

Circuit conductors must be protected at their source, and the overcurrent protection must not exceed the allowable conductor ampacity. Circuit breakers (not fuses) are used in modern ac distribution systems to serve branch circuit loads such as rectifiers. Common circuit breaker sizes are shown in Table 5.43 (this table shows ratings to 225 A; larger standard ratings are available—see Article 240.6(A) of [29]). This table also shows the maximum allowed circuit breaker size for smaller conductors (14, 12, and 10 AWG).

Example 5.47 Determine the circuit breaker rating for the rectifier input circuit of Example 5.43. The insulation type is THW with a maximum conductor temperature rating of 75°C.

Solution The full-load current of the rectifier was found to be 17.6 A. The required circuit ampacity is 1.25 × 17.6 = 22 A. The conductor size was given as 10 AWG. From Table 5.43 this conductor has a basic allowable ampacity of 35 A, which exceeds the required ampacity. Table 5.43 shows the highest circuit breaker rating for 10 AWG conductors is 30 A, which is suitable on this circuit. Since the single-phase rectifier is connected line–line with two current-carrying conductors, a two-pole circuit breaker is required.

Example 5.48 Determine the circuit breaker size for the rectifier input circuit of Example 5.45. The insulation type is THW with a temperature rating of 75°C.

Table 5.42 Adjustment Factors for More Than Three Current-Carrying Conductors in a Raceway or Cable

Number of Current-Carrying Conductors	Adjustment Factor
4–6	0.80
7–9	0.70
10–20	0.50
21–30	0.45
31–40	0.40
≥ 41	0.35

Source: Data from NEC Table 310.15(B)(2)(a) [29].

Table 5.43 Standard Circuit Breaker Ratings up to 225 A for ac Circuits

Circuit Breaker Size (A)	Smallest Conductor Size (AWG)
15	14
20	12
25	—
30	10
35	—
40	—
45	—
50	—
60	—
70	—
100	—
110	—
125	—
150	—
175	—
200	—
225	—

Source: Data from Article 240.4(D) and 240.6(A) of [29].

Solution The required circuit ampacity was found to be 66 A. The nearest circuit breaker rating that exceeds the required ampacity is 70 A. Since the 4 AWG conductors have allowable ampacity of 85 A at 75°C, they are adequately protected by a 70-A circuit breaker. Also, since there are three current-carrying conductors in the circuit, a three-pole circuit breaker is required.

5.9 DIRECT CURRENT POWER SYSTEM BONDING AND GROUNDING

The design of an overall telecommunications grounding system is beyond the scope of this book; however, this section will describe the bonding and grounding of the dc power system.[37]

5.9.1 Building Principal Ground

The building principal ground (BPG) is the mechanical and electrical interface between the interior and exterior grounding systems and is the ground reference point for the facility. Numerous names have been given to this functional element, such as main ground bar (MGB), master ground bar, and CO ground bus.

The BPG bar (BPGB) is a plain copper or tin or silver-plated copper busbar and should be at least $\frac{1}{4}$ in. thick and 4 or 6 in. high. Depending on the purpose and number of wire terminations, the bar can be between 6 and 48 in. long, although longer bars have been used in practice. The BPG should be as close as possible to where the grounding electrode

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[37] Information on telecommunications bonding and grounding may be found in [46, 47, 53], and grounding information not specific to public telecommunications systems may be found in [54–56].

system conductor enters the building. The dc power system grounding connection may be made directly to the BPG if it is on the same floor of the facility or through a floor ground bar (FGB) if on a different floor.

The BPG is partitioned (conceptually, not physically) for connection purposes into four segments called P-A-N-I (Fig. 5.68). This layout simplifies grounding audits and visual inspections and is thought to reduce interference between systems connected to it (but this thinking has not been proven with rigorous analysis).

5.9.2 Direct Current Power Equipment Bonding and Grounding

In modern telecommunications equipment, the dc power return is isolated (insulated) from the equipment frame ground. Such an arrangement is called an *isolated return.* The return circuit conductors from the equipment are connected to an insulated return bus termination bar in the powerboard. The return bus termination bar is bonded to the equipment grounding conductor at one point only, typically the BPGB or a floor ground bar, using the dc grounding (DCG) conductor. In older systems and some modern equipment designed for enterprise applications, the dc power return is bonded internally to the equipment frame ground or it may be bonded externally to ground at more than one point. The return conductors are connected to the return bus termination bar in the powerboard and then to the equipment grounding conductor as for the isolated return described above. This bonding arrangement is called an *integrated return.* Figure 5.69 shows a simple schematic for the two arrangements.

All power equipment frames, cabinets, battery racks, cable racks, and other metallic enclosures and supports in the dc power system area are bonded to the common bonding network (CBN) or the isolated bonding network (IBN) depending on where they are located. This bond preferably is called dc equipment grounding conductor (DCEG conduc-

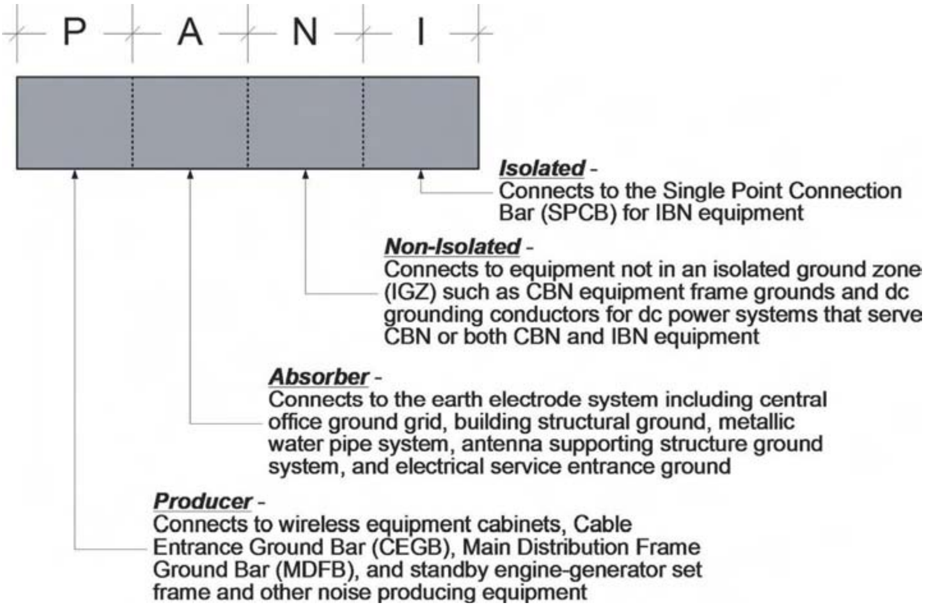


Fig. 5.68 Building principal ground bar (BPGB) segmentation.

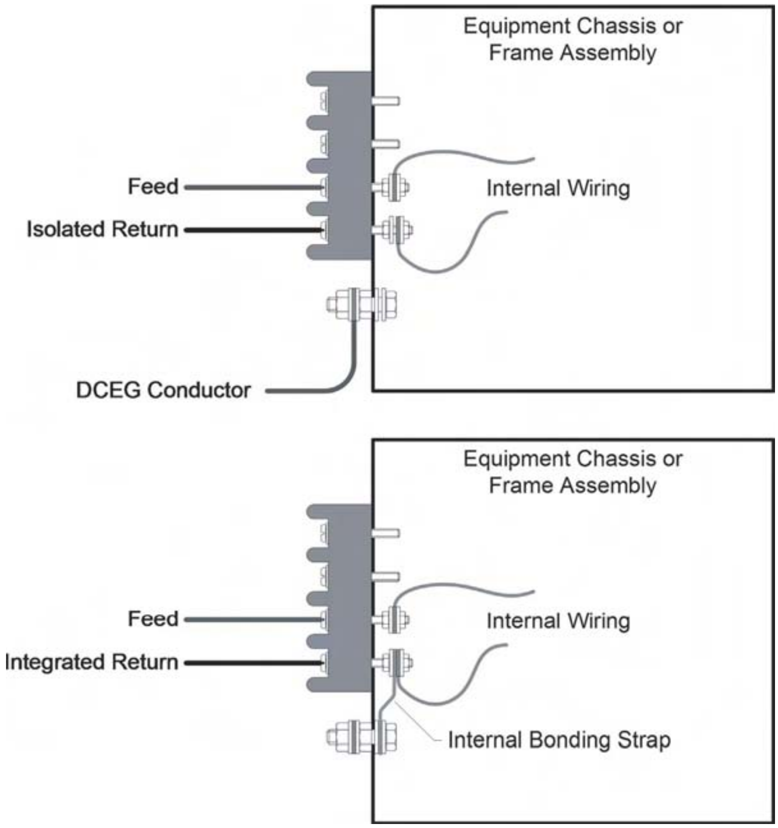


Fig. 5.69 Isolated (*upper*) and integrated (*lower*) return for load equipment chassis or frame assembly.

tor) but also has been called frame ground conductor (FGC) and equipment grounding conductor (EGC).

The powerboard return bus is bonded to the grounding system using a dc grounding conductor (DCG conductor). Figure 5.70 shows the configuration for a typical central office in which the powerboard serves both IBN and CBN equipment or just CBN equipment. The sizes of the DCG and DCEG conductors are discussed in Section 5.9.3.

A typical bonding configuration for a multifloor central office with both CBN and IBN equipment is shown in Figure 5.71. In this case

- Only one single-point connection bar (SPCB) is used for all IBN equipment.
- The SPCB can be separate from the dc power system or a section of the insulated dc power return bar.
- All IBN equipment should be within one floor of the dc power system.
- The dc power return bar is insulated from the framework and bonded to the SPCB by the dc system grounding (DCG) conductor.
- The dc power system framework is bonded to the floor ground bar (FGB) of the floor on which the dc power system is located.

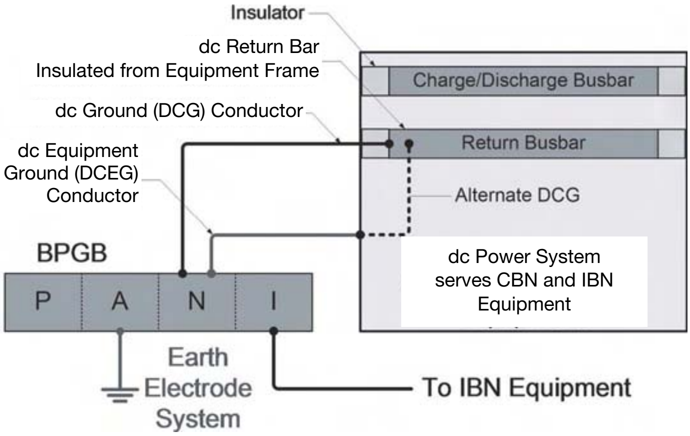


Fig. 5.70 Typical powerboard bonding. Note that the DCG conductor may be bonded to the powerboard frame (shown as alternate DCG) or directly to the BPGB. The DCEG is required in either case.

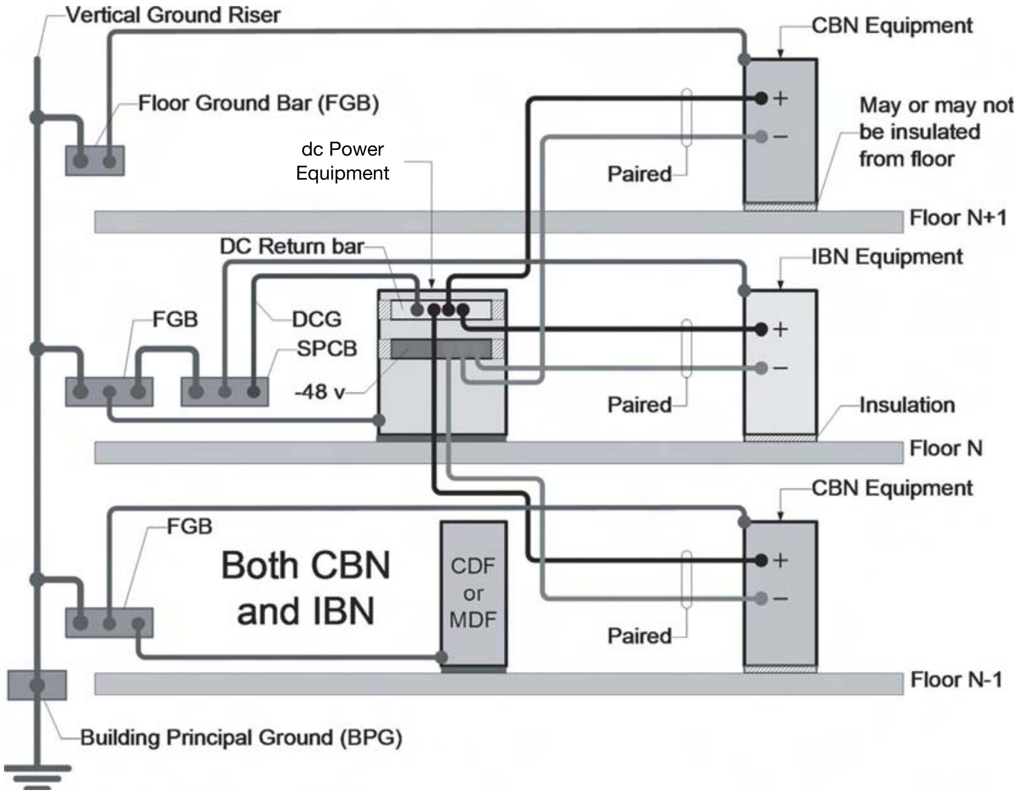


Fig. 5.71 Bonding a mixture of IBN and CBN equipment.

A typical configuration used in multifloor central offices with only IBN equipment is shown in Figure 5.72. In this case

- There is only one single-point connection bar (SPCB) and it is located on floor N for all equipment.
- All IBN equipment is located within one floor of the SPCB (A, B, C).
- Location a is preferred for dc power system, but b and c are acceptable.
- The dc power return bar is insulated from the framework and bonded to the SPCB by the DCG conductor.
- The dc power system framework is bonded to the SPCB if it is on the same floor as the SPCB or to the FGB (or BPGB) if on a different floor.

The SPCB sometimes is called a ground window bar (GWB), although other names have been used throughout the years. An example is shown in Figure 5.73. The SPCB forms a window (SPC window, or SPCW), which conceptually is < 6 ft diameter through which grounding conductors pass. In a mixed CBN and IBN environment, the SPCB and dc power return bar can be the same bar. If so, the bond from the return bar to the FGB also serves as the SPCW bond.

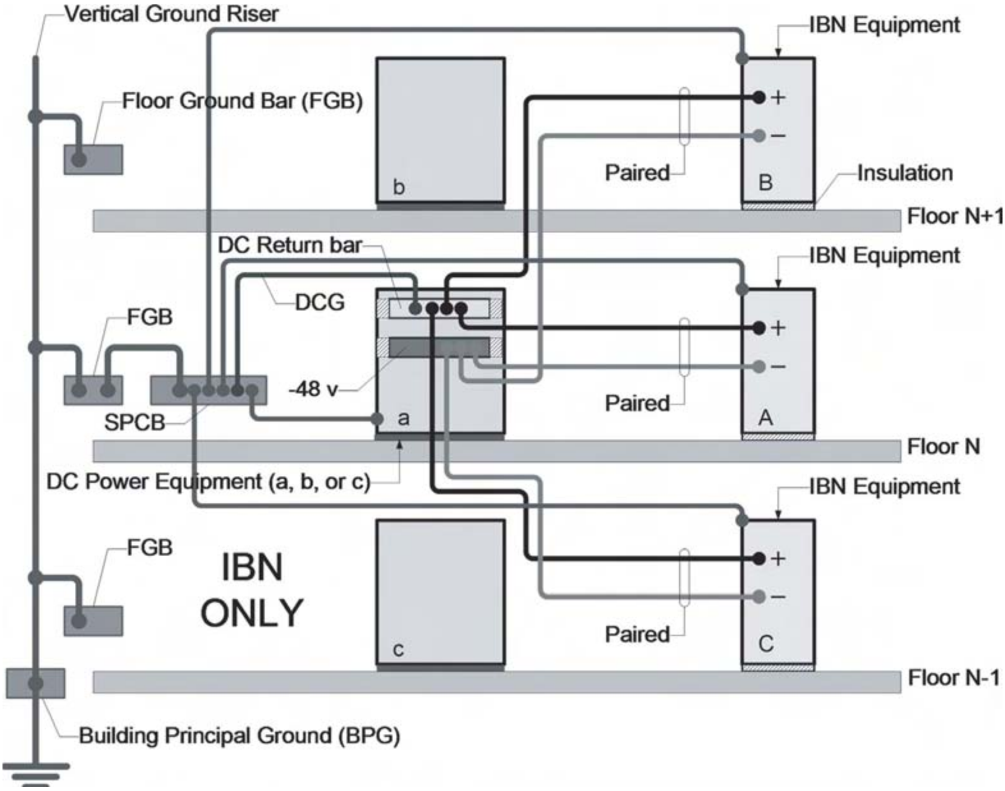


Fig. 5.72 Bonding of IBN equipment only.

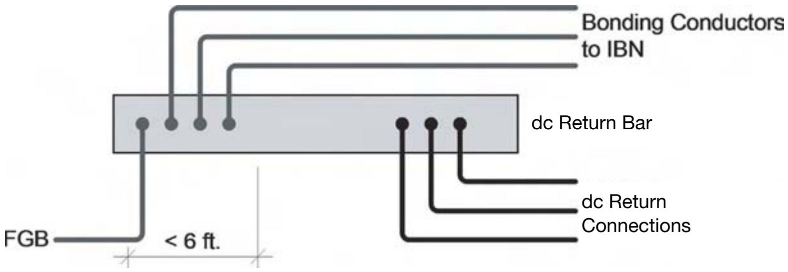


Fig. 5.73 Single-point connection bar (SPCB) can be part of the dc return bar.

Many CBN and IBN bonding arrangements have been used since 1980. The current standard is given in [46]. Generally, if industry practices in effect at the time the equipment was installed were followed, they are acceptable today (retrofit generally is not required). However, many systems may have been installed properly, but the bonding arrangements were inadvertently corrupted by subsequent installations and related activity. Some acceptable alternatives based on past practices are [47]:

- The dc power system may be located several floors from the IBN equipment.
- Only one SPCB may be used for all IBN equipment (rather than separate SPCB for each separate IBN installation).
- The SPC usually is located within one floor of the IBN equipment.
- The dc power return bar is insulated from the framework and bonded to the SPCB by the DCG conductor.
- The dc power system framework is bonded to the FGB of the floor on which the dc power system is located.
- If CBN equipment is served by the same dc power system serving the IBN equipment, the –48-V feeders to the CBN should be routed within 3 ft of the SPCB and the CBN dc power return conductors connected to the SPCB.

Some other considerations are:

- There should be only one SPCW associated with each dc power system.
- If the dc power system is shared between IBN and CBN equipment, the preferred location for the SPCW is near the power system or as part of the power system battery return bus.
- If the dc power system is dedicated to the IBN equipment, the preferred location for the SPCW is the IBN equipment room.
- To overcome termination space limitations, single-point collector bars may be located within the SPCW or < 3 ft away for connection to the SPCB.
- Older equipment frames not insulated from the floor and with multiple grounding connections are considered a mesh bonding network (MBN), which is an extension of a CBN. MBN dc power return leads usually are connected to the surrounding CBN at a single point only, but they are permitted to be connected to system framework at multiple points (return current will follow multiple paths).

5.9.3 Grounding Conductor Size

In isolated return systems, the DCG and DCEG conductors are based on industry requirements [47]. They are sized to safely carry the fault current and to provide a low-impedance fault current path. There is a perception that larger conductors provide an added benefit of better noise control, but there is no agreement on the conductor size for this purpose. The DCG or DCEG conductor is the larger of

1. 6 AWG (copper).
2. Conductor size with resistance that achieves a voltage drop ≤ 90% of system nominal voltage (48 or 24 V) during a fault, assuming the fault current is ≥ 10× the rating of the largest overcurrent device feeding the frame or frame assembly, or

$$R_{\max} \leq \frac{0.9V_{\text{nom}}}{10I_{\text{opd}}} \tag{5.108}$$

where $R_{\max}$ = maximum resistance of fault current path (Ω)
V_{nom} = nominal source voltage (V)
I_{opd} = current rating of overcurrent protective device (A)

In most installations, the powerboard is the first point of distribution and is not being fed by an overcurrent device in the same manner as load equipment. In this case, the current in the above calculation is based on the largest overcurrent device in the powerboard.

3. Conductor size is based on the largest dc overcurrent device feeding the equipment frame or frame assembly (Table 5.44).

Table 5.44 dc Equipment Grounding (DCEG) and dc Grounding (DCG) Conductor[a]

Overcurrent Device Rating (A)	Conductor Size (Copper)
15	14 AWG
20	12 AWG
30	10 AWG
40	10 AWG
60	10 AWG
100	8 AWG
200	6 AWG
300	4 AWG
400	3 AWG
500	2 AWG
600	1 AWG
800	1/0 AWG
1,000	2/0 AWG
1,200	3/0 AWG
1,600	4/0 AWG
2,000	250 kcmil

[a] This table is identical to Table 250.122 in the NEC [29].

Source: Data from [47].

Where the equipment frames use an integrated return, they are considered properly bonded to ground if the return conductors and grounding conductors are common and their total cross-sectional area is at least as large as the cross-sectional area of the conductors that feed the frames.

Example 5.49 A 48-V powerboard bus is rated 800 A and the largest circuit breaker size is 225 A. The DCG conductor is 110 ft long. Determine the DCG conductor size.

Solution The conductor will be the larger of

First Test 6 AWG

Second Test $R_{\text{Max}} \leq \dfrac{0.9V}{10I_{\text{opd}}} = \dfrac{0.9 \times 48\text{ V}}{10 \times 225\text{ A}} = 0.0192\ \Omega$

Based on the calculated maximum conductor resistance, the unit resistance must be ≤ 0.0192 Ω ÷ 110 ft = 0.000175 Ω/ft. From Table 5.13 (at 30°C in column 4), a copper conductor that meets the requirement is 2 AWG copper (unit resistance of 0.000165 Ω/ft).

Third Test From Table 5.44, with an overcurrent device rating of 225 A, the DCG conductor is 4 AWG.

The three tests above give 6 AWG, 2 AWG, and 4 AWG. The 2 AWG conductor is the largest so it is the minimum conductor size for this particular application.

5.9.4 Inverter Bonding and Grounding

The inverter output grounding configuration depends on whether or not the inverter is connected to the commercial ac service. If it is completely isolated from the commercial ac service (continuous operation, See Chapter 3, DC Power System Components), the inverter is considered a separately derived system and the output neutral terminal is bonded directly to the nearest frame ground bar or building structural member (Fig. 5.74). In a separately derived system all circuit conductors on the ac side, including the grounded (neutral) conductor, are independent of the building ac supply conductors. If the inverter is connected to the commercial ac service (active standby operation or passive standby

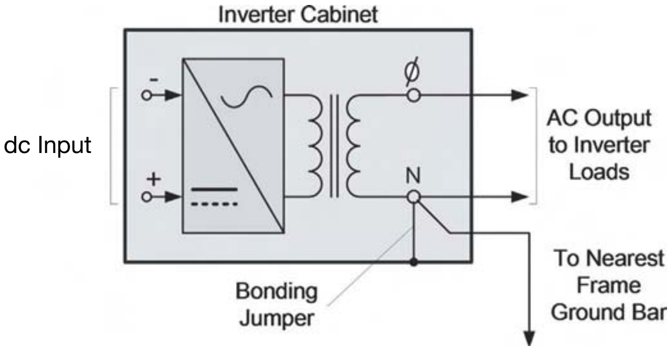


Fig. 5.74 Inverter bonding and grounding.

operation), the neutral terminal in the inverter is bonded to the grounded (neutral) conductor at the service or ac distribution panel and is not bonded directly to any local ground at the inverter. The inverter frame always is bonded to the nearest frame ground bar. The size of the bonding conductors is as discussed in Section 5.9.3.

If the inverter is located in an IBN, it normally is bonded and grounded according to IBN equipment manufacturer requirements. In this case, the IBN inverter typically feeds equipment in the same frame as the inverter. Where the NEC applies to nonexclusive use environments, Articles 250.20 and 250.30 apply to bonding and grounding.

5.9.5 The DC–DC Converter System Bonding and Grounding

If the converter system consists of two or more converters connected in parallel, size the converter system grounding conductor based on the largest overcurrent device in the system. The output is bonded to the converter frame and to nearest frame ground bar or extension of grounding electrode system (Fig. 5.75). The size of the conductor is as discussed in Section 5.9.3.

5.9.6 Battery Rack Bonding and Grounding

Each battery rack or enclosure is bonded to the nearest floor ground bar or directly to the BPGB with a 6 AWG conductor [28] (Fig. 5.76).

5.9.7 Cable Racking Bonding and Grounding

All cable racks are bonded and grounded to ensure a low-resistance path for ground fault currents. A 6 AWG or larger strap is used to bond sections of cable rack where they are spliced or joined (Fig. 5.77), and the cable rack is then bonded to the nearest floor ground bar or the BPGB.

5.9.8 Equipment Frame Bonding and Grounding

It is common practice to install a small (typically 1 in. × $\frac{1}{4}$ in., 318.3 kcmil) copper busbar at the top of each equipment frame. The busbars are spliced to form a continuous busbar

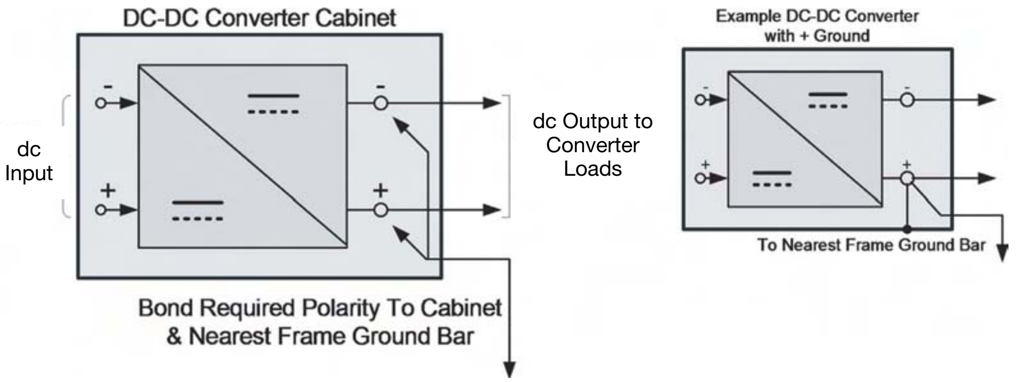


Fig. 5.75 The dc–dc converter bonding and grounding.

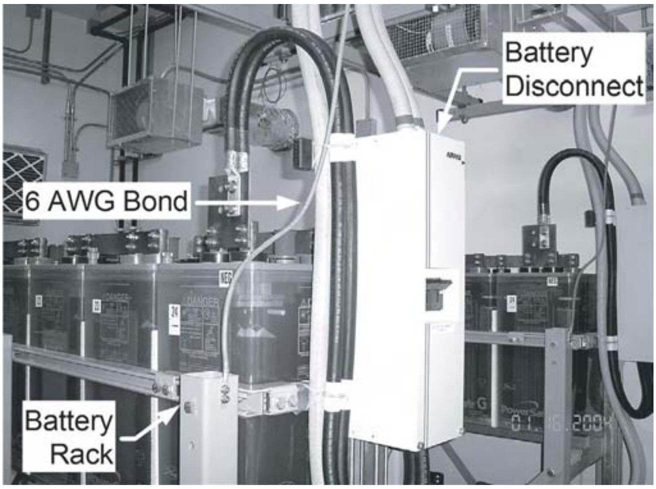


Fig. 5.76 Battery rack bonding.

from one end of the lineup to the other. This busbar is bonded to the nearest floor ground bar or BPGB and serves as a termination busbar for the DCEG conductor from each chassis or shelf in the equipment frame. Any one of three methods may be used to bond the frame grounding busbar to the grounding system (floor ground bar or BPGB):

Method 1 Run an individual conductor from the bar on each frame to the grounding system [Fig. 5.78(a)]. The conductor should be sized according to the largest overcurrent protective device feeding the equipment in the frame as described in Section 5.9.3. This conductor is never smaller than 6 AWG. In many installations, a small fuse or circuit breaker panel at the top of the frame is fed by a 30- to 80-A overcurrent device; if this is the largest overcurrent device feeding equipment in the frame, then the DCEG conductor size would be based on it. This method can be used with or without the small busbar at the top of each frame.

Fig. 5.77 Cable rack bonding. Note the paint has been removed where the bonding strap connector lugs are fastened to the cable rack stringers.

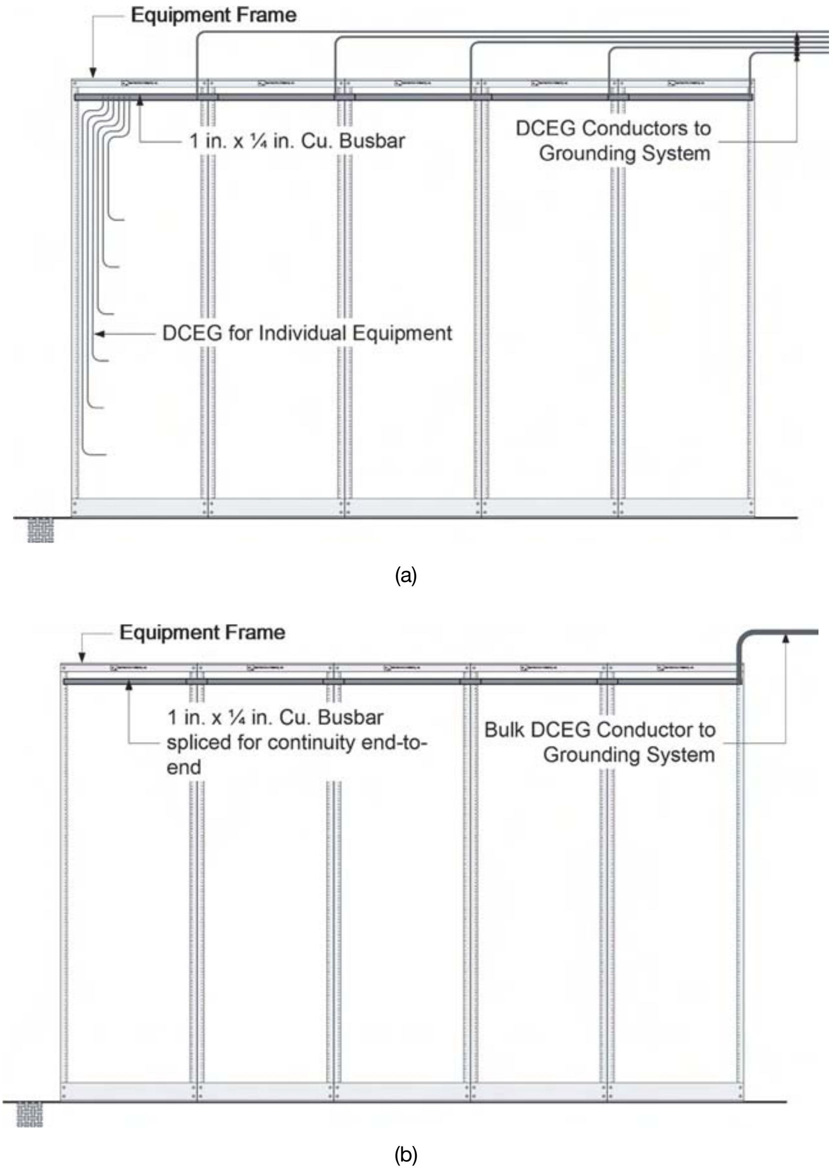
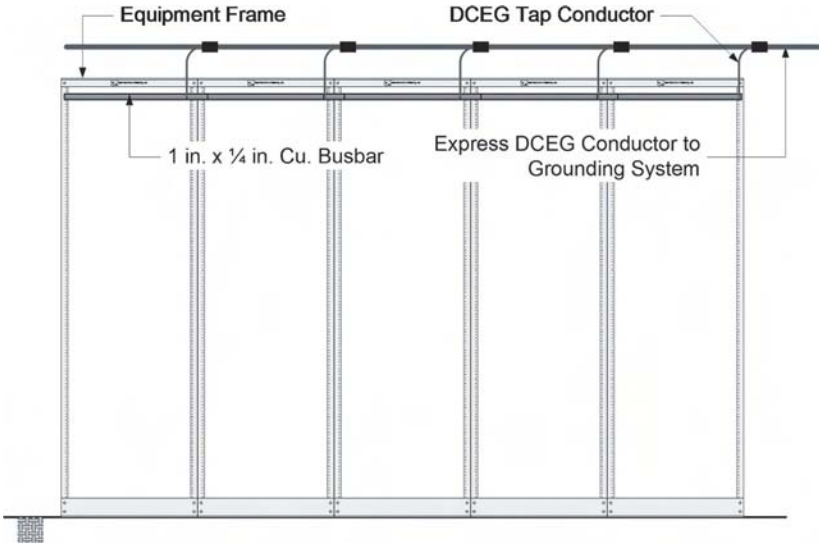


Fig. 5.78 Equipment frame bonding and grounding, showing the elevation view of a lineup of five equipment frame and the various bonding methods. (a) Equipment frame bonding using an individual conductor, (b) equipment frame bonding using a bulk conductor. (*continued*)

Method 2 Run a large “bulk” conductor from the grounding system to the end of the equipment frame lineup and bond to the equipment frame grounding busbar [Fig. 5.78(b)]. Although the minimum size of the bulk conductor is determined according to Section 5.9.3, it is common practice to use a conductor with a cross-sectional area equal to the sum of the cross-sectional areas of individual conductors that could be used in its place (method 1). Generally, this DCEG conductor is limited to 2/0 or 4/0 AWG unless the calculations in Section 5.9.3 require a larger conductor.



(c)

Fig. 5.78 Equipment frame bonding and grounding, showing the elevation view of a lineup of five equipment frame and the various bonding methods. (c) Equipment frame bonding using a tapped express conductor.

Method 3 Run a large "express" conductor from the grounding system to the equipment frame lineup and along the top of the lineup in the cable rack and then run a short tap from the express conductor to each frame [Fig. 5.78(c)]. The express conductor is sized as in method 2 above, and the tap conductors are sized as in method 1 above. This method is often used when the lineup has eight equipment frames or less or, for longer lineups, it may be used for each group of eight frames. Like method 1, this method can be used with or without the small busbar at the top of each frame, but the busbar still is useful for terminating small bonding leads from equipment shelves.

The selected method should take into account maintenance requirements as well as future addition or removal of equipment and equipment frames. Method 3 has the most flexibility in larger facilities.

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CHAPTER 6

SYSTEM INSTALLATION AND MAINTENANCE

PART I DIRECT CURRENT POWER SYSTEM INSTALLATION

This part covers telecommunications dc power system installation requirements that may lead to field questions or field problems and does not cover every aspect of dc power system installation. Except where industry standards are referenced, the discussions in this part represent various industry *practices* and the author's own experience and, as such, are presented as guidelines. The methods can be changed to suit company practices or specific installations, but the methods used in the field must always reflect good judgment and common sense. Some companies may have practices that differ significantly from those described here.

6.1 INSTALLATION SAFETY GUIDELINES

- Use factory insulated or taped tools when installing power equipment. Use a high-quality electrical tape; do not use cheap electrical tape like that available at automotive parts stores or department stores.
- Use only battery-powered or double-insulated power tools (double-insulated power tools should be regularly tested).
- Remove all jewelry, watches, metal-rimmed eye glasses, and belt buckles when performing any power system installation work.
- Wear safety goggles or a face shield and gloves when working with batteries.
- Wear safety glasses or face shields when working with hand tools.
- Do not use or place metal-framed ladders, metal desks, or metal chairs in the immediate vicinity of energized power equipment.
- Use nonconductive rulers (e.g., carpenter's folding wood ruler) in the vicinity of energized equipment; use a metal measuring tape only for floor measurements.
- Be alert and cautious when working in the vicinity of rotating equipment and tools especially when wearing loose clothing, neck ties, and long hair.

dc Power System Design for Telecommunications. By Whitham D. Reeve

- Protect working equipment from dust and debris with antistatic, fire-retardant tarps when drilling and vacuuming in the vicinity of equipment. Use tarps that meet the requirements of NFPA-701 [1] and are designed for telecommunications antistatic applications
- Use fire-retardant pegboard to protect fan-cooled equipment; remove the pegboard immediately after completion of the daily work.
- Place insulated blankets that meet the requirements of ASTM D1048-05 [2] over energized busbars and components and when working near energized busbars, terminations, and other power equipment.
- Remove drill shavings and other debris with a shop-type vacuum cleaner. The vacuum components that may contact electronic equipment should be made from insulating rubber or plastic materials.
- Place fiberboard or PVC floor mats on the floor to prevent scuffing and scratching power wire insulation during installation.
- Use electrostatic discharge (ESD) protective devices (e.g., grounded wrist straps) when handling and storing circuit packs and other sensitive electronic equipment.
- Use a vacuum cleaner or a drill equipped with a vacuum attachment when drilling floors, ceiling, and walls.

6.2 MATERIAL COMPATIBILITY

All metals used in the electrical system must be compatible to prevent galvanic corrosion (Table 6.1).[1] Generally, aluminum wiring is not used in telecommunications dc power systems because telecommunications workers seldom are trained in its correct application and installation. Occasionally, aluminum busbar will be found in existing installations. Connections to them must use connector lugs designed for the purpose (e.g., connector lugs suitable for both copper and aluminum conductors).

6.3 CIRCUIT WIRING

The dc power circuits always use paired conductor configurations. The following information is required to properly install circuit wiring:

- Circuit route or path
- Wire length
- Conductor size and bend radius
- Terminal connector lug type, width, fastener hole diameter and hole spacing
- Compression (crimping) tool and die that matches the terminal connector lug
- Fastener torque values
- Securing methods

[1] Galvanic corrosion (also called galvanic action) is caused by the electrical contact of dissimilar metals in the presence of moisture (electrolyte) causing the metal higher in the galvanic series (the more anodic or least noble) to corrode sacrificially.

Table 6.1 Material Compatibility

Conductor Material	Compatible Bracket, Terminal, and Hardware Material
Copper	Copper Bronze and brass[a] Silicon bronze Stainless steel Steel
Aluminum	Aluminum Steel Iron

[a] Because brass hardware has comparatively low strength, it should be used only where provided in factory assemblies.

Source: From [3].

6.3.1 Circuit Routing and Wire Length

To minimize the amount of material and installation effort, circuit wiring should follow the most direct and shortest route; however, this may lead to excessive pileup and congestion on some cable racks especially at cable rack junctions. Therefore, routes should be planned to distribute the power wiring as evenly as possible on the cable racks even if it means a longer run. If the route to be followed is longer than originally used in the circuit design calculations, it will be necessary to recalculate the voltage drop and possibly increase the wire size to keep the drop below the design value. The conductors of any given circuit, including all paralleled feed and return conductors, must follow the same route. Minimizing the length of low-voltage dc circuits is critical to maintaining voltage drop within the design requirements, especially in 24-Vdc systems.

6.3.2 Conductor Size and Bend Radius

Conductor sizes are determined on the basis of current rating and voltage drop criteria as described in Chapter 5, System Design. Where insulated wires are installed in cable racks and formed around corners and cable rack exit points, bending them too sharply may damage the conductors and insulation. The minimum bend radius for insulated wire is shown in Table 6.2 for ASTM B8 Class B (concentric-lay coarse-strand) and ASTM B172 Class I (bunch- or rope-lay fine-strand) wires.

Measurement procedure for cable bend radius after wire is placed on the cable rack:

- Place a framing square over the inside edge of the 90° bend (Fig. 6.1).
- Measure lengths A and B from the outside corner of the square to where the wire intersects the straight edge; A and B should be approximately the same.
- A and B should be $\geq$ minimum bend radius for the wire size.

A properly bent wire will show no visible deformation of the insulation. Improperly bent wire usually is obvious even if there is no deformation (Fig. 6.2). A conduit hickey never should be used to bend insulated wire because it may damage the insulation.

Table 6.2 Training Bend Radius for Stranded Wire[a]

Wire Size (AWG or kcmil) (1)	Recommended Bend Radius (in.) (2)	Minimum Bend Radius (in.) (3)
14	$1\frac{1}{2}$	$\frac{1}{8}$
12	$1\frac{1}{2}$	$\frac{1}{2}$
10	2	$\frac{1}{2}$
8	$2\frac{1}{2}$	1
6	$2\frac{3}{4}$	1
4	3	1
2	$3\frac{3}{4}$	$1\frac{1}{2}$
1	4	$1\frac{1}{2}$
1/0	$4\frac{1}{2}$	$1\frac{1}{2}$
2/0	$5\frac{1}{4}$	$3\frac{1}{2}$
3/0	$5\frac{1}{2}$	$3\frac{1}{2}$
4/0	$5\frac{1}{2}$	$3\frac{1}{2}$
250	$6\frac{1}{4}$	5
300	$6\frac{3}{4}$	5
350	$7\frac{1}{2}$	5
400	8	5
500	9	5
600	9	7
750	10	7
1,000	11	10

[a] Measured on the inside of the bend. Column (2) based on 8X wire outside diameter; Column (3) for Class B only [3]. This table applies to wires installed on cable racks and does not apply to wires installed in conduit or pulled over sheaves or other curved surfaces during installation, in which case larger bend radii may be required to limit sidewall pressure and to prevent insulation damage.

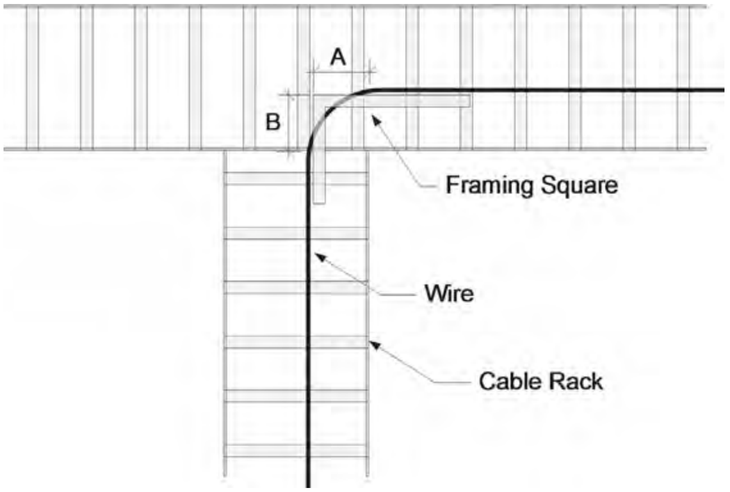

Fig. 6.1 Measuring wire bend radius with a carpenter's framing square. Place the square on the inside edge of the bend as shown and measure lengths *A* and *B* from the outside corner of the square to where the cable intersects the straight edge.

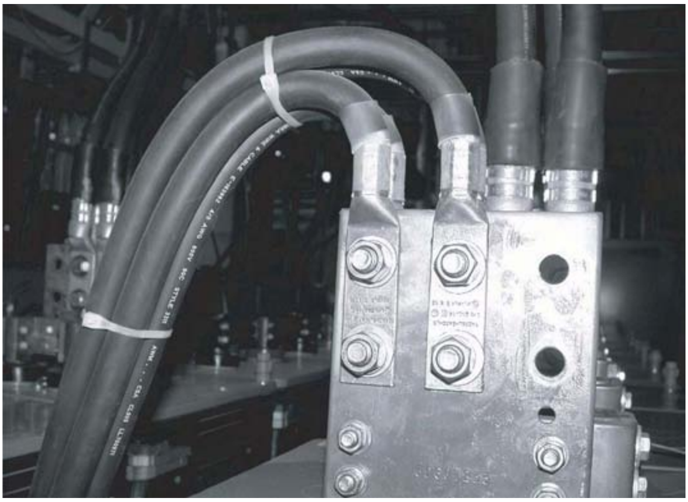

Fig. 6.2 Unacceptable wire bend radius at a battery terminal. (Photo courtesy of M.W. Migliaro.)

6.3.3 Cable Rack Fill

Generally, when wire is operated at or less than 25% load factor (actual load current divided by current rating), self-heating is negligible, and the wires can be installed with no separation and in multiple layers. When wire is to be operated at its free-air ampacity, only a single wire layer may be installed on a cable rack and the axial spacing between wire centers must be greater than two times their outer diameter (spacing between outer insulations equal to the wire outer diameter). For other installation conditions, such as reduced separation, wires touching, multiple layers, and bundled wires, the wires must be operated at derated ampacity values. See Chapter 5, System Design.

6.4 TERMINAL CONNECTOR LUGS

Five or six parameters must be known to properly specify connector lugs (Fig. 6.3):

- Conductor and termination material (usually copper–copper)
- Conductor size and strand configuration
- Connector type (compression or mechanical)
- Lug width
- Hole diameter
- Hole spacing (two-hole lug only)

Generally, connector lugs should be listed by a nationally recognized testing laboratory (NRTL)[2] and have the proper dimensions. Both irreversible compression and mechani-

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[2] NRTL is an organization recognized by the U.S. Occupational Safety and Health Administration (OSHA) to perform safety tests and list, label, or accept equipment or materials. Familiar examples of NRTLs are Underwriters Laboratory (UL) and Intertek Testing Services NA, Inc. (ITSNA, formerly ETL Testing Laboratories, Inc.). A complete listing of NRTLs may be found at http://www.osha.gov/dts/otpca/nrtl/index.html#nrtls.

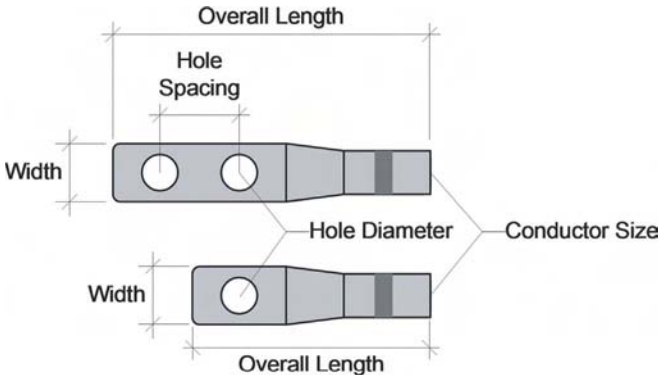

Fig. 6.3 Two-hole and one-hole connector lug dimensions.

cal connector terminal lugs may be used, but irreversible compression are preferred. The following sections describe both types in greater detail.

The conductor and connector lug materials in most installations will be copper–copper, and standard connector lugs rated for these materials are readily available. The fastener materials used with connector lugs and conductors also must be compatible as discussed in Section 6.2.

For the same conductor size (AWG or kcmil), fine-strand conductor diameter is larger than coarse-strand and a larger connector lug may be required. For example, consider 4/0 AWG stranded conductors of different classes as specified in ASTM standards (Table 6.3).

The diameters of Class A, B, C, and D wires are very close and the same connector lug may be used on any one of them. However, Class G and above are significantly larger, and it is unlikely that a connector designed for, say, Class B (coarse) stranding will work for Class I (fine) stranding. Generally, but not always, the connector lug for Class I wire is two sizes larger than for the same AWG or kcmil Class B wire.

6.4.1 Compression-Type Connector Lugs

Compression-type connector lugs use either a circumferential crimp or indent crimp to hold the conductor in the connector barrel. Generally, circumferential crimps are recommended for low-voltage applications. Many tools used to install connector lugs are ratchet-types that, once the compression begins, do not release until the lug is properly

Table 6.3 Diameter of Different 4/0 AWG Stranded Conductor Classes

ASTM	ASTM B-8				ASTM B-173		ASTM B-172		
Class[a]	A	B	C	D	G	H	I	K	M
No. Strands	7	19	37	61	133	259	532	2107	5320
Diameter (in.)	0.522	0.528	0.529	0.530	0.599	0.601	0.613	0.627	0.645

[a] Fine-strand conductors, Class G through M, generally are not recommended for use as grounding and bonding conductors because the strands do not adequately carry surge currents.

crimped. When a circumferential crimp is made, the tool die index is embossed on the barrel to allow the connector and die combination to be easily verified. Crimped barrels may be covered with heat-shrink tubing; however, clear tubing should be used so the crimp may be examined later during routine site inspections.

The shape of the crimp varies with the connector manufacturer and may be square (also called diamond or box), hexagonal, or other shape. It is the practice of some companies to use only hexagonal crimps. Although compression lugs cost more than mechanical lugs because of the tooling, the bond between the connector and conductor is superior to mechanical lugs. The compression provides a gas-tight molecular bond between the lug and conductor with little chance for oxidation of the conductor material (Fig. 6.4).

For indent connectors, the tool compresses the connector barrel and wire strands by deeply indenting the barrel on one side. Indent connectors can be used for any application except small insulated ring- or fork-lug terminals and splices. Indent compression works well for terminating fine-strand wire; however, the tool must be properly matched to the connector lug.[3]

6.4.2 Mechanical-Type Connectors

Mechanical-type connector lugs use a wrench-tight bolt (or screw) and clamp to hold the conductor in the connector barrel (Fig. 6.5). Mechanical connectors have a tendency to loosen over time due to thermal expansion and contraction even if properly tightened during installation. Generally, mechanical-type connectors should be avoided unless the termination is specifically designed for use only with a mechanical connector. In some cases, mechanical connectors will be used when the correct compression connector cannot be located or obtained in time for the job.

Set screw-type connectors (Fig. 6.6) should not be used with fine-strand wire because the set screw will damage the individual strands and will not adequately hold the conductor. The only kind of mechanical connector that should be used with fine-strand wire is one that completely encases all the strands (such as a V-shape clamp). The conductor size should be toward the lower end of the connector's range. For example, say the ranges of two connectors are 300 to 500 kcmil and 500 to 800 kcmil. The recommended connector for Class I 500-kcmil wire would be the larger 500- to 800-kcmil connector.

6.4.3 Connector Lug Installation Guidelines

- Use the proper connector lug for the conductor size being terminated as specified in the manufacturer's catalogs.
- Use irreversible compression-type connector lugs with fine-strand wire wherever possible.
- Do not use abrasive paper or pads on plated lugs; unplated copper lugs may be cleaned with abrasive paper or pads (see Section 6.6.11 for methods).
- Use flat washers under bolt (screw) heads and under all nuts unless specified otherwise by the equipment manufacturer.
- Use two-hole terminal connector lugs for all connections unless the lug landing does not accommodate a two-hole lug.

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[3] Indent compression (nest indentors) should not be used on aluminum wire.

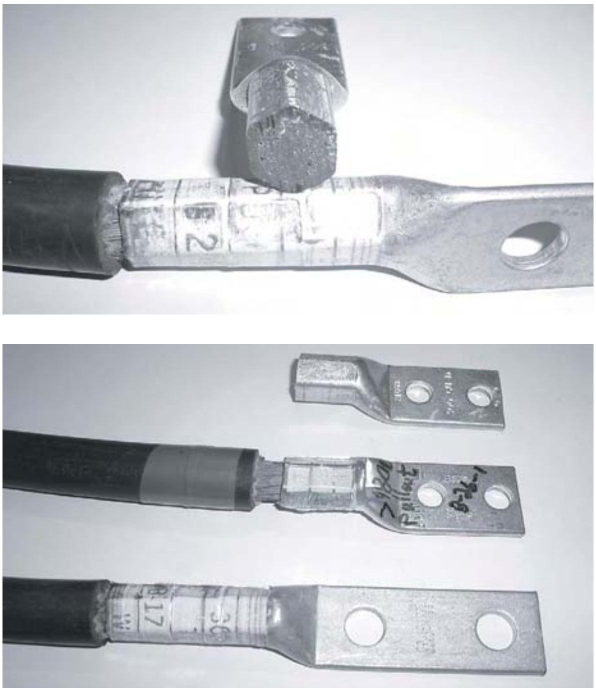

Fig. 6.4 Compression-type connector lugs. (*Top photo*) The upper lug was crimped to a fine-strand wire and then cut for examination. Note that the crimp was hexagonal and that the individual strands are almost invisible. The lower lug shows embossing from the crimping operation. (*Bottom photo*) The lug in the middle was subjected to tension during a pull test that exceeded its rated pull-out force. Note that the middle lug has a standard barrel and the lower lug has a long barrel. The upper lug is the same one shown in the top photo.

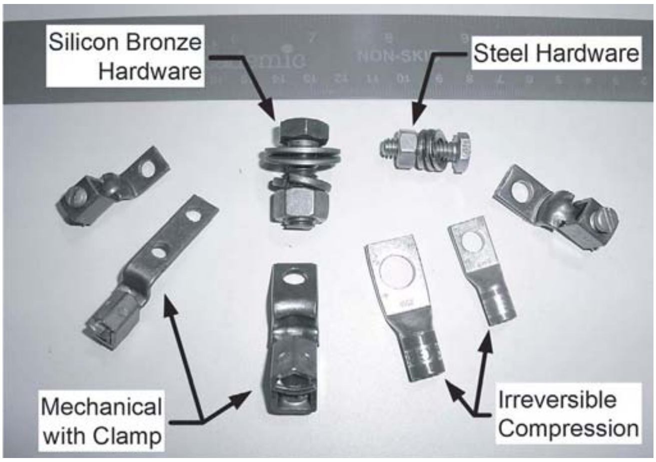

Fig. 6.5 Mechanical connector lugs. Four small clamp-type mechanical connector lugs are shown with two short-barrel compression lugs. For size comparison, the two compression lugs are for 4 AWG and $\frac{3}{8}$-in. stud (left) and 6 AWG and $\frac{1}{4}$-in. stud (right).

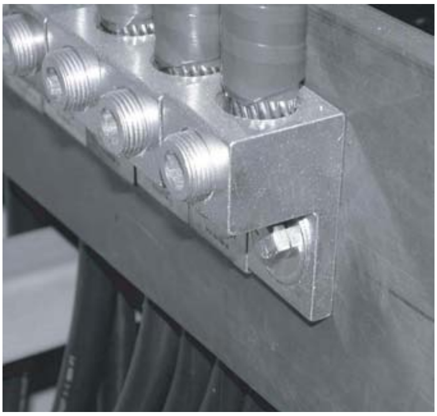

Fig. 6.6 Set-screw mechanical connector lugs used with coarse-strand wire. Set-screw types damage both fine and coarse strands and are not recommended in low-voltage applications. Other deficiencies shown in this photo are the one-hole lug and no apparent oxidation inhibitor. (Photo courtesy of M.W. Migliaro.)

- Where a one-hole lug must be used, install it with flat and lock washers under the nut (with lock washer closest to the nut) or use a self-locking nut instead of a lock washer. If attaching to a captive nut, use a flat washer under the bolt (screw) head.
- Choose a bolt or screw length such that when installed the threaded end does not protrude beyond the nut more than one diameter.
- Use long-barrel lugs wherever possible (the extra conductor-barrel contact area is important in low-voltage applications).
- Never attempt to crimp more than one stranded wire in a connector lug unless the lug is specifically designed for more than one wire.
- Never attempt to crimp solid wire in a connector lug unless the lug is specifically designed for solid wire.
- Do not remove strands from a larger wire to fit a smaller connector lug.
- Do not fold a smaller wire to fit a larger connector lug.
- Strip only enough insulation such that the gap between the wire insulation and the connector barrel end is less than $\frac{1}{16}$ in. (shiner length), and never allow the insulation to extend into the connector barrel. Some lugs have a built-in stripping gauge.
- When stripping 8 AWG and larger wire, use a sharp electrician's knife and a whittling motion so that the strands are not damaged; alternately, use a properly adjusted stripping tool specifically made for the conductor size and with cutting blades adjusted properly for the insulation thickness.
- Always use a stripping tool on 10 AWG and smaller wire.
- Scuff untinned conductors with a wire brush (do not scuff or sand tinned conductors) and then coat the conductor with oxidation inhibitor before crimping (Table 6.4) (some connector lugs are factory filled with oxidation inhibitor in which case the conductor does not need to be coated).
- Insert the conductor to the full depth of the connector lug barrel before compressing (some connector lugs have an inspection hole).

- Do not crimp in the tab area.
- Larger lugs require more than one crimp (the number of crimps is marked on the barrel by bands); do not overlap crimps.
- Apply the first crimp nearest the connector tab and crimp successively toward the barrel end—do not skip. On splice connectors, apply the first crimp adjacent to the center and crimp successively in both directions toward the barrel ends.
- Use a flashing cutter to remove the flashing left on the barrel where the die jaws come together.
- Generally, place only one lug on a lug landing location; however, where necessary to place more than one connector lug on a lug landing because of space constraints, various stacking means are available (Fig. 6.7).
- To provide a neat appearance, do not cut wire to final length and do not install the connector lugs until the wires have been formed and secured.

6.4.4 Insulated Terminal Connector Lugs for Small Wire

Color-coded insulated terminal lugs may be used only with the proper conductor sizes (Table 6.5). These types of lugs are not designed for solid conductors (the barrels are soft copper and cannot adequately grip a solid conductor). However, there may be situations where it is necessary to use solid wire with ordinary soft copper insulated terminal lugs. If so, follow these steps:

1. Pull the barrel insulator off the lug and discard.
2. Slip a piece of heat-shrink tubing over the wire (the tubing must be large enough to slip over the barrel).
3. Strip and insert the conductor. The shiner length should be $\leq \frac{1}{32}$ in. and the conductor should protrude $\frac{1}{32}$ to $\frac{1}{16}$ in. beyond the barrel toward the ring or fork tab.
4. Crimp with a tool made for uninsulated terminal lugs (either oval crimp or indent crimp).
5. Solder the crimped conductor to the lug being sure to fill the barrel with solder.
6. Slip the heat-shrink tubing over the barrel and shrink with a heat gun.

Table 6.4 Oxidation Inhibitors

Brand Name	Manufacturer	Address	Remarks
Penetrox-E	Burndy	www.fciconnect.com	Cu–Cu, contains copper dust
Noalox	Ideal	www.idealindustries.com	Cu–Cu, contains zinc dust
NO-OX ID “A-Special”	Sanchem	www.sanchem.com	Soft, wax based with small amount of solvent. This type of oxidation inhibitor typically is used on terminal pads or busbars (flat mating surfaces) and is not used to coat conductors before installation in a connector lug barrel
Cual-Gel	Penn-Union	www.penn-union.com	Cu–Cu, contains copper dust

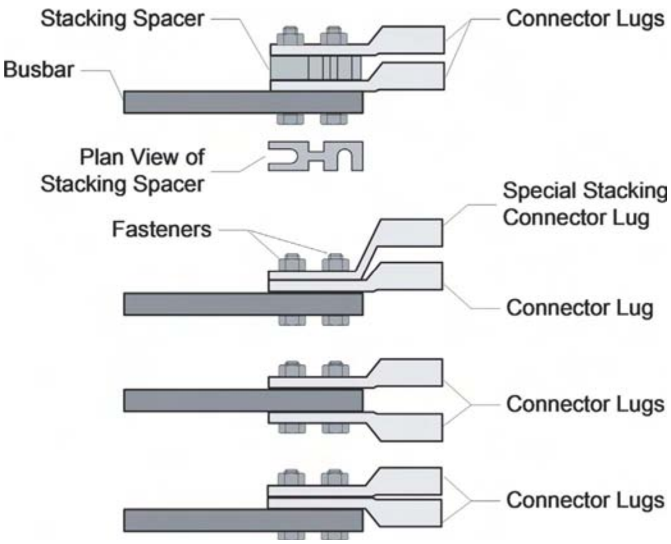

Fig. 6.7 Stacking configurations for terminal connector lugs.

Table 6.5 Insulated Terminal Lugs

Terminal Lug Insulator Color	Stranded Conductor Size Range (AWG)
Red	22–18
Blue	16–14
Yellow	12–10

6.4.5 Insulated Terminal Lug Installation Guidelines

- Strip wire insulation such that the shiner length ≤ $\frac{1}{32}$ in. unless the barrel insulator is bulged to accommodate the insulation; in this case, strip the insulation so that it may be inserted in the insulator but not in the lug barrel.
- Strip insulation and insert wire so that it protrudes between $\frac{1}{32}$ and $\frac{1}{16}$ in. beyond the end of the barrel toward the ring or fork tab.
- Apply only one barrel crimp and one insulator crimp using a crimping tool that has a full-cycle ratchet mechanism. Some tools simultaneously crimp both barrel and insulator.

6.5 FASTENERS

The main application parameters for fasteners (bolts, screws, nuts, and washers) are

- Diameter
- Length

- Thread pitch
- Material strength
- Material compatibility

Bolts are headed, externally threaded fasteners that are meant to be tightened by turning a nut. Screws are headed, externally threaded fasteners that are meant to be tightened into a preformed internal thread or by forming its own thread while being turned. The two terms are often used interchangeably, but in common usage a screw generally is $\frac{1}{4}$ in. or less in diameter and has a slotted or cross-recessed (e.g., Phillips) head.

Nonmetric fastener dimensions (diameter and length) in the United States are in inches and thread pitch is in inches/thread (e.g., a $\frac{3}{8}$-16 designation indicates $\frac{3}{8}$-in. diameter bolt with a thread pitch of $\frac{1}{16}$ in./thread). The corresponding tightening torque values are specified in inch-pounds (in.-lb) or foot-pounds (ft-lb.) Metric dimensions frequently are used in new equipment and some equipment may have a mixture of metric and nonmetric. Metric fastener size designations begin with M or MJ followed by nominal diameter and thread pitch, both in millimeters and separated by "x" (e.g., M6x1 indicates 6 mm nominal diameter and 1 mm thread pitch). For metric fasteners the default thread pitch is coarse (also called regular) and may be omitted from the designation (e.g., M6 indicates 6 mm nominal diameter and standard coarse thread pitch). Metric torque values usually are specified in newton-meters (N-m).

Fasteners must be properly tightened. When fasteners are tightened by applying torque to the head or nut, the thread helix converts the torque to a tensile force (tension or preload) and the bolt stretches. The preload clamps the material between the head and nut and holds the joint together. In electrical applications the parts in the joint may be subjected to mechanical forces from vibration, shock (shipping, handling, installation, and seismic events) and thermal cycling, and proper clamping is essential to keep them from loosening and to ensure a low-resistance connection.

Torque values can be determined from the fastener's characteristics and required clamping force

$$T_q = KF_CD \quad \text{in.-lb} \tag{6.1}$$

where T_q = torque (in.-lb)
K = coefficient of friction (0.2 for ordinary fasteners used in electrical work)
F_C = clamping force (lb)
D = nominal diameter (in.)

The clamping force generally is 75% of the proof load force on the fastener, or

$$F_C = 0.75S_pA_S \tag{6.2}$$

where S_p = proof load (lb/in.^{2})—see below
A_S = bolt or screw stress cross-sectional area (in.^{2})

The proof load is the tensile load a fastener must support without permanently deforming. Proof loads generally are a high fraction of the minimum yield strength of the fastener material. For example, the proof load of SAE Grade 2 fasteners, which are made from low or medium carbon steel, is approximately 96% of the yield strength (Table 6.6).

Table 6.6 SAE Grade 2 Mechanical Properties for $\frac{1}{4}$–$\frac{3}{4}$ in. Diameter Fasteners[a]

Minimum Strengths (lb/in.^{2})		
Proof Load	Tensile Strength	Yield Strength
55,000	74,000	57,000

[a] Grade 2 bolts do not have any grade identification marks on the head.

Combining Eqs. (6.1) and (6.2) gives

$$T = K \times 0.75 S_p A_S D \quad \text{in.-lb} \tag{6.3}$$

Torque values for nonmetric fasteners are given in Table 6.7 and for metric fasteners in Table 6.8. These values may be used when more specific information is not available from the fastener manufacturer; however, manufacturers always should be consulted when in doubt.

The following conversion factors may be used to convert torque value units:

- To convert from inch-pound to newton-meter, multiply in.-lb by 0.11298
- To convert from newton-meter to inch-pound, multiply N-m by 8.8507
- To convert from newton-meter to foot-pound, multiply N-m by 0.7376
- To convert from inch-pound to foot-pound, multiply in.-lb by 0.08333
- To convert from foot-pound to inch-pound, multiply ft-lb by 12

Table 6.7 Suggested Torque Values for Nonmetric Fasteners, Applicable to Unlubricated, Unplated Steel, Stainless Steel and Silicon-Bronze Fasteners[a]

Fastener Size (1)	Nominal Diameter (in.) [7] (2)	Tensile Stress Area (in.^{2}) [7] (3)	Hex-Head Cap Bolt (in.-lb) [4] (4)	Slotted-Head Cap Screw (in.-lb) Calculated (5)	Hex-Head Cap Bolt (in.-lb) Calculated (6)
6-32 UNC	0.1380	0.00909	—	10	—
8-32 UNC	0.1640	0.0140	—	19	—
10-24 UNC	0.1900	0.0175	—	27	—
12-24 UNC	0.2160	0.0242	—	43	—
1/4-20 UNC	0.2500	0.0318	80	66	66
5/16-18 UNC	0.3125	0.0524	180	—	135
3/8-16 UNC	0.3750	0.0775	240	—	240
7/16-14 UNC	0.4375	0.1063	—	—	384
1/2-13 UNC	0.5000	0.1419	480	—	585
9/16-12 UNC	0.5625	0.182	—	—	845
5/8-11 UNC	0.6250	0.226	660	—	1,165
3/4-10 UNC	0.7500	0.334	1,050	—	2,067

[a] The torque values given in column (4) are cited in NEMA CC 1-2002 [4] and should be used as defaults for the bolt sizes shown; columns (5) and (6) are calculated from Eq. (6.3). Differences between column (5) and (6) are due to different proof load force assumption.

Table 6.8 Suggested Torque Values for Metric Fasteners Used on Electrical Connections (Class 5—Equivalent to SAE Grade 2)

Cap Screw Size (1)	Nominal Diameter (mm) (2)	Tensile Strength Area (mm^2) (3)	Torque (N-m) (4)
M2	2	2.1	0.2
M3	3	5.0	0.9
M4	4	8.8	2.0
M5	5	14.2	4.0
M6	6	20.1	6.9
M8	8	36.6	16.7
M10	10	58.0	33.0
M12	12	84.3	57.5
M16	16	157.0	142.9
M20	20	244.8	278.5

The accuracies of various tightening methods are shown in Table 6.9. Although a torque wrench is not the most accurate method of tightening fasteners, it is adequate, inexpensive, and simple to use in the field. A high-quality torque wrench (e.g., click-type, micrometer-adjustable torque wrench shown in Fig. 6.8) should be used in all electrical installation work; cheap automotive style (needle- or beam-type) torque wrenches should not be used because they cannot be insulated and they are inaccurate. In some specific applications, for example, when tightening connections to large semiconductors, the turn-of-nut method may be specified. In this case, the nut is finger tightened (or wrench tightened to contact) and then a wrench is used to tighten a specified number of turns beyond.

6.5.1 Fastener Installation Guidelines

- Use oxidation inhibitor on the joints of all electrical connections.
- Use pan-head or hex-head cap screws.[4]
- Use SAE[5] Grade 2 steel or equivalent for slotted machine and hex cap screws.
- Use fasteners and hardware made from silicon bronze, 316 stainless steel, or steel that has a corrosion protective finish.
- Use lock washers, disk spring washers (Belleville washers), or self-locking nuts on connections subject to vibration or thermal expansion and contraction.
- To minimize torque and the chance of stripping the threads on tapped copper busbars < $\frac{1}{4}$-in. thick, use only slotted No. 8-32, No. 10-32, 12-24, or $\frac{1}{4}$-in. machine screws. Where larger size screws or bolts are required, drill out the busbar and use nuts.

6.5.2 Belleville Washers

Belleville washers originally were developed for use with relatively soft aluminum busbar to overcome connection problems due to creep of the busbar material (cold-flow under

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[4] Cap screw is a general term used to describe hex-head, slotted-head, square-head, and socket-head screws.

[5] Society of Automotive Engineers, or SAE International (www.sae.org).

Table 6.9 Accuracy of Bolt Tightening Methods [1]

Method	Accuracy (%)	Method	Accuracy (%)
By feel	± 35	Computer-controlled wrench	
Torque wrench	± 25	Below yield point	± 15
Turn-of-nut	± 15	Yield-point sensing	± 8
Preload indicating washer	± 10	Bolt elongation	± 3–5
Strain gauge	± 1	Ultrasonic sensing	± 1

pressure). However, they also are used in many other electrical applications, including copper–copper connections that carry high currents and are subject to thermal cycling (expansion and contraction).

A Belleville washer also is known as a cupped spring washer, constant-force disk spring washer, compression washer, and conical washer. It has a slight conical or cup shape, which gives the washer a spring characteristic. When the fastener and washer combination is tightened, the washer is compressed or flattened a certain amount and exerts an opposing force on the threads. This force compensates for any creep or expansion and contraction in the joint materials.

Three parameters define the characteristics of the disk spring washer—torque, diameter, and finish. The torque of the washer must match the torque of the bolt. If the washer is compressed too much (a few percent) by overtorque, the locking action and the washer will be ruined. Undertorque does not compress the washer enough and the connection will be loose. A disk spring washer generates a clamping force along its outside edge or cup perimeter. If the washer diameter is too large and overhangs the connection, it will not clamp properly. Large flat washers never should be used under the disk spring washer to compensate for overhang since the flat washer will deform rather than transmit the force to the connection. However, in copper busbar applications, a hardened thrust washer frequently is installed underneath the disk spring washer to eliminate face damage and indentation (Fig. 6.9). Disk spring washers used in battery rooms should not have an electroplated finish because of the possibility of hydrogen embrittlement.

Fig. 6.8 Click-type, micrometer adjustable torque wrench. This wrench is about 12 in. long and has a $\frac{3}{8}$-in. drive. The torque is set by rotating the handle to the desired micrometer setting.

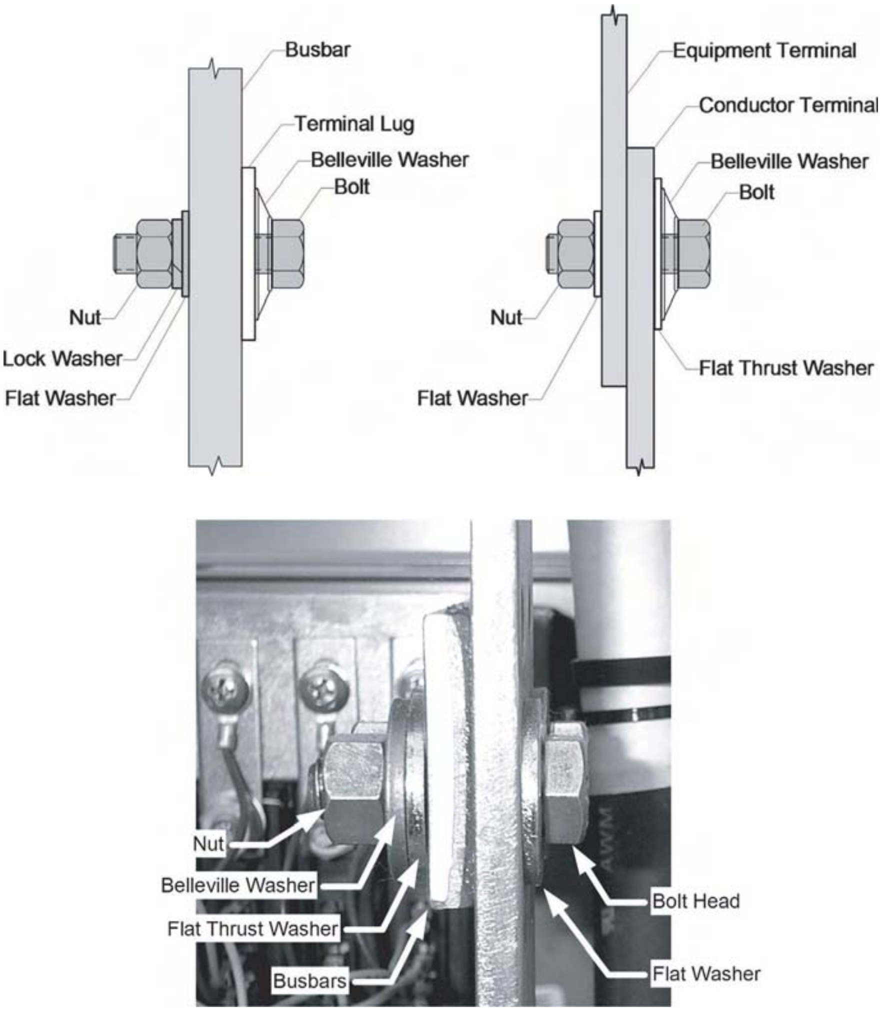

Fig. 6.9 Belleville washer applications. The "cup" of the cone points toward the flat surface and the "peak" points toward the fastener head (*upper two drawings*) or nut (*lower photograph*).

Disk spring washers are installed with their cup pointed toward the contact surface. Most disk spring washers have a shallow cup (approximately 10 to 20 thousandths of an inch), which may be difficult to discern. In this case, the washer may be laid on a flat surface and viewed from the side (Fig. 6.10).

A little practice is required to correctly tighten a fastener assembly with a disk spring washer, and extra washers should be ordered for any job to allow for ruining a few. As the washer is compressed, an abrupt change will be felt in the wrench when the washer flattens. Overtightening (overflattening) usually ruins the washer. Disk spring washers normally are compressed no more than 75% of their total possible deflection. When more than one set of fasteners is used in a joint or connection, each fastener should be partially tightening in turn and in multiple stages. Some manufacturers recommend that the washer be flattened and then backed off slightly.

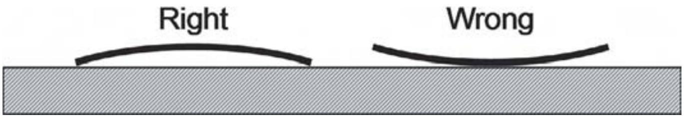

Fig. 6.10 Belleville washer orientation.

6.6 POWER WIRING INSTALLATION

6.6.1 Routing Guidelines

- Run unprotected battery circuit wires (i.e., circuits with no overcurrent protection) on a separate cable rack from protected circuit wires.
- Run power system control cables (e.g., voltage sensing and rectifier control cables) with physical separation from dc power circuit wires.
- Run all circuit wires (feed and return) as pairs, side-by-side on the cable rack (Fig. 6.11).
- Lay wire evenly in the cable rack and wiring troughs (Fig. 6.12).
- Group small wires in bundles approximately the same size as larger wires in the same layer, but, if laced, do not exceed the maximum number of wires per stitch (see Section 6.6.3).
- Avoid twisting the wires.
- Avoid crossovers wherever possible.
- Plan and lay wire runs so they can easily exit the cable rack where required.
- During installation, run multiple wires simultaneously wherever possible.

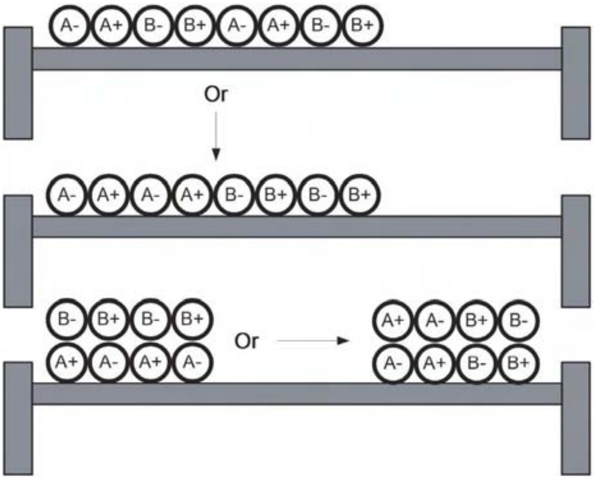

Fig. 6.11 Power wire polarity arrangements on cable rack. Polarity shown for parallel wires in one circuit or individual circuits in one layer (*upper and middle*) and two layers (lower). For more than two layers, extend the sequence shown in the lower drawing.

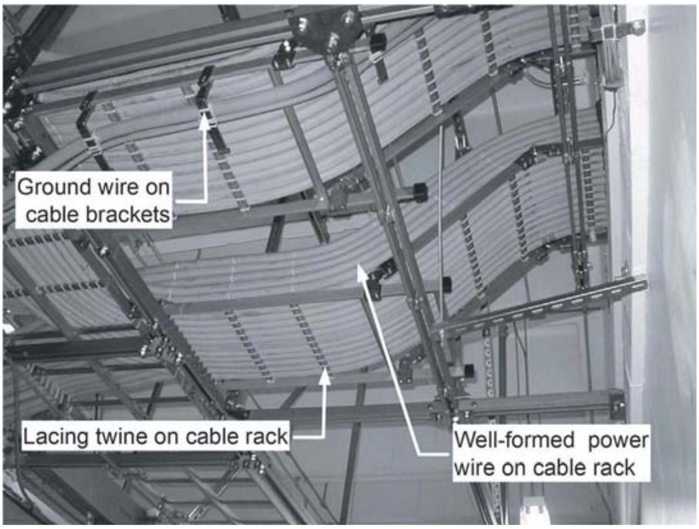

Fig. 6.12 Even forming and lacing of power wires. Note sloped "waterfall" cable rack arrangement where an elevation change was needed. (Photo courtesy of Schultz Brothers Electrical Company.)

- When forming wire vertically down toward equipment shelves from the cable rack, start forming at the top and bundle downward.
- Form wires in such a way that outside wires do not disappear into the bundle.
- Do not bundle power wires with signal cables.
- Where only one level of cable rack is available, and a larger number of signal cables than power wires needs to be run, run the power wires on stand-off brackets mounted on the cable rack stringers; in the reverse situation, run the signal cables on stand-off brackets.
- Never route wires through or between cable rack cross members; always route wires over the side of the cable rack stringers.
- Never route power wires through cable rack wall brackets.
- To avoid accidental shorts during installation, always tape the bare ends of cut power wires before running.
- Do not fill a cable hole more than 75% of its cross-sectional area, and do not place cables closer than 3 in. to edges of cable holes (there must be adequate space for fire-stopping materials).
- On vertical runs in equipment frames, route the dc load circuit wires closest to the framework for lower mounted equipment shelves or chasses, progressively moving the circuit wires outward for higher mounted shelves.

6.6.2 Guidelines for Securing and Physically Protecting Power Wiring

- Provide a neat appearance by banding the wire leaving cable racks and entering equipment frames.
- Secure power wires on every cable rack cross member (every 9 in.) on vertical runs (any run that is > 60° from horizontal is considered vertical) and on at least every

fourth cross member (every 36 in.) on horizontal runs; it is typical practice to secure on every other cross member on horizontal runs.

- Secure wires where they leave the cable rack (Fig. 6.13).
- Support 1/0 AWG and smaller power wire no farther than 24 in. and 2/0 AWG and larger wire no farther than 36 in. after leaving a cable rack and entering an equipment frame. Secure the wires at the first support at the top of the equipment frame.
- Secure power wires within 36 in. of their termination point.
- Use lacing twine or cable ties (tie-wraps) to secure power wires; see respective guidelines.
- Protect all wires with sheet fiber (vulcanized fiber sheet or "fish paper") wherever passing over cable rack stringers or coming into contact with sharp edges.
- Protect soft rubber and neoprene insulated power wires from compressive damage and sharp edges with sheet fiber where it is secured (Fig. 6.14); wrap with two layers of $\frac{1}{64}$-in. or one layer of $\frac{1}{32}$-in. sheet fiber. Insulated wires with a "textile" (cotton braid) jacket or a cross-linked polyethylene (XLPE) jacket normally do not require sheet fiber protection where they are secured, but extra protection should be provided where they can rub metal edges.
- Install permanent labels on all power wires near their termination; use tie-wraps or lacing twine to fasten the labels.
- Do not use a pileup larger than 7 in. on vertical runs.
- If a vertical run exceeds three floors, break it up with a 20 ft horizontal run (see Chapter 5, System Design).
- To prevent sag at corners or junctions, install a $\frac{1}{8}$-in. × 1-in. flat steel bar diagonally across the corner and secure with lacing twine (Fig. 6.15).

Vulcanized fiber sheet, commonly called fish paper, may be obtained in sheets, rolls, and hollow tubes and is specified in ASTM D710-97, Standard Specification for Vulcan-

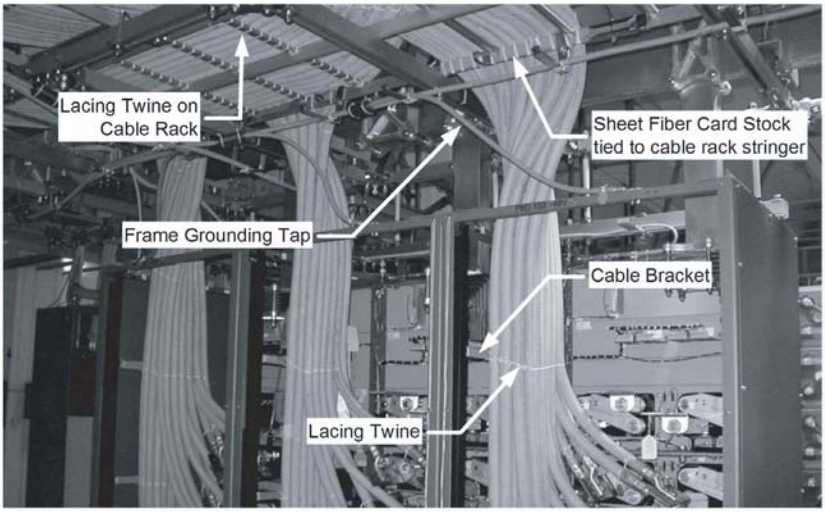

Fig. 6.13 Securing power wires. (Photo courtesy of Schulz Brothers Electric Company.)

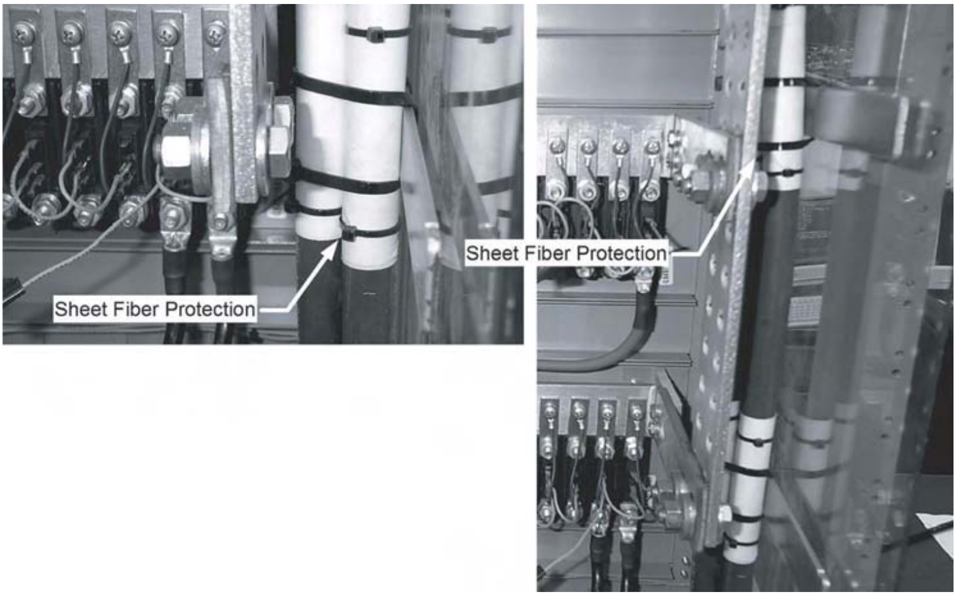

Fig. 6.14 Protecting insulation with vulcanized fiber card stock (fish paper). Note sheet fiber cards wrapped around wires adjacent to bolt heads and held in place with cable ties.

ized Fibre Sheets, Rods and Tubes Used for Electrical Insulation.[6] Fish paper originally was made from old cotton rags that were treated with zinc chloride to dissolve the cellulose. The paper obtained from this process does not have a definite fiber structure but is hard and tough in both directions and does not delaminate. Although most commonly used as electrical insulation (it has a dielectric strength of 200 to 400 V/mil), its purpose here is to provide physical protection of the wire insulation wherever the insulation could be abraded or deformed.

6.6.3 Lacing (Stitching or Sewing) Power Wires

Two lacing stitches are most commonly used: “Kansas City” and “Chicago” stitches. Generally, the Kansas City stitch is used to secure power wires to cable rack cross members, cable brackets, and supports, and the Chicago stitch is used to band wires where not secured. Both use the same starting stitch method as shown in Figure 6.16(a). Subsequent stitches differ. Refer to Figure 6.16(b) for the Kansas City stitch on the first layer and Figure 6.16(c) for the second and subsequent layers. Refer to Figure 6.16(d) for the Chicago stitch and Figure 6.16(e) for ending either the Kansas City or Chicago stitches with a square knot or Hawthorne knot. Finally, refer to Figure 6.16(f) for a method to splice double twine.

Lacing twine generally is installed in multiples of two strands. The required number of lacing twine strands and number of wires held by each stitch depend on the wire size and whether the wires are run horizontally or vertically (Table 6.10).

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[6] The name fish paper is thought to come from its original use as a tabletop surface in the London fish markets.

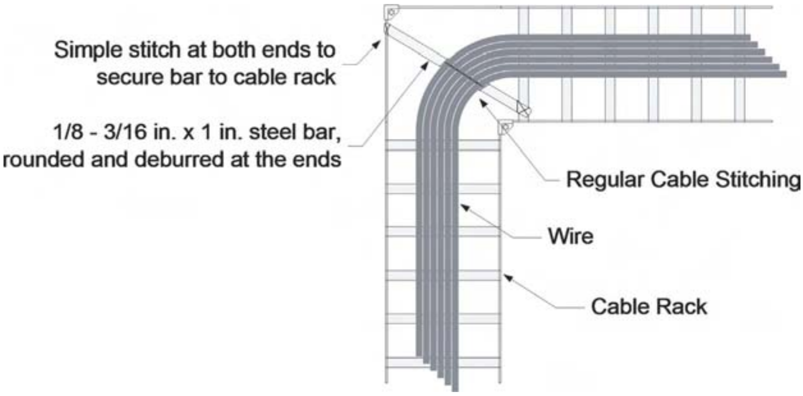


Fig. 6.15 Plan view of wire support at turns and corners using a locally fabricated steel bar.

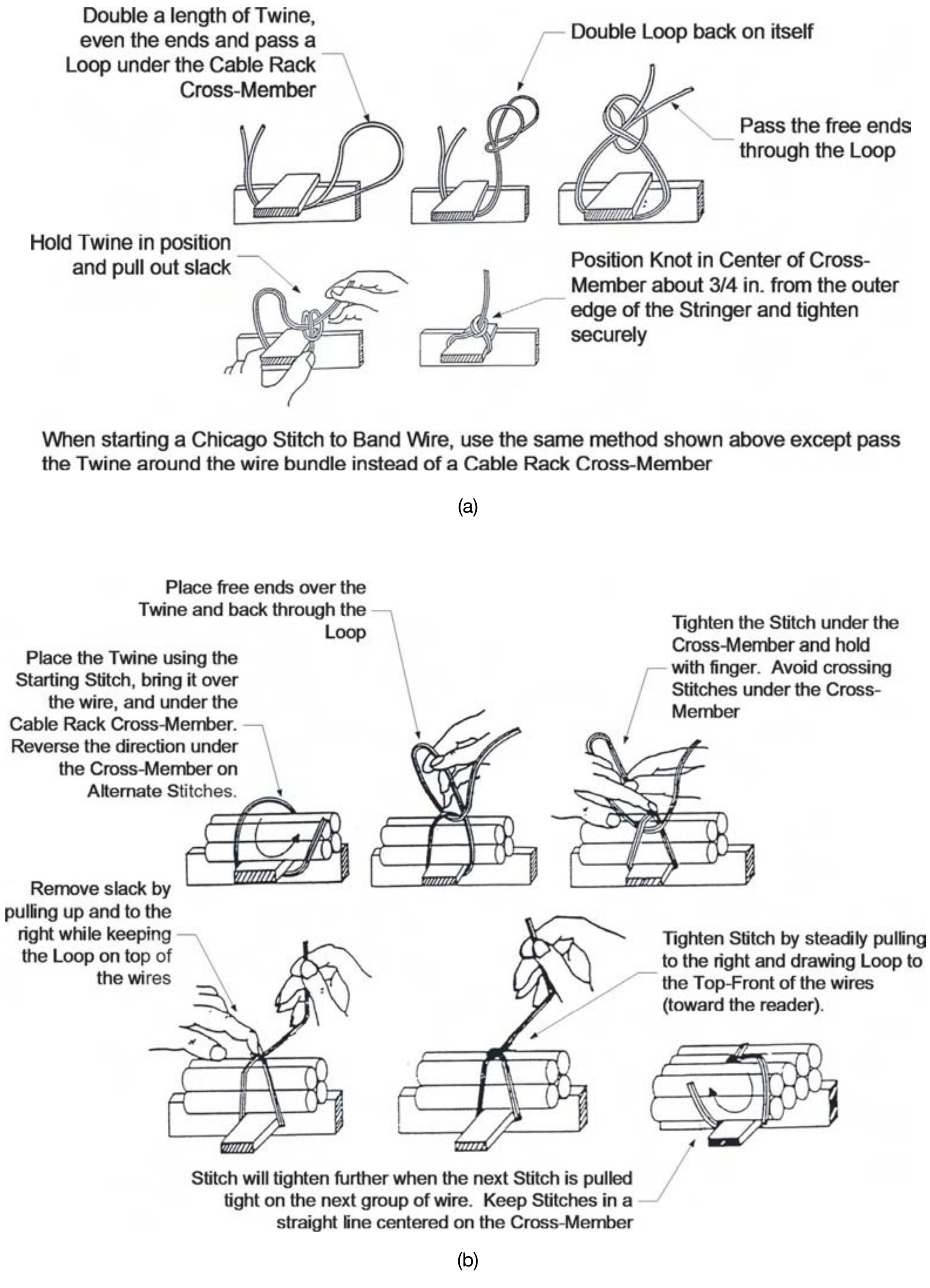
6.6.4 Using Cable Ties on Power Wiring

Cable ties (tie-wraps) are controversial because they are sometimes used improperly. If applied and installed properly, they can be a time saver and will provide a trouble-free and safe installation. The two main objections to their use with power wire is the possibility of insulation creep (cold-flow) under the tie and personnel injury and insulation damage caused by the sharp edges left by improperly cut tails. Although both problems can be mitigated by proper installation and application, some company practices do not allow cable ties except in limited circumstances.

Although cable ties are available in a number of different materials, the most common in electrical installations are nylon and vinyl. Nylon is hygroscopic (absorbs moisture from the air) whereas vinyl is nonhygroscopic and performs better in both low- and high-humidity environments.

6.6.5 Cable Tie Application and Installation Guidelines

- Do not overtighten and do not tighten so much that the wire insulation is deformed.
- Use the cable tie manufacturer's recommended tool for tensioning and cutting; generally, the tool is set to 18 lb tension and cuts off the tail flush with the tie head. If the manufacturer's tool is not available or cannot be used, ties may be tightened by hand; however, do not overtighten the tie and always use a flush cutting tool and check for a sharp edge at the "eye" of the tie. If a sharp edge exists and it cannot be placed in a position that eliminates the possibility of personnel injury or other problem, quickly touch the sharp protrusion with the flat side of a hot soldering iron tip (being careful to keep the hot soldering iron parts from touching anything else). Note: Some fire detection systems may detect smoke from hot soldering irons.
- Use cable ties to band wires where they leave a cable rack and between L-brackets mounted on cable rack stringers.
- Use cable ties to band fiber card stock to cable rack cross members and stringers, but be sure to locate the cable tie head where it cannot contact the insulation on other wires.



Double a length of Twine, even the ends and pass a Loop under the Cable Rack Cross-Member

Double Loop back on itself

Pass the free ends through the Loop

Hold Twine in position and pull out slack

Position Knot in Center of Cross-Member about 3/4 in. from the outer edge of the Stringer and tighten securely

When starting a Chicago Stitch to Band Wire, use the same method shown above except pass the Twine around the wire bundle instead of a Cable Rack Cross-Member

(a)

Place free ends over the Twine and back through the Loop

Place the Twine using the Starting Stitch, bring it over the wire, and under the Cable Rack Cross-Member. Reverse the direction under the Cross-Member on Alternate Stitches.

Tighten the Stitch under the Cross-Member and hold with finger. Avoid crossing Stitches under the Cross-Member

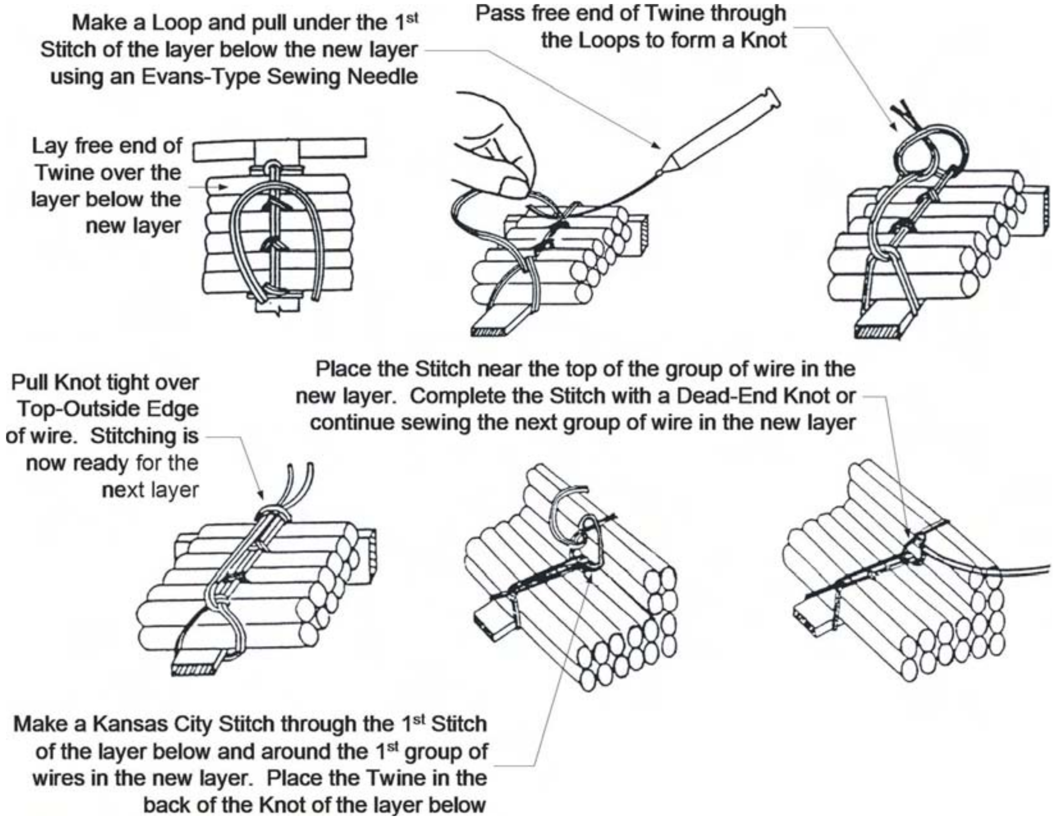
Remove slack by pulling up and to the right while keeping the Loop on top of the wires

Tighten Stitch by steadily pulling to the right and drawing Loop to the Top-Front of the wires (toward the reader).

Stitch will tighten further when the next Stitch is pulled tight on the next group of wire. Keep Stitches in a straight line centered on the Cross-Member

(b)

Fig. 6.16 (a) Starting stitch for Kansas City and Chicago stitching methods. (b) Kansas City stitching method for securing wire to a cable rack. The method is illustrated on a bundle of four wires in two layers, but it also can be used on individual wires or groups of two in one layer.



Make a Loop and pull under the 1st Stitch of the layer below the new layer using an Evans-Type Sewing Needle

Pass free end of Twine through the Loops to form a Knot

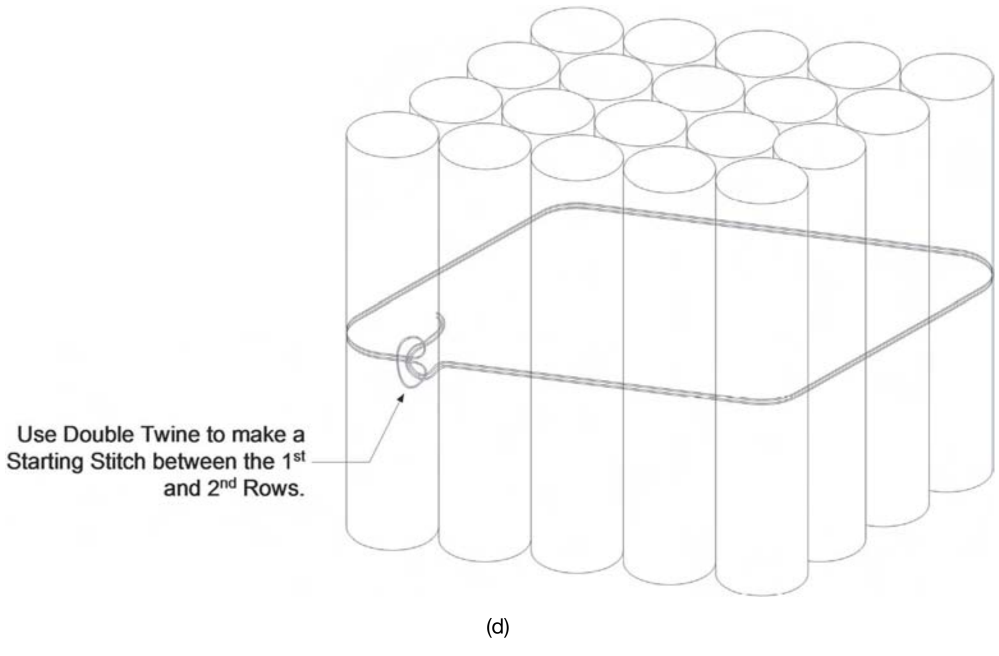
Lay free end of Twine over the layer below the new layer

Pull Knot tight over Top-Outside Edge of wire. Stitching is now ready for the next layer

Place the Stitch near the top of the group of wire in the new layer. Complete the Stitch with a Dead-End Knot or continue sewing the next group of wire in the new layer

Make a Kansas City Stitch through the 1st Stitch of the layer below and around the 1st group of wires in the new layer. Place the Twine in the back of the Knot of the layer below

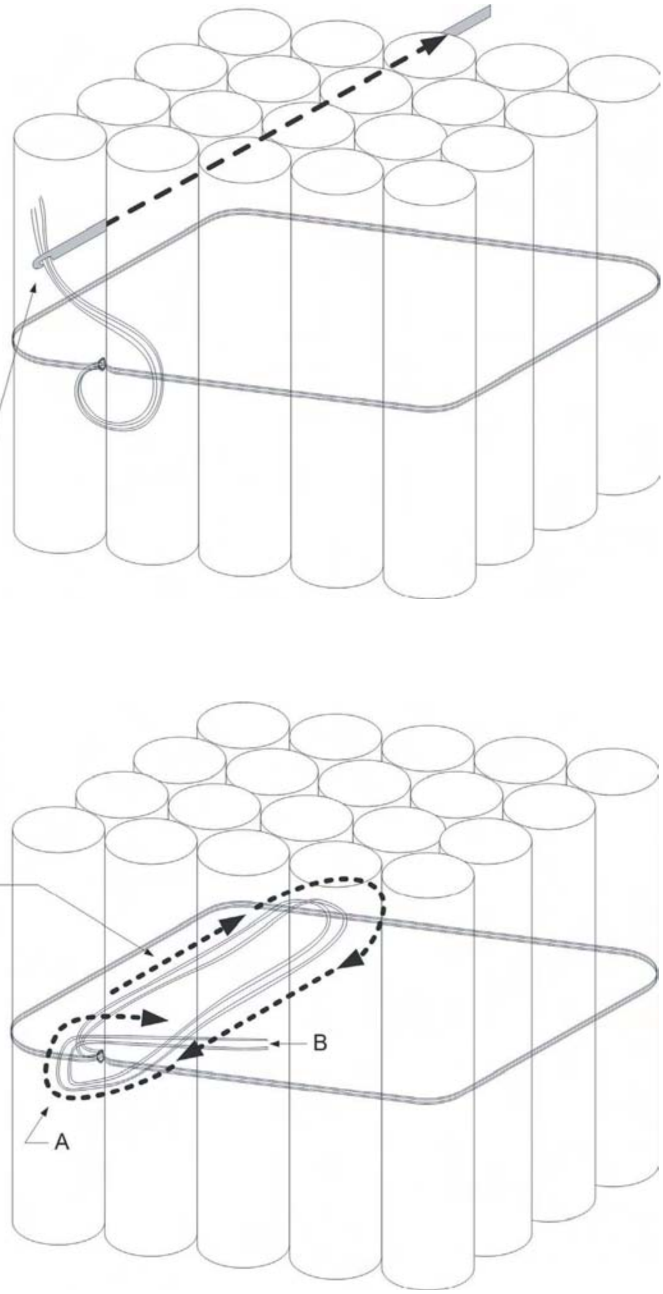
(c)



Use Double Twine to make a Starting Stitch between the 1st and 2nd Rows.

(d)

Fig. 6.16 (c) Kansas City stitching method for securing second and subsequent layers of wire to a cable rack. (d) Chicago stitching method for banding wires. (*continued*)

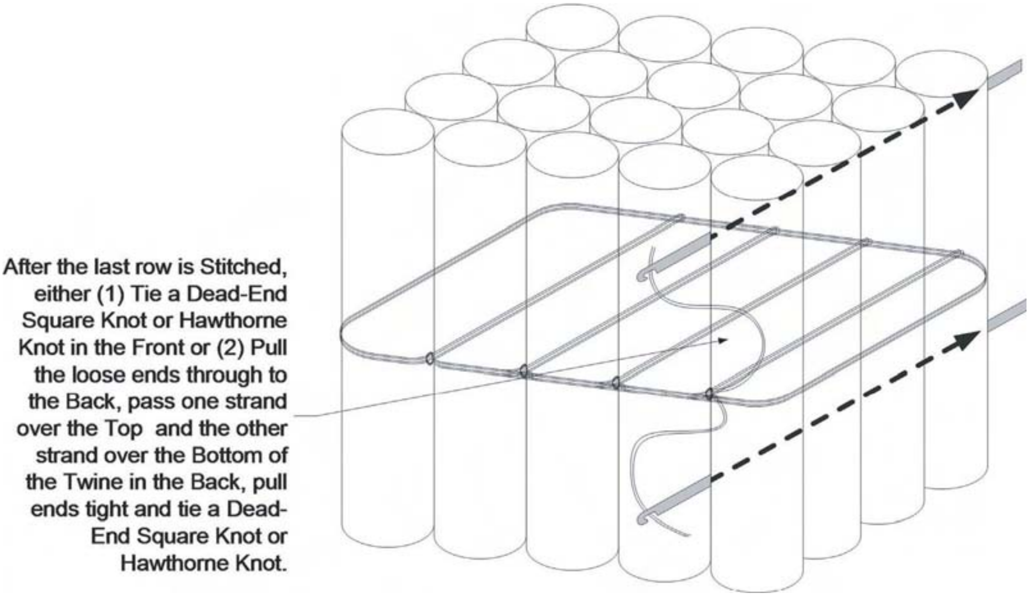


Pass the Twine above the starting Stitch and between the 1st and 2nd Rows using a Straight Metal Lacing Needle (Chicago-Type). Leave enough Slack on both Front and Back so the Twine can be easily grabbed for tightening.

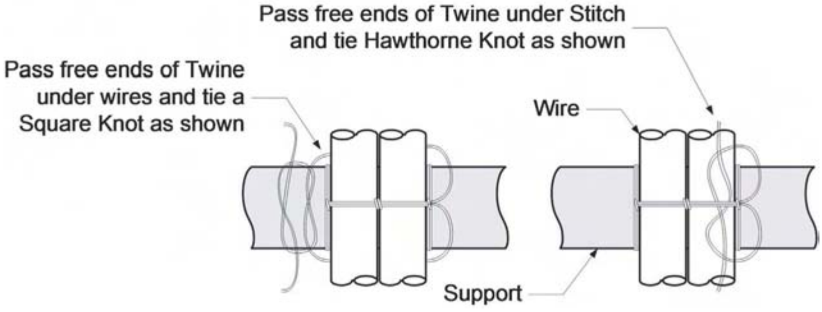
Pass the free end over the top of the Twine in the Back and then pass it through to the Front using the Needle. Pass the free end through the Loop above the Starting Stitch. Lock the Stitch by first pulling on A and then B. Repeat this sequence for each row.

(d)

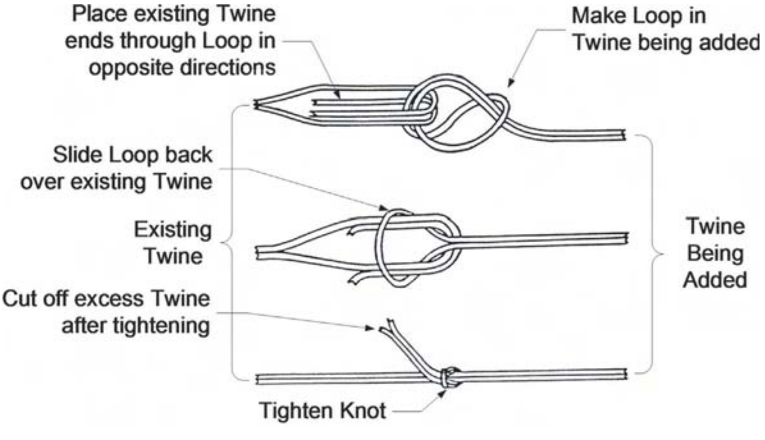
Fig. 6.16 (d) Chicago stitching method for banding wires.



(d)



(e)



(f)

Fig. 6.16 (d) Chicago stitching method for banding wires. (e) Dead-end knot (ending stitch) for Kansas City and Chicago stitching methods. (f) Splicing method for double twine strands.

Table 6.10 Securing Horizontal and Vertical Power Wire Runs—Typical Practice[a]

Wire Size (AWG or kcmil)	Secure at . . . Cross Member	Number of Twine Strands	Wires per Stitch	Ultimate Number of Layers	Maximum Pileup (in.)
Horizontal Runs					
14–8	Every	2	2	Any	Any
6–1	Every	2	4	Any	Any
1/0	Every	2	2	Any	Any
2/0–4/0	Every other	2	2	Any	Any
250–350	Every other	2	2	Any	Any
400–750	Every other	4	2	Any	Any
Vertical Runs					
14–8	Every	2	Any	Any	7
6–1	Every	2	1	Any	7
1/0	Every	4	1	≤ 3	7
2/0–4/0	Every	4	1	≤ 3	7
250–350	Every	4	1	> 3	7
400–750	Every	4	1	Any	7

[a] Some variations exist; for example, on horizontal runs, power wires may be secured on every other or every third or every fourth cable rack cross member regardless of wire size. However, on vertical runs, most practices require that wires be secured on every cross-member.

- Use cable ties to secure power wiring within a power equipment frame or other equipment frame; apply in a crisscross arrangement for best results (Fig. 6.17). Note: It is common practice to use twine rather than cable ties on the top bracket where the wires first enter the top of the frame.
- Wrap all rubber and neoprene insulated power wire with protective sheet fiber cards before securing the wire to a cable rack with a cable tie; secure the sheet fiber to the wire with cable ties or twine.

6.6.6 Drop Wires from Equipment Frame Fuse Panels

Small hookup wires dropped from a fuse panel at the top of an equipment frame are easier to handle and bundle when the wire pairs are twisted. The twisting also helps minimize noise coupling from one power circuit to another.

The procedure shown in Figure 6.18 uses an aviation safety-wire twisting tool available from any aviation tool supply company.

6.6.7 Wire Taps

Taps generally are used to reduce the conductor size where the main conductor is too large for a termination and in some equipment frame bonding and grounding arrangements (see Chapter 5, System Design). Where it is necessary to tap a smaller power (nongrounding) conductor to a larger main conductor, the smaller conductor must be protected by the overcurrent protection device feeding the larger main conductor. For example, say a small secondary distribution fuse panel is fed by a 50-A circuit breaker in the primary distribution system and the input terminations on the fuse panel accept conductors no larger than 6

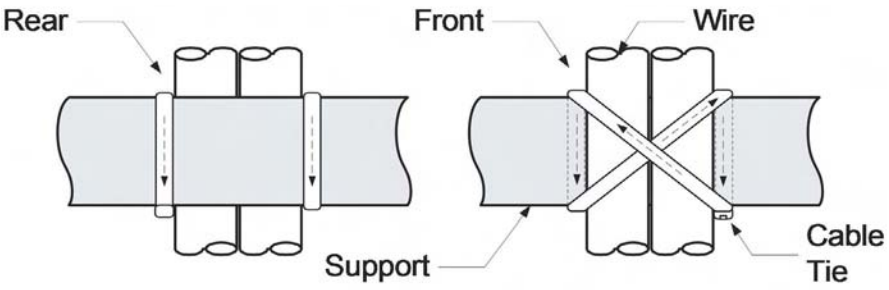


Fig. 6.17 Cable tie installation on a support by crisscrossing on the front.

Fig. 6.18 Twisting small hookup wire (16, 14, 12, and 10 AWG) using an aviation safety-wire twisting tool (Milbar brand shown). Secure the wire in a vise or clamp at the far end. Comb out any twists and crossovers. Place the free end in the jaws of the tool, squeeze the handle, and set the lock. Pull the twisting handle several times until the two wires have the desired twist. Do not overtwist such that the insulation is deformed; generally, use 1-in. twist length for 16 AWG, 1.25-in. twist length for 14 AWG, 1.5-in. twist length for 12 AWG, and 2-in. twist length for 10 AWG hookup wire.

AWG. However, because of the circuit length and voltage drop requirements, a 2 AWG conductor is required. In this case, short pieces, or pigtails, of 6 AWG (no more than 1 or 2 ft long) would be tapped to the main 2 AWG feed and return conductors at the fuse panel end. The 6 AWG is adequately protected by the 50-A circuit breaker, and the pigtails are short enough to have no appreciable effect on the circuit voltage drop.

6.6.8 Tap Installation Guidelines

- Where the tap wire is smaller than the main wire, be sure the smaller wire is protected by the overcurrent device.
- Only use irreversible compression-type H-taps; do no use mechanical-type H-taps (for the same reason that mechanical-type connector lugs should not be used), and do not use C-taps (because C-taps do not have a separate crimp station for the tap conductor).
- Crimp H-taps with the tooling recommended by the connector manufacturer, typically a circular die (do not use a hex die).
- Use an insulating cover designed for the tap connector.
- Place taps between cable rack cross members to minimize cable rack pileup (Fig. 6.19).

6.6.9 Repairing Damaged Insulation

If wire insulation is damaged in any way (scratched, chipped, dented, or ripped), it must be repaired. If the damage is not too severe, wrap with a minimum of two half-lapped layers of rubber tape followed by two half-lapped layers of electrical tape. Extend the rubber and electrical tape a minimum of 2 in. past the damaged section. If the damage is severe, cut out the damaged insulation and replace with a section from a loose piece of the same size wire.[7] Cover the replaced section with one layer of half-lapped electrical tape and heat-shrink tubing or two layers of half-lapped electrical tape or two layers of heat-shrink tubing. Do not use electrical tape sold at automotive parts stores or department stores unless it is a name brand.

6.6.10 Busbars

Busbars are supported by auxiliary framing using hardware designed for the purpose. If copper busbars have to be bent on the jobsite, the bend radius must be at least equal to the bar thickness (Table 6.11). For example, a $\frac{1}{4}$-in. busbar must have at least $\frac{1}{4}$-in. radius on the inside of the bend. Bends that are too sharp will crack the metal on the outside of the bend and crush it on the inside of the bend.

6.6.11 Busbar Installation Guidelines

- Splice busbars and install T-junctions and L-joints with clamps; drill busbars only where terminal connector lugs are to be installed.
- Clean all bare contact surfaces with a fine-grain abrasive paper (aluminum oxide sandpaper) or scouring pad just prior to assembly; sand in a circular motion across

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[7] This type of repair is not recommended for wires used with systems operating at voltages higher than 60 Vdc.

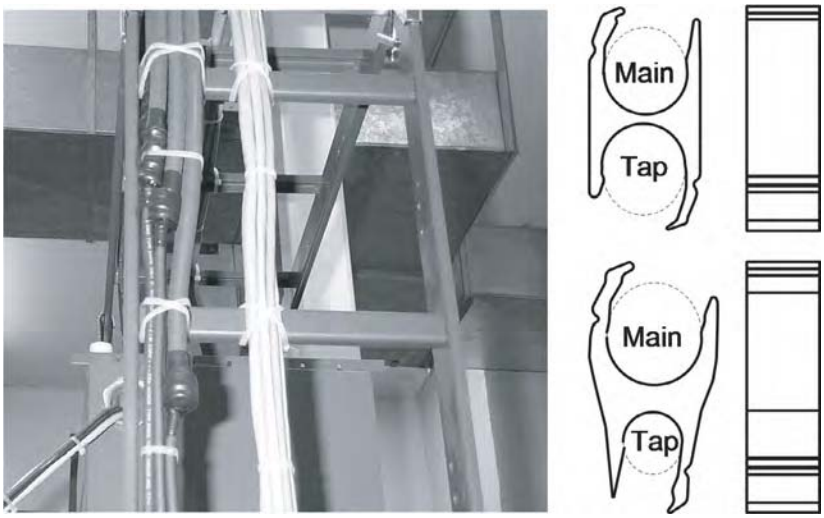

Fig. 6.19 (*Left*) Application of taps to reduce wire size. (*Right*) Cross-section views of typical H-tap connectors.

the metal grain, clean off sandpaper grit and metal oxides and coat with oxidation inhibitor compound before connecting or assembling; wipe off excess oxidation inhibitor after assembly. If the parts are not assembled within a few minutes, cover with paper until assembled.

- Do not use abrasives on lead- or silver-plated or tinned contact surfaces but clean with a mild cleaner and dry cloth and coat with oxidation inhibitor.
- Some busbars may be factory coated with a clear sealant, which makes the busbar appear clean and bright; this sealant must be removed from the contact area with sand paper or scouring pad and the area coated with oxidation inhibitor before assembly.
- Tighten busbar clamps by drawing up all four corners until snug. Start at one corner and draw the fastener a little tighter. Cross to the diagonal corner and tighten the fastener a little tighter. Tighten the fastener in the adjacent corner and then crossover and repeat. Continue tightening each fastener a small amount using the same sequence until the required torque values are reached. Clamps are slightly convex and will bend flat when properly tightened. Overtorquing will bow out the clamp or bend the ears and cause a loss of contact surface area. Do not use clamps that have a concave busbar contact surface or bent ears because they are defective.

Table 6.11 Minimum Bend Radius for Copper Busbar (Measured on the Inside of the Bend)[a]

Busbar Thickness (in.)	Minimum Bend Radius (in.)
$\frac{1}{4}$	$\frac{1}{4}$
$\frac{3}{8}$	$\frac{3}{8}$
$\frac{1}{2}$	$\frac{1}{2}$
$\frac{3}{4}$	$\frac{3}{4}$

[a] Generally, the bending radius should be at least equal to the bar thick-

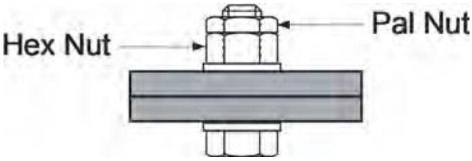

Fig. 6.20 Pal nut: Install with flat side toward nut.

- Install locknuts (self-locking nuts) or a combination of ordinary hex nuts and Pal nuts (Fig. 6.20) on all busbar clamps. Torque the hex nuts before applying the Pal nuts. Install the Pal nut with the smooth (flat) side in, open side out; run to the regular nut until snug and then one-quarter turn beyond. Generally, if a connection has a Pal nut and needs to be taken apart, the old Pal nut should be replaced by a new one.
- Use zinc-plated (SAE J429 Grade 5) or cadmium-plated and chromate-treated hardware or silicon-bronze (ASTM B-99) or copper finished hardware with American Unified National Coarse (UNC) free-fit (Class 2 fit).
- Busbars $\frac{1}{4}$ in. and thicker may be drilled and tapped.
- For untapped connections, oversize drilled holes in busbar by $\frac{1}{64}$ to $\frac{1}{32}$ in. ($\frac{1}{16}$ in. also is acceptable).
- Support busbars at 6-ft intervals or less; install supports as close as possible to right angle turns and risers. In high-risk seismic areas, support busbars on both sides of a mechanical splice.
- Over passageways, provide a minimum busbar height of 7 ft above floor level.
- Provide at least 3-in. clearance between busbars of different voltages and between busbars and cable racks, auxiliary framing, threaded rods, equipment frames, and other conductive apparatus. Where possible, increase the clearance to 12 in. If the 3-in. minimum clearance cannot be achieved, the clearance can be reduced to $\frac{1}{2}$ in. for 24- and 48-Vdc systems but only in low-risk seismic areas.
- Wrap busbars with sheet fiber card stock and tape where protection is required to prevent contact with lighting fixture diffuser covers and frames (preferably, remove or relocate the fixture).
- Where splicing, joining, or extending busbars, overlap the busbars by at least the busbar width but no more than the busbar width plus 2 in.
- Install all busbars arranged in an L or T at the joint so that the adjoining bars are even and flush wherever possible; if not possible, use a maximum extension of $\frac{1}{2}$ in. for the L-joint and 2 in. for the T-joint.
- Where exposed busbars are located outside the power system room or space, such as above or below secondary power distribution frames, cable racks, and auxiliary framing, protect with noncombustible covers or wrap with two half-lapped layers of plastic insulating tape (e.g., Scotch 33 or 88 vinyl electrical tape).
- It is good practice to tape the grounded return busbars where they are close to exposed live terminals, studs, and equipment. Similarly, it is good practice to tape live busbars where they are close to grounded terminals, studs, and equipment.
- Install busbars with the long edge vertical wherever possible.
- Observe current ratings corresponding to the busbar orientation (vertical or horizontal); see Chapter 5 (System Design).

6.7 POWER EQUIPMENT FRAMES

Power equipment may be installed in any common frame type, including unequal flange and channel-type frames, box-frames, and cabinets. Power equipment frames must be able to support substantial loads (equipment weight and cable rack, overhead structure, and seismic loads), which usually precludes the use of light-duty frames in power applications.

6.7.1 Frame Installation Guidelines

- Bolt adjacent frames together using hardware made for the frames. Where unequal flange frames are used in the same lineup with channel-type frames, adapters must be used to bolt the two different types together or the different frame types should be separated by at least 2 in. and independently supported.
- Use a top angle on all channel-type and unequal flange equipment frames, and install a 1-in. rigid steel conduit underneath the top angle along the full length of the lineup to stiffen the lineup (this is effective for stiffening a lineup consisting of different frame types such as channel and unequal flange).
- Support mechanically isolated frames and frames at each end of a lineup with two top supports; other frames in the lineup may be supported by one top support
- Plumb frames to the tolerances shown in Table 6.12
- Anchor frames to the floor with a minimum of two fasteners, one in the front and one diagonally across in the back; repeat the established pattern throughout the lineup. Use four fasteners in seismic installations. The anchors must be suitable for the seismic area of the installation

Table 6.12 Equipment Frame Lineup Tolerance

Frame Height	Maximum Deviation of Top from Vertical (in.)
≤ 4 ft 6 in.	$\frac{1}{16}$
4 ft 6 in.–7 ft 0 in.	$\frac{1}{8}$
7 ft 0 in.–9 ft 0 in.	$\frac{3}{16}$
> 9 ft 0 in.	$\frac{1}{4}$
Lineup length	Maximum deviation from straight horizontal line (in.)
Any	$\frac{1}{16}$
	Maximum deviation between adjacent frames (in.)
Any	$\frac{1}{4}$
	Maximum deviation from level (in./ft of length)
Any (Note: no more than 1-in. shim stack on any frame)	$\frac{1}{16}$

6.8 AUXILIARY FRAMING

Auxiliary framing consists of paired channels or bars (Fig. 6.21) installed as a structural grid to provide mechanical support for equipment frames, cable racks, and other apparatus installed above equipment frames (Fig. 6.22). Two auxiliary framing levels may be required where the ceiling height is more than 5 ft above the equipment frames. The upper level effectively lowers the ceiling height and uses a truss for bracing against lateral loads and movement (Fig. 6.23). The upper level also may be used to support cable racks in a multilevel cable racking scheme.

In some buildings, the ceiling may not be designed to provide resistance to lateral loading during a seismic event. In this case, the auxiliary framing may be attached to load-bearing walls and building columns, or a floor-mounted, cross-braced stanchion system may be used.

6.8.1 Auxiliary Framing Installation Guidelines

- Use no more than 5-ft spacing between auxiliary framing levels. Run the low-level framing in continuous lengths at right angles to the frames and equipment it supports.
- Support auxiliary framing with $\frac{5}{8}$-in. diameter threaded rod attached to the ceiling or higher level framing.
- For maximum rigidity, install the auxiliary framing in 20-ft stock lengths wherever possible; however, use shorter lengths to stagger splices.
- Install all paired parallel bars and channels in equal lengths.
- Install auxiliary framing supports on 5-ft intervals where possible, but where necessary to avoid obstructions extend to no more than 6-ft intervals.
- Use clip-type or through-bolt splices in low seismic areas with no more than one splice between supports; use through-bolt splices in high seismic areas. Where through-bolt splicing is used, drill or punch before it is installed. If after drilling or punching, the holes do not line up with the auxiliary framing splice, enlarge or elongate the holes, but use flat washers on the splice bolts. Do not exceed $\frac{1}{4}$-in. gap between the ends of spliced auxiliary framing.

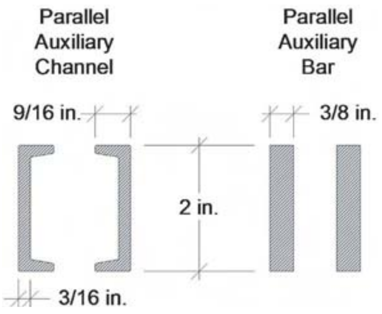

Fig. 6.21 Cross-section views: Parallel auxiliary channels and bars. The parallel components act as beams to support cable racks, busbars, and other apparatus, which may be suspended above or below. They also may support equipment frames from the top.

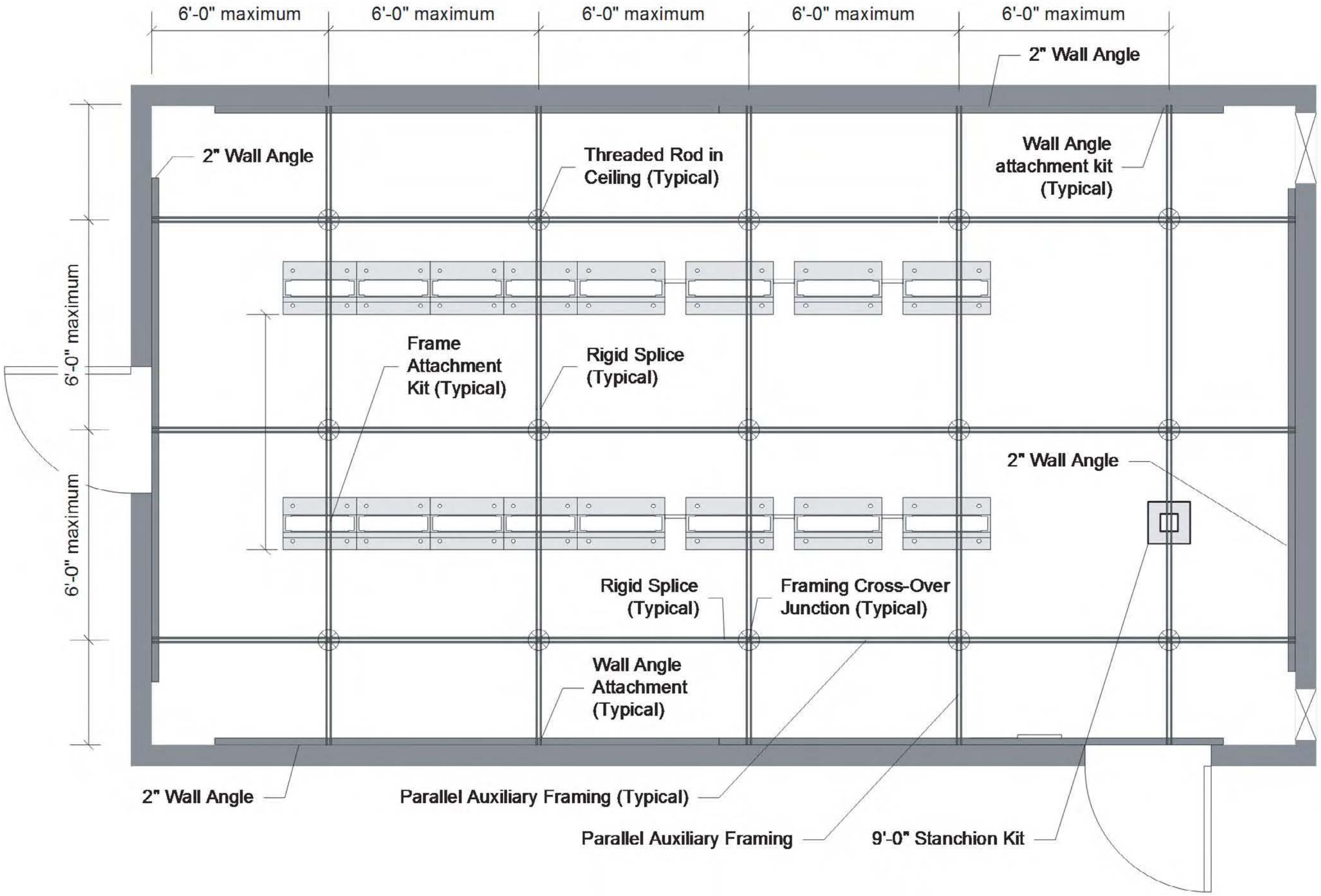

Fig. 6.22 Plan view: Basic layout for auxiliary framing on a 5-ft grid.

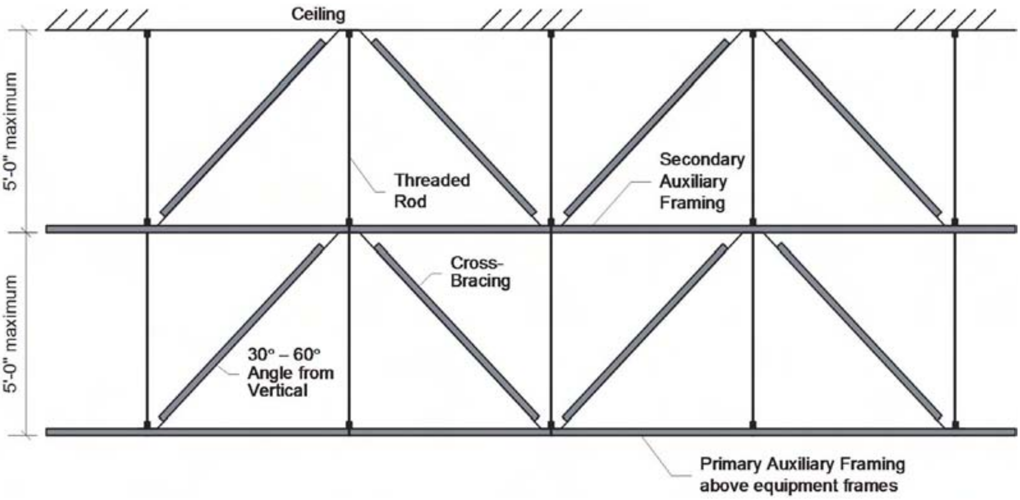

Fig. 6.23 Elevation view: Truss arrangement for multilevel auxiliary framing (the type shown is called a Warren truss).

- Do not splice auxiliary framing past the last support (in other words, splices must be supported on both sides).
- In low-risk seismic installations, provide at least $\frac{1}{2}$-in. clearance between the ends of the auxiliary framing and any building component, such as columns and walls; in high-risk seismic installations provide at least 5-in. clearance.
- Install supports so that the horizontal distance between the last hanger or support and the cable rack or other equipment load is no more than 36 in.
- Install auxiliary framing cross-bracing with 30° to 60° slope, preferably 45° (Table 6.13).
- Where the auxiliary framing is used to support only cable rack, install cross-bracing as required to ensure rigidity.
- For personnel protection, install finishing caps and clips on all paired framing bars and channels and on any exposed ends of framing installed or protruding below the main auxiliary framing.
- To prevent bending when moving auxiliary bars and channels from one location to another, carry them with the edge down and not flat.
- File rough or sharp edges at cuts and paint before installing.
- Measure the heights of the auxiliary framing from the floor to a common reference, such as to the bottom of the paired channels or parallel bars.
- Cover threaded rods with vulcanized fiber tubes (ASTM D710-97) or PVC tubing to prevent insulation damage during power wire installation. The tubes should be long enough to protect the cabling to the ultimate pileup height.
- If the threaded rod end protrudes beyond the fasteners more than one diameter of the rod, cut the rod end except where the protrusion is between the top nut and the ceiling.
- Turn rods into ceiling inserts so that it contacts all the threads of the insert but do

Table 6.13 Auxiliary Framing Cross-Bracing

Distance Between Auxiliary Framing and Equipment Frames	Cross-Brace Type
≤ 1 ft 6 in.	Single rod
1 ft 6 in.–4 ft 10 in.	2 in. × 2 in. × $\frac{3}{16}$ in. (or $\frac{1}{4}$ in.) thick angle brace

not turn so deep that it binds against the ceiling; install a nut and washer on the outside of the insert.

6.8.2 Additional Requirements for High-Risk Seismic Areas

- To prevent fasteners from sliding off, extend the end of the auxiliary framing at least 3 in. beyond the last support point (hanger rod, brace, or cable rack attachment) where possible; otherwise, install a $\frac{3}{8}$-in. stop-bolt through the ends of the auxiliary framing.
- Install stiffening clips on paired channels and parallel bars on no more than 24-in. centers between auxiliary framing supports. Stiffening clips may be omitted at locations where an earthquake brace, cable rack, or other clipped fastening, $\frac{1}{2}$ in. or larger, is located.
- Extend conduits supported on auxiliary framing to wall-mounted switches, lights, and outlets with flexible conduit or cable.

6.9 CABLE RACKS

Cable racks typically are installed in two levels, one for power and one for signal cables; however, in small installations one level may be installed for both (Fig. 6.24). If two levels are used, the upper layer should be separated by 12 to 18 in. from the ultimate pileup on the lower level. Cable racks may be installed directly on the auxiliary framing, supported by threaded rods attached to the auxiliary framing, or suspended above it.

6.9.1 Cable Rack Installation Guidelines

- Install all cable rack level and aligned with existing cable rack or equipment.
- Install sufficient side bracing to ensure rigidity and prevent cable rack sway.
- Install J-bolts on both cable rack stringers at each end of the cable rack run and staggered on alternate sides at each support in between; in high-risk seismic areas install J-bolts on both sides at each support.
- Where cable rack is spliced, keep the gap below $\frac{5}{8}$–in.
- Except for elevation changes, do not install more than one cable rack splice between any pair of supports; do not splice beyond the last support.
- Support cable racks at 5-ft intervals wherever possible, but 6-ft intervals may be used if necessary.

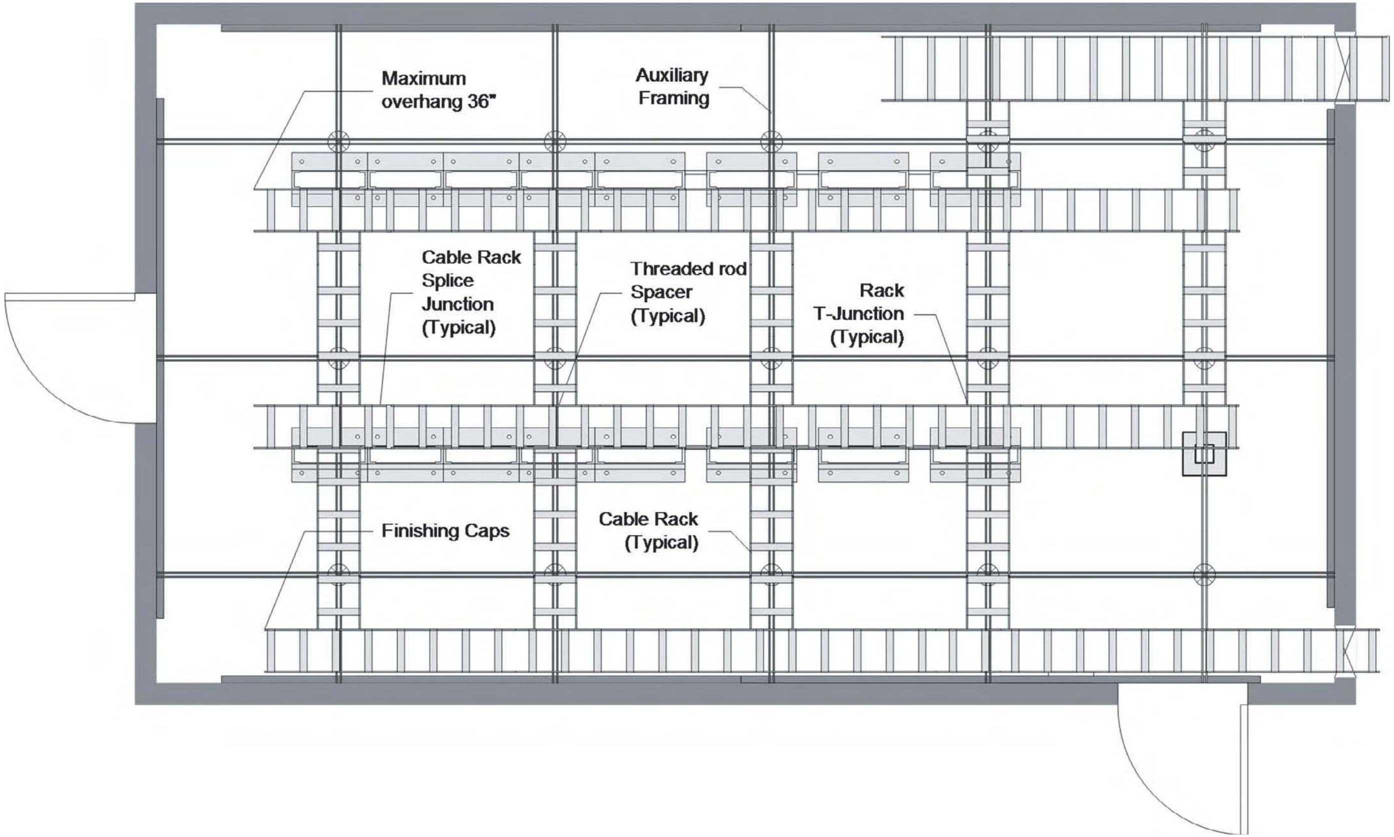

Fig. 6.24 Plan view: Basic layout for cable rack fastened to auxiliary framing.

- Do not extend cable rack more than 36 in. beyond the last support.
- In low-risk seismic installations, provide at least $\frac{1}{2}$-in. clearance between the cable rack and any building component, such as columns and walls; in high-risk seismic installations provide at least 5-in. clearance.
- Do not extend cable rack through a floor penetration (it cannot be adequately fire stopped).
- Never support a cable rack by its cross members.
- Support vertical cable racks at the floor and install intermediate supports at no more than 5-ft intervals.
- Place fastening clips or J-bolts on either the inside or outside of the cable rack stringers.
- Place horizontal cable rack with the cross members at the top. A cable rack with solid stringers, smaller than 25 in. in width, may be inverted to gain additional cabling height where there are obstructions. Never invert cable rack that has reinforced cross members.
- Install unprotected battery circuit conductors on dedicated power cable racks wherever possible.
- Do not use a cable rack larger than 20 in. on vertical runs.
- Provide at least 4-in. hand and arm clearance between the maximum pileup on a cable rack and any obstruction.
- Provide at least 18-in. working space for installation access on at least one side of the cable rack.
- Install cable rack toward the front of equipment frames so that cables can be routed over the side and down to the terminations at the rear of the frame.

6.10 SLEEVES, WALL OPENINGS, AND FLOOR OPENINGS

Temporarily close openings at the end of each workday or sooner if no further cabling work is anticipated that same day:

Install the cover on one side (bottom for floor openings).
Fill the opening with fire-stopping bags to prevent any draft through the opening.
Install the other cover using a minimum of two screws.

Permanently close openings after all cables have been installed:

Cut the covers to accommodate the new cables; make straight cuts so the covers will be close to the cables but not touch them.
Install one cover (bottom for floor openings).
Fill the opening with fire-stopping bags, overlapping each layer until the opening is full.
Install the other cover and seal between the cover and cables with sealing compound.

When a floor opening is uncovered to run cable, protect personnel by roping off the area and placing signs similar to “Danger—Cable Opening.”

6.11 BASIC INSTALLATION SEQUENCE

The following sequence may not apply to all installations and should be altered to suit field conditions or the particular type of equipment being installed.

1. Install ceiling-supported auxiliary framing.
2. Install powerboard equipment frames and remaining auxiliary framing.
3. Install all cable support systems, including cable rack and conduit systems.
4. If the charge and discharge busbars are separate assemblies, install them at the required locations.
5. Assemble battery rack (VLA) or place battery modules (steel encased VRLA). The height of free-standing racks and the stacking height of battery modules may be limited in seismic installations. Place cells using the procedures specified in the battery manufacturer's documentation. Install and torque cell interconnecting straps on the cells. Do not connect the battery string to the charge and discharge bus bars at this time.
6. Run all wiring between the charge bus and battery and between the discharge bus and primary distribution. Do not connect the battery at this time.
7. Run the ac input power leads to each rectifier and run the dc output power leads from each rectifier or rectifier shelf to the charge bus. Do not turn on ac power to the rectifier system at this time.
8. Install external control and alarm cables. If remote battery voltage sensing is required, run the leads to the battery but do not connect them to the battery terminals at this time; if the voltage sensing circuit is equipped with a fuse or circuit breaker at the battery, all terminations may be made, but the fuse should be removed or the circuit breaker turned off. If local battery voltage sensing is specified, connect the sense leads in the powerboard according to the manufacturer's instructions.
9. Run distribution leads from the power system overcurrent protection devices (circuit breakers or fuses) and return bus to the loads.
10. Run all remaining system interconnecting leads and alarms, but do not make the final connections at the battery terminals at this time.
11. Perform a battery initial charge with a separate rectifier and temporary wiring.
12. Check out and set up power system controller according to the manufacturer's instructions.

DANGER—The next step applies power to the battery system. Before contacting any uninsulated conductor surfaces, always use a voltmeter to ensure that no voltage, or the expected voltage, is present.

13. Before connecting the battery, turn off or (if modular) unplug all rectifiers, open all load distribution circuit breakers, and remove all load distribution fuses and their associated alarm fuses.
14. Connect the circuit wiring between the battery terminals and the termination busbars by first connecting to the termination busbars and then to the battery terminals. To prevent sparking when the final connections are made to the battery, tem-

porarily connect a regular household 60- to 100-W incandescent lightbulb as shown in Figure 6.25.

15. Turn on the rectifiers, one at a time. Test each rectifier according to the procedures given in the manufacturer's rectifier manual.
16. Verify the operation of the fuse and circuit breaker alarms as follows: Short the alarm leads on each circuit breaker and verify that the power alarm lamp on the controller front panel or alarm monitor lights. To verify fuse alarm operation, insert a blown fuse in each alarm fuse position. Verify that the appropriate fuse alarm lamp lights.
17. Verify the operation of capacitor precharging circuits as follows: Place the circuit breaker with a load precharge switch in the off position. Remove the load circuit conductor. Connect a voltmeter between the circuit breaker output terminal and return. Press the circuit breaker precharge switch and look for battery voltage reading on the multimeter. Release the precharge switch and disconnect the multimeter. Reconnect the wiring previously removed.
18. If the power system is equipped with a low-voltage disconnect, test it according to the manufacturer's instructions.

WARNING—Follow the manufacturer's power-up instructions before applying power to load equipment.

19. Connect the loads, one at a time, by turning on the load circuit breakers or inserting the load (and associated alarm) fuses for each circuit.

6.12 BATTERY SYSTEM INSTALLATION

The applicable industry installation standards are [5] for VRLA and [6] for VLA battery systems. Battery installations require consideration of structural and space requirements, among other things. Adequate space must be provided around a battery for cooling air

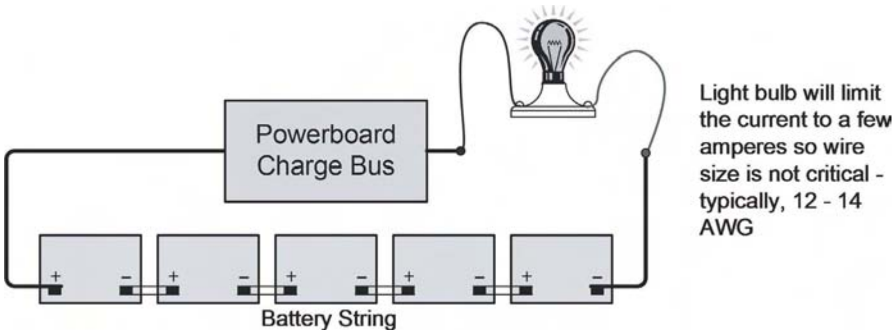

Fig. 6.25 Using a 60- to 100-W lightbulb to raise battery voltage when connecting a battery to an energized bus. The bulb acts as current-limiting resistor to provide a small charging current to the battery string. The voltage difference between the power system bus and the battery will cause current to flow through the bulb and light it dimly. When the bulb extinguishes completely, the battery and bus voltages are the same and the connection may be made without a spark.

movement and to allow space to replace a cell or the entire battery. Structural requirements include the effects of the battery weight on the floor and during seismic events.

Another installation consideration is that VRLA batteries require less floor space than VLA batteries because they are more compact and can be stacked (although stacking height may be limited in seismic installations), but VRLA floor loading usually is higher. Floor loading restrictions may limit the amount of space that can be saved in some buildings.

Vented lead–acid cells always are installed vertically (vent at the top) but many VRLA cells may be installed either horizontally or vertically. Some VRLA battery types [e.g., AGM (absorbed glass mat) in steel modules] must be installed horizontally to ensure proper wicking of the electrolyte in the cell separators. Manufacturer's installation instructions should be checked to determine the proper orientation.

Good practice is to locate the battery rack or frame at least 6 in. from a wall but 12 in. of clearance may be needed in seismic areas (Fig. 6.26). The cells themselves should have at least 8 in. of clearance from a wall. At least one VRLA battery manufacturer does not require clearance at the back of a battery, but an installation should never be made in this manner without first discussing it with the manufacturer and also determining if it meets seismic requirements.

In addition to spacing from a wall, adequate clearance must be provided for working space in front of the battery and for removal (Fig. 6.27 shows an unacceptable installation). Many VRLA installations use a horizontal cell arrangement, and space must be provided to not only make electrical measurements and check fastener torque but also to pull a cell or monobloc horizontally from a cell cage during replacement. The minimum clearance typically is 30 in. in the direction of cell removal, but more may be required by a particular battery type. Clearances between a battery rack and other equipment and building structure is shown in Table 6.14. Where the National Electrical Code applies, the clearance requirements of Article 110 must be used (36-in. clear space from any energized component).

6.12.1 Cell Installation Guidelines

- Do not mix lead–calcium and lead–antimony VLA cells within a battery string or within a battery system even in an emergency.

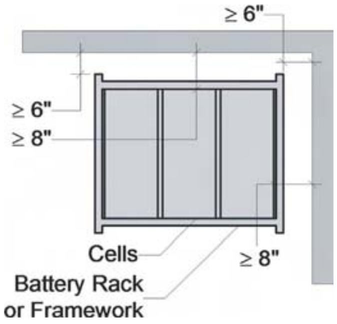

Fig. 6.26 Wall clearance requirements.

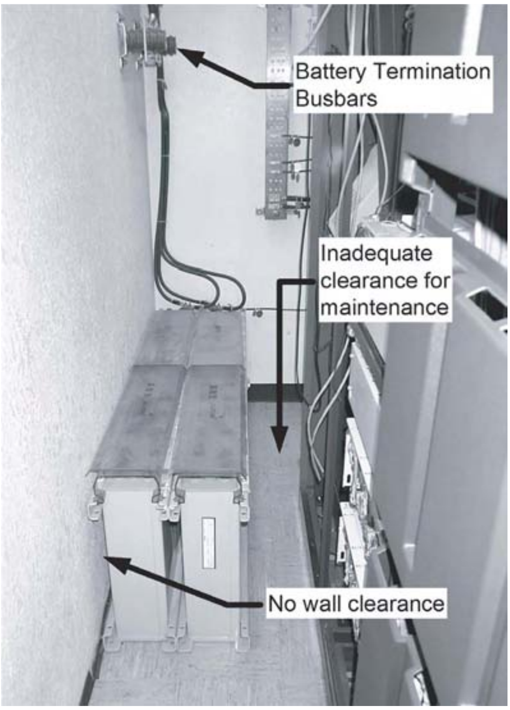

Fig. 6.27 Unacceptable battery installation in an access node equipment enclosure.

- Do not mix VRLA and VLA battery strings within a battery system even in an emergency because of the different float voltages and charge and discharge characteristics. Exception: To ensure battery service continuity when converting a facility from lead–calcium VLA to VRLA, the voltage of the VLA may be raised to equal the required VRLA float voltage, the VRLA string connected in parallel with the VLA string, and then the VLA disconnected, all in one operation lasting a few minutes.
- Do not mix cells with different ampere-hour capacity within a string even in an emergency.

Table 6.14 Minimum Clearances for Battery Racks

Location	Minimum Clearance (in.)
From battery rack to adjacent or parallel battery rack	36
From a double-row battery rack to a wall or permanent obstruction	36
From the back of a single-row battery rack to a parallel wall or permanent obstruction	8
From a battery rack to equipment frames	36
From the end of a battery rack (6 ft or longer) to a wall or permanent obstruction	36
From the back of any cell to a wall or permanent obstruction	6

- Be sure flame arrestor vents are in place on VLA cells when making connections at the battery. The flame arrestor vent funnel must extend below the surface of the electrolyte.
- VLA cells exposed to prolonged agitation, such as during shipment, can build up a dangerous concentration of hydrogen gas at the top of the cell in the space between the electrolyte and cover. Use extreme caution and care when handling cells that were just delivered. Take particular care to prevent static electricity from discharging near the filling funnels and vents even with the shipping plugs in place. The gas concentration will dissipate after the cells have rested for 24-h. Take normal precautions after the 24 h period.
- Inspect newly delivered cells for signs of electrolyte leakage and any obvious shipping damage before removing from the shipping containers. Look for dampness or discoloration of the shipping containers and pallets (Fig. 6.28). If hoisting straps or ropes have been exposed to electrolyte spillage, they could be unsafe to use. Be sure to document any adverse findings.
- When handling cells where electrolyte spillage may occur, wear protective clothing:
  - Chemical safety goggles
  - Rubber gloves
  - Coveralls
  - Rubber apron
  - Overshoes
- Remove the shipping cartons and closely examine the cells for physical damage to the cell container (jar) and cover (top) and for missing electrolyte that has exposed the plates (the latter applies to VLA only) (Fig. 6.29).
- Where more than one string has been delivered in the same shipment, the cells in a given string will be factory matched by colored stickers (Fig. 6.30). There are four

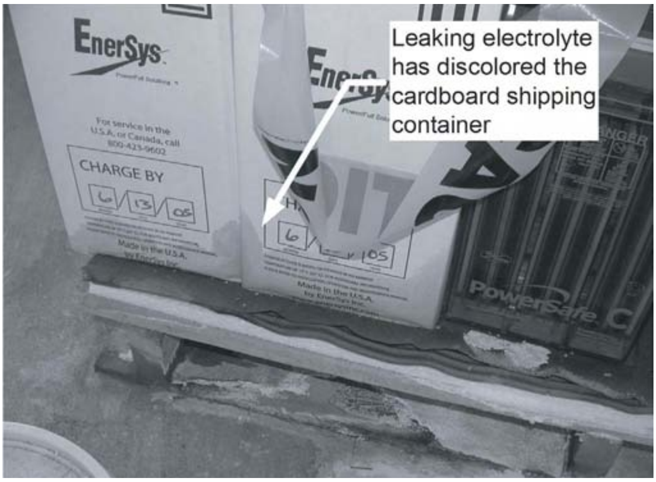

Fig. 6.28 Cell shipping container with obvious discoloration from spilled electrolyte. (Photo courtesy of M.W. Migliaro.)

Fig. 6.29 New cells still on the shipping pallet with one cell uncovered. (Photo courtesy of M.W. Migliaro.)

basic colors and each represents a 10-mV difference in float voltages (it is necessary to contact the manufacturer to determine the voltage corresponding to each color). Generally, keep cells of a like color together and do not mix with cells with an unlike color from another string. However, it normally is acceptable to use another color cell in a group if it is within ±10 mV of the base voltage of the group. For example, say the stickers are ordered white, yellow, green, and orange. It would be acceptable to use a white or green cell with a yellow cell but not an orange cell with a yellow cell. Similarly, a green cell should not be used with a white cell.

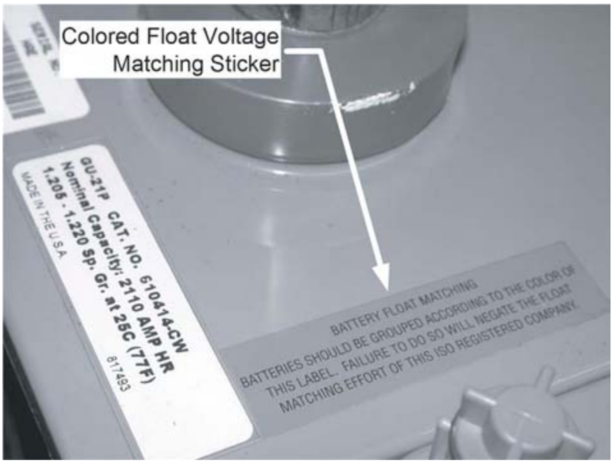

Fig. 6.30 Float voltage matching stickers are used when more than one battery string is in a shipment. (Photo courtesy of M.W. Migliaro.)

- If the electrolyte has been spilled from a VLA cell and the plates exposed while moving from the delivery truck into the battery room or storage location, the cell can be saved if the exposure is less than 20 min and a small amount of electrolyte is transferred from a number of other cells until the plates are covered (use the cells with the highest electrolyte levels). If the exposure is more than 20 min, the cell probably is permanently damaged.
- It is not unusual to have some electrolyte leakage from VLA cells during shipment (from sloshing) that collects on the cover and sides of the cell. Neutralize the electrolyte with a solution of 1-lb baking soda to 1-gal water. Never use solvents, mineral spirits, commercial detergents, ammonia, or other cleaning compounds or oils, waxes, or polishes. Wet a cleaning cloth with the baking soda–water solution and wring out sufficiently to prevent dripping. With the shipping caps in place, wipe the container (jar) and cover taking care not to allow the solution into the cell (soda solution can destroy the cell). If a part that is coated with oxidation inhibitor shows signs of acid contamination, clean the parts thoroughly with a dry cloth and neutralize with the soda solution. After neutralizing, rinse the cell and parts with clean water. If a white residue appears afterwards, the cell should be rinsed again. Remove the rinse water with a clean dry cloth. If oxidation inhibitor was removed from any parts, recoat with a thin film.
- After all VLA cells are on the battery rack or VRLA modules are stacked, the cell interconnecting straps can be installed.
- Clean all electrical contact areas prior to strap installation. It may be necessary to remove oxidation inhibitor, clean with a cleaning pad, and recoat.
- Check all cell posts and terminals to be sure they have a thin coat of oxidation inhibitor (Fig. 6.31). As each interconnecting strap is installed, apply a thin coat on that portion of the strap that will be in contact with the post. Also coat the contact portion of the bolt head, stud, and nut before installing.

Fig. 6.31 Cell interconnecting straps.

- Almost all battery manufacturers use 316 stainless steel fasteners (bolts, nuts, washers) at cell post connections. Do not substitute.
- Stamped flat washers should be assembled with the smooth (“rounded) side toward the cell post and the “sharp” side pointed away from the cell post.
- Do not tighten interconnecting strap fasteners beyond finger-tight until all straps are in place. Once all straps are in place, tighten all fasteners to the manufacturer’s recommended initial torque value—do not overtorque or the cell post may be damaged. At the time of final acceptance, tighten the fasteners to the manufacturer’s retorque values (retorque values may be the same as or different than initial values).
- Although different practices exist in the field, the following cell numbering scheme may be used on 2-tier, 24-cell battery racks (the actual numbering scheme is not as important as using the same scheme throughout the organization):
  - Lower tier: Cells 1 to 12
  - Upper tier: Cells 13 to 24
- Again, although different practices exist in the field, the lowest numbered cell is at the positive end of the battery [6].
- In high-seismic areas, install factory-provided cell separators between cells.
- In low-seismic areas, install cell separators between cells if factory provided. If no separators are provided, install cells so they do not touch each other or adjacent framework and with a typical spacing of $\frac{3}{8}$ to $\frac{5}{8}$ in. Where two rows are installed on one rack, use a spacing of $\frac{3}{4}$ in. between rows.
- Never use foam packing material as cell separators.

6.12.2 Battery Circuit Wiring

Battery circuit wiring is sized based on current rating and voltage drop as discussed in Chapter 5, System Design. In high-seismic risk areas, slack must be provided in all cable runs from busbar to the battery terminals to allow 6 in. of movement. Refer to Part III, Battery System Maintenance, for information and procedures for initial charging, testing, and acceptance.

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PART II SYSTEM MAINTENANCE

This part covers basic maintenance requirements for telecommunications dc power systems.

6.13 OVERALL MAINTENANCE REQUIREMENTS

Maintenance consists of inspection, overhaul, repair, adjustment, preservation, and parts replacement. The main objective of scheduled maintenance is to reduce the number of avoidable breakdowns and thus increase power system and network availability. The costs of scheduled maintenance are high but not as high as unscheduled maintenance. Whereas scheduled maintenance increases equipment reliability and system availability, the lack of maintenance always decreases reliability and availability. The failure of dc power systems in a telecommunications facility affects virtually every part of a network operator's operation at that facility. The cost of network outages caused by dc power system failures usually amount to many times the actual cost of repair.

Maintenance can be categorized as proactive and reactive. Proactive maintenance consists of routine and preventive maintenance. Routine maintenance helps to ensure continued operation of the dc power system, whereas preventive maintenance attempts to prevent failures and is particularly important with battery systems. Reactive maintenance is maintenance performed after a failure (also called breakdown maintenance) and consists of the actions taken after a failure to restore equipment operation.

6.13.1 Maintenance Schedules

Maintenance schedules take into account that too frequent inspections are a waste of money and that insufficient inspections allow components or subsystems to deteriorate and jeopardize network operation. Deterioration of dc power system equipment is normal and begins as soon as the equipment is installed. If this deterioration is not checked and corrected, it can cause failures. Deterioration includes alterations that are made haphazardly and without overall engineering coordination. The inspection frequency depends on the equipment duty cycle and loading, predicted life and age, overload history, and other pertinent factors and is usually based on equipment manufacturers' instructions and industry standards.

The development of maintenance schedules involves establishing instructions, procedures, and methods to ensure that the equipment and system components operate without failure. The program should include procedures and instructions for thoroughly servicing all equipment and components. These procedures should reference manufacturer's operating and maintenance manuals to the extent possible. The maintenance program should include shutdown procedures, safeguards, equipment interlocking and lock-out procedures, the meaning of alarms and response to them, and methods of recording data and reporting unusual conditions to the proper authority.

6.13.2 Maintenance Analysis

Equipment failures should be analyzed to determine the reasons for failure. The cause may be obvious. Although reliability can be built into dc power equipment, it generally requires continuous upkeep to retain it. Continuous upkeep is particularly important to batteries. Unfortunately, the tendency to ignore regular maintenance generally prevails over regularly scheduled maintenance because regular maintenance may be considered unnecessary, too expensive, or of lower priority than other activities.

6.13.3 Tools and Test Equipment

- Multimeter, 0.02% dc accuracy, 1-mV dc resolution, 0.2% ac accuracy, 100-mV ac resolution
- Clamp-on ammeter, 1 or 2% accuracy—ac/dc
- Noncontact thermometer
- Screwdriver assortment (Phillips No. 0, 1, 2, and 3 and slotted $\frac{1}{8}$-in., $\frac{3}{16}$-in., $\frac{1}{4}$-in., and $\frac{5}{16}$-in. blade)
- Nut driver assortment ($\frac{1}{8}$ in. through $\frac{9}{16}$ in.)
- Torque wrenches, adjustable click-type (40 to 200 in.-lb and 15 to 250 ft-lb)
- Socket set, nonmetric ($\frac{3}{16}$ in. through $\frac{3}{4}$ in., drive size to match torque wrench)
- Socket set, metric (5 through 20 mm, drive to match torque wrench)
- Torque screwdriver, cam-over torque-limiting clutch-type (5 to 40 in.-lb)

6.13.4 Test Equipment and Tool Calibration

All test equipment, including torque wrenches, should be periodically calibrated (Table 6.15), and calibration records should be kept showing date and results of all calibrations and tests.

6.13.5 Fuse Replacements

A common field problem occurs when a fuse is replaced. Through ignorance, inadequate markings, or lack of spare fuses of the proper rating, technicians sometimes use a replacement fuse rating that is too small or too large. Within certain maximum and minimum ratings, fuse dimensions usually are the same; for example, it is possible, but never acceptable, to substitute a 20-A fuse where a 5- or 10-A fuse should be used. Often when a correctly rated replacement is not available (or the correct fuse rating blows too often), a higher rating is substituted although this never is acceptable practice. The only way to prevent these

Table 6.15 Test Equipment Calibration Frequency

Type of Test Equipment	Calibration Interval	Remarks
Field test sets and tools	6–12 months	Depends on handling and use
Laboratory test sets	12 months	
Leased specialty equipment	12 months	

kinds of problems is to properly mark all fuse positions, equip the site with an adequate supply of spare fuses of the proper ratings, and to train operating personnel of the hazards involved in using incorrect fuse sizes. The most important hazards are injury or fire.

Many older fuse panels with fuse holders rated < 30 A use $\frac{1}{4}$-in. diameter × $1\frac{1}{4}$-in. long AGC (glass) or ABC and MDL (nonglass, such as bakelite, fiber, ceramic) cartridge fuses. These fuses also are known as type 3AG and 3AB. Glass cartridge fuses should be avoided because of the obvious cleanup difficulty if they are broken. Also, they may explode if accidentally used in an application that supplies higher fault currents than the fuse is rated to handle.

Many Northern Telecom (Nortel Networks) fuse panels require $\frac{9}{32}$-in. diameter × $1\frac{1}{4}$-in. long type ABS cartridge fuses, but this is not marked on the panel (these fuses also are known as type 4AG or 4AB). A common mistake is to install $\frac{1}{4}$-in. diameter AGC or ABC fuses in these panels. Since the fuse holder does not properly clamp the fuse, it will overheat and eventually blow the fuse for no apparent reason. In the process of replacing the fuse many times, the fuse holder will be ruined by arcing. The problem is compounded by the fact that ABS fuses are hard to obtain.

Type GMT alarm indicating fuses are available to up 15 A, but many GMT fuse panels are rated 10 A maximum per fuse position. Therefore, craft personnel must be careful to never install a fuse rated higher than 10 A in these fuse panels. Unfortunately, even though some of these panels are marked with the maximum fuse rating, the label is hidden on the side or on the back of the fuse panel where it is unreadable (a textbook example of poor engineering and manufacturing design).

6.14 ANNUAL SYSTEM MAINTENANCE CHECK

- Review maintenance logs and alarm logs.
- Review overall system operation with site personnel, and record and report any recommended power system enhancements or equipment operation changes.
- Check each system for general operation; perform rectifier system maintenance as described in the next section and battery system maintenance as described in Part III of this chapter.
- Check the power equipment room environment for temperature, dust, and humidity control.
- Check the operation of room vents and fans.
- Visually check all equipment, cable racks, and supporting structures for abuse, smoke damage, and general mounting security (particularly important in seismically active areas).
- Open all doors, drawers, and covers and examine all power equipment frames for foreign objects, dead animals, and nests. Dust and vacuum the interiors of all dc power equipment frames using only rubber or plastic vacuum attachments (never attempt to disassemble and clean subassemblies while in service). Exterior panels can be cleaned with a mild cleaning solution. Transparent panels should be removed and cleaned with a mild soap and water solution or a cleaner specifically made for the panel material. When finished, restore all doors and covers to their secured condition.
- Check and test the dc power system controller using its built-in diagnostics (if equipped and only if the tests are not service affecting).

- Examine all power wiring for signs of overheating, discoloration, abrasions, burns, and damaged insulation; pay particular attention to locations where the wiring is secured to metallic components such as cable racks and cable brackets.
- Examine all visible components for signs of overheating, swelling, and leaking.
- Scan all power circuit connections and components using a noncontact thermometer; if any abnormal temperatures are found, check for loose connections and retorque as necessary.
- Replace or clean air filters at regular intervals. Site conditions will determine how often the filters should be serviced, but generally, they will need to be cleaned or replaced at least every 6 months in clean environments. If more frequent cleaning or replacement is required, consider upgrading the facility's dust control measures.
- Check system alarms for proper thresholds (overcurrent alarm, undercurrent alarm, system minor alarm, system major alarm, system critical alarm, fuse and circuit breaker alarms, high- and low-voltage alarms, low-voltage disconnect alarm).
- Simulate a system or component failure to check overall alarm system operation (but avoid any simulation that could possibly affect service).
- Check all meters (voltmeters and ammeters) for proper calibration.
- Verify that the bonding connections between the dc power equipment frames and racks and the floor ground bar are secure and in good condition (small installations may have only a building principal ground bar).
- Verify that the bonding connection between the dc power system return bar and the grounding system is secure and in good condition.
- Measure and record the dc load currents at the main shunt and all distribution shunts; look for unexpected changes (either higher or lower).
- Check building and other metallic components for corrosion or discoloration; for example, discolored door hinges and air conditioning vents indicate the presence of corrosive chemicals or hydrocarbons (smoke). Hydrogen embrittlement can occur on hardware that uses electroplated finishes, particularly in battery rooms.
- Resolve any previous outstanding problems.

6.15 RECTIFIER SYSTEM MAINTENANCE

Modern rectifier systems require little maintenance, but the rectifiers at most remote or unattended sites require at least a periodic cleaning. Particular care must be exercised when working on rectifiers because of the dangerous ac voltages on their inputs. Almost all procedures described in this section, except references to ac voltages and currents, also apply to dc–dc converter systems.

6.15.1 Annual Rectifier System Check

- Before performing any maintenance, verify proper operation of the rectifier system.
- If rectifiers are equipped with fans, check their operation. Note: Some fans operate only when the internal rectifier or ambient temperature is above a preset threshold. In this case, the rectifier or rectifier controller may be equipped with a fan test switch to verify operation.

- Measure and record ac input voltage and current for each rectifier.
- Measure and record rectifier dc output voltage and current. The output voltage should be set accurately for the battery technology used (see Part III, Battery System Maintenance).
- Check rectifier load sharing (see Section 6.15.2).
- Check rectifier temperature-compensated charging if equipped (see Section 6.15.3).
- Measure and record ac ripple voltage across the battery terminals with a true-rms ac voltmeter (a true-rms meter accurately measures ac waveforms with harmonics).
- Measure and record ac ripple current on the battery circuit with a true-rms clamp-on ammeter set to measure ac.
- Compare rectifier panel meter readings with a calibrated multimeter. Many modern modular rectifiers are equipped with a simple low-resolution bar-graph display used for both voltage and current, so its accuracy does not need to be measured.
- Examine all visible rectifier components for signs of overheating, swelling, and leaking.
- To the extent possible, scan the internal components, circuitry, and all rectifier-related cabling and connections with a noncontact thermometer. Note: Active semiconductor components inside a rectifier may be designed to run hot and if the rectifier operation is otherwise normal, high measured temperatures of these devices normally are no cause for alarm.
- Scan the rectifier ac load center (ac distribution panel) with a noncontact thermometer and look for overheated circuit breakers. Overheated circuit breakers can be caused by overload or by a poor electrical connection to the panelboard bus or by a poor connection to the load circuit wiring.
- Clean the rectifiers with a vacuum. If the rectifiers are standalone types, turn off the ac input at the circuit breaker panel before cleaning and verify no input voltage is present; if the rectifiers are modular, remove them one at a time and clean. Do not turn off or remove any rectifiers unless the remaining rectifiers are capable of carrying the load.

6.15.2 Rectifier Load Sharing Tests

The rectifiers should share the load in proportion to their rating (within approximately 10%) according to

$$I_{\mathrm{RNL}} = I_{\mathrm{RNC}} \frac{I_L}{I_{\mathrm{RTC}}} \tag{6.4}$$

where I_{RNL} = load current on rectifier N (A)
I_{RNC} = full load capacity of rectifier N (A)
I_L = load current (A)
I_{RTC} = total rectifier full-load capacity (A)

For example, if the total load on two 50-A rectifiers and one 100-A rectifier (total rectifier full-load capacity of 200 A) is 100 A, the two small rectifiers each should carry 25 A and the large rectifier should carry 50 A.

Modern modular rectifiers use a common controller for output voltage and load sharing, and there are no separate load sharing adjustments. However, standalone rectifiers generally are self-controlled and require independent adjustment. First, the load share control lead output voltage must be adjusted using the procedures specified in the manufacturer's instruction manual. Then, the float output voltage of each rectifier is adjusted so that they properly share the load.

The following adjustment procedures are easy when there are three or less rectifiers but can be used with a larger number. The best way to make these adjustments is to set the rectifiers to the proper output voltage and then very slightly adjust each one until they all share the load in proportion to their rating. If one rectifier is taking more than its share of the load ("hogging"), its output voltage is slightly higher than the others. Very slightly reduce this rectifier's output voltage to reduce its load. If one rectifier is not carrying any load at all, its output voltage is slightly lower than the others. Very slightly increase its output. Repeat this basic procedure for all rectifiers until they are proportionally sharing the load. All output voltage changes should be made in very small increments. Once all rectifiers are sharing the load, check the battery terminal voltage. If it is low, then start with one rectifier and very slightly increase its output. If the voltage is high, then start with one rectifier and very slightly decrease its output. Repeat for all rectifiers until the proper voltage is measured at the battery terminals and all rectifiers are sharing the load. It may be necessary to repeat this procedure several times.

The sharing accuracy generally is better when the rectifiers are operating above 50% of their output rating (typically they will share within 10 to 20% of each other). The rectifiers may not share the load at all when operating at less than 10% of rating, and one or more rectifiers may show a low-current alarm even though the rectifiers are fully operational. This situation is encountered at sites where the load is relatively small and the battery reserve time is relatively long. A large rectifier system capacity is required to recharge the battery and, once it is recharged, the rectifier output current decreases enough that the load sharing function is inaccurate.

6.15.3 Temperature-Compensated Charging Tests

If temperature-compensated charging is used, the temperature of the cell on which the sensor is mounted needs to be determined to ensure the rectifiers are adjusted properly. The sensor temperature should be checked with a noncontact thermometer such as an infrared (IR) thermometer or an insulated contact thermometer. The amount of compensation in the rectifier will determine the rectifier setting. For example, if the rectifier compensates by reducing its output voltage by 3.0 mV/°C/cell and the cell temperature is 28°C, the compensation is (28° – 25°) × 3.0 mV/cell = 9 mV (0.009 V) per cell. If the battery consists of 24 cells and the desired voltage is 54.48 V at 25°C, the new voltage is 54.48 – (0.009 × 24) = 54.26 V at 28°C. Similar calculations can be made for temperatures in degrees Fahrenheit. For example, if the rectifier compensation is 2 mV/°F/cell and the temperature of a 12-cell battery is 80°F, the new voltage is (80° – 77°) × 2 mV/cell = 6 mV (0.006 V)/cell. If the desired voltage is 27.24 V at 77°F, the new voltage is 27.24 – (0.006 × 12) = 27.17 V at 80°F.

Temperature-compensated charging may be tested by directing warm air from a hair dryer or heat gun onto the battery temperature sensor while simultaneously measuring the battery float voltage [for safety, do not use an all-metal heat gun, and hold the heat source at least 12 in. (300 mm) from the sensor so it is not overheated]. As the temperature of the sensor rises, the voltage should drop. There will be a time delay and the voltage drop may be small, so the voltmeter will have to be watched closely. When the voltage drops, the rectifier current also will drop until the battery discharges to the new voltage. When the heat source is removed and the sensor cools down, the voltage should return to a value normal for the cell temperature.

6.16 INVERTER SYSTEM MAINTENANCE

Particular care must be exercised when working on inverters because of the dangerous ac output voltages.

6.16.1 Annual Inverter System Check

- Before making any measurements, verify proper operation of the inverter system.
- Measure and record dc input voltage and current for each inverter.
- Measure and record inverter ac output voltage, current, and frequency.
- Check inverter load sharing.
- Compare inverter panel meter readings with a calibrated multimeter.
- If inverters are equipped with fans, check their operation. Note: Some fans operate only when the internal or ambient temperature is above a preset threshold. In this case, the inverter or inverter controller may be equipped with a fan test switch to verify operation.
- Examine all visible components for signs of overheating, swelling, and leaking.
- To the extent possible, scan the inverter internal components, subassemblies, and circuitry with a noncontact thermometer; if any abnormal temperatures are found, check for loose connections and retorque as necessary. Note: Active semiconductor components inside an inverter may be designed to run hot and if the inverter operation is otherwise normal, high measured temperatures of these devices normally are not cause for alarm.
- To the extent possible, scan all inverter power circuit connections with a noncontact thermometer; if any abnormal temperatures are found, take the inverter offline (see next section), check for loose connections and retorque as necessary.
- Scan the inverter ac output load centers or outlet panels with a noncontact thermometer and look for overheated connections.

6.16.2 Offline Inverter Maintenance

- Do not perform offline maintenance unless the inverter loads can be powered from an alternate source or else the loads themselves may be shut down.
- Transfer inverter loads to an alternate source and shut down the inverter system as detailed in the manufacturer's instruction manual.
- Verify that all input and output voltage sources are securely locked-out and isolated for maintenance.

DANGER—Prior to examining or cleaning the inside of the inverters, use an ac multimeter to check all areas of the inverter that may be energized

and be cautious and alert at all times. Every circuit or connection is "hot" (energized) unless proven otherwise. Always use the "one hand in the pocket" rule.[8]

- Verify that all electrical connections are properly tightened.
- Verify secure connections on all capacitors.
- Clean the inverters with a vacuum. If the inverters are standalone types, turn off the dc input at the circuit breaker or fuse panel before cleaning and verify no input or output voltage is present; if the inverters are modular, remove them one at a time and clean.
- Clean the inside of inverters with a vacuum cleaner being careful of areas that may have voltage present.
- If necessary for calibration or testing, restore only input power.
- If the inverter system is equipped with a maintenance bypass panel, check the operation of all switch positions (typically, offline, online, maintenance, and test).
- Once the inverter system is properly adjusted and tested, restore inverters to full operation as detailed in the manufacturer's instruction manual and verify operation.

PART III BATTERY SYSTEM MAINTENANCE

This part describes the requirements for operating and maintaining vented lead–acid (VLA) and valve-regulated lead–acid (VRLA) batteries used in telecommunications applications. The first section discusses common requirements that apply to both battery technologies followed by individual sections for VLA and VRLA. Excellent sources of information on battery problems and maintenance are [1] and [2].

6.17. GENERAL REQUIREMENTS

Three general statements can be made about battery maintenance:

- There is nothing a user can do to prevent a battery from eventually wearing out, but a good battery maintenance program will increase the odds of attaining design life.
- Network operators can pay now or pay later for battery maintenance, but paying now increases reliability and paying later decreases reliability.
- Just about any battery maintenance statement, rule of thumb, or procedure has exceptions. Always read, understand, and follow manufacturer's recommendations.

6.17.1 Test Equipment

Only a few test sets are required for *basic* battery operation and maintenance—a nonmetallic flashlight, voltmeter, and an accurate thermometer and, for VLA batteries, a hydrometer. However, additional types of test equipment, such as a clamp-on dc ammeter,

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[8] When working on electrical equipment of any type, keep one hand in a pocket to prevent a harmful electrical current from flowing from one hand through the upper body and heart to the other hand.

microohmmeter, cell internal resistance, impedance or conductance tester, and insulation resistance tester, will greatly aid battery maintenance and increase the chances the network operator will attain battery system design goals.

Measuring and adjusting battery voltage with an accurate 4½ digit (or 6000 count) digital voltmeter or multimeter is *critical* to long battery life. A multimeter is preferred because it can be used for other electrical testing. Accuracy should be at least ± 0.1% with a resolution of 0.1 mV, and the voltmeter should be calibrated at least annually.

A high-quality thermometer is necessary to measure cell and ambient temperature. Traditional glass–mercury or glass–alcohol thermometers are available from battery manufacturers. Thermocouple or thermistor temperature sensors with digital readouts are suitable if they can be safely immersed in battery acid and do not contaminate the battery. Perhaps the most useful thermometer type is an accurate noncontact IR thermometer or camera. It can be used to measure not only cell and ambient temperatures but also the temperatures of electrical connections and wiring; however, it is important that these devices be calibrated at intervals recommended by the manufacturer. Although bulb-type hydrometers may be used, electronic hydrometers also measure electrolyte temperature and automatically correct the specific gravity reading to the reference temperature.

Increasingly important for battery maintenance is a test set that measures cell internal impedance, resistance, or conductance, which is a good indicator of cell condition. It is particularly useful in VRLA installations because the internal components of VRLA cells cannot be visually examined to determine their condition. Cell testers are relatively expensive but will help locate faulty cells and therefore increase the overall reliability of both VLA and VRLA installations. Also, they usually have other test functions that allow measurement of the cell interconnection resistances and other low-resistance connections.

Cell testers variously measure internal impedance, resistance, or conductance. Extensive published test data indicate that these parameters yield equivalent results [3, 4]. It has been shown that impedance, resistance, or conductance measurements do not directly indicate cell capacity but changes in measured values can be used to predict cell failure.

6.17.2 Records

An important aspect of battery operation and maintenance is keeping proper and updated records (Fig. 6.32). Form 1 (Vented Lead–Acid) and Form 2 (Valve-Regulated Lead–Acid) at the end of this chapter may be used for regular battery maintenance; Form 3 may be used for cell and interconnection resistance records. These forms may be modified to take into account different battery post and terminal lug designs.

6.17.3 Cleanliness

Battery cleaning kits are available from most battery system manufacturers and other manufacturers specializing in these types of products. The kits include tubs, containers, and squirt bottles to hold the cleaning and neutralizing solution, bristle brushes and towels as well as personal protective gear.

Keep battery connections clean, bright, and corrosion-free and lightly coated with a corrosion inhibitor. Any corrosion that does form must be cleaned off terminals; otherwise it will spread into areas between posts and connectors and will develop into a high-resistance connection causing heat and wasted capacity. Any corrosion that has blue, green, mustard yellow, or maroon color indicates that copper is involved in the corro-

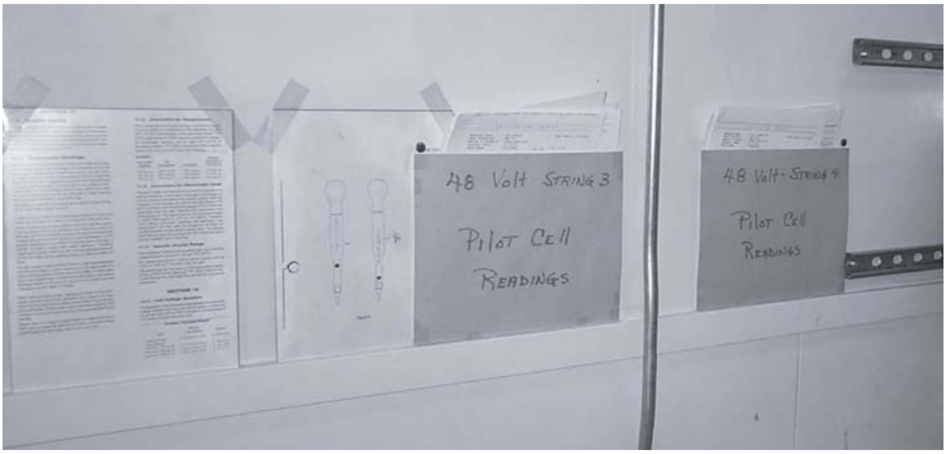

Fig. 6.32 Battery system records. The informal nature of the records in this photo does not detract from their usefulness.

sion process. The copper is coming from somewhere (such as post or connector) and the source must be found and corrective action taken. Keep the battery and surrounding parts clean, dry, and free of acid. Sulfuric acid electrolyte absorbs moisture, and spilled electrolyte does not dry up or evaporate so it must be neutralized before it is cleaned up.

Neutralize spilled electrolyte with a solution consisting of 1 lb (0.1 kg) of bicarbonate of soda (baking soda) to 1 gal (1 liter) of clean water, then rinse with distilled water and dry with a soft lint-free cloth or towel (be sure to dispose of properly). Do not allow the soda–water solution to get into the cells.

6.17.4 Safety Practices and Tools

Battery system testing must be performed or supervised only by qualified persons. Even relatively small telecommunications batteries store large amounts of chemical and electrical energy, and failure by personnel to be alert and knowledgeable will lead to injury and equipment damage. Although special tools are not usually required, they must be handled and used carefully:

- Use insulated or taped tools when working on batteries and electrical connections (Fig. 6.33). Use a high-quality electrical tape; do not use cheap electrical tape like that available at automotive parts stores or department stores.
- Always use a good quality micrometer-style, click-type torque wrench to tighten all electrical fasteners; do not use cheap automotive torque wrenches with wing-style torque indicators. If the torque wrench is not insulated, be sure to tape it before use.
- The torque values in most battery installations are in inch-pound units; however, some newer battery installations may use metric fasteners in which case the torque-wrench should be calibrated in metric units (newton-meters or kilogram-meters).
- See also Section 6.1.

Fig. 6.33 Insulated tools. (Photo courtesy of M.W. Migliaro.)

When working on battery systems and handling electrolyte, wear protective equipment at all times, including

- Acid-resistant gloves
- Acid-resistant aprons
- Goggles or face shields (be sure the face or eye shields do not have bare metallic frames or rims that can cause a battery short if dropped)

Avoid splashing the electrolyte. Electrolyte can seriously injure eyes and skin and damage clothing and equipment and must always be handled carefully. The eyes in particular should be guarded with face shields or protective glasses. If acid is splashed into the eyes or anywhere on the skin, flood with water for at least 15 min. For electrolyte contact with the eyes get medical attention. Do not use bicarbonate of soda solution on the skin or eyes because it may aggravate the burn.

Provide a combination eye-wash, face, and body spray unit within 25 ft of the battery room or battery system. These units can be permanently mounted and connected to the facility's potable water system or can be a portable pressurized unit. Keep the area in front of the washing station clear.

Remove all metallic jewelry (large metal belt buckles, rings, watches, bracelets, necklaces) when working around batteries and electrical circuits. Remove metallic pens and other implements from shirt pockets. Use a nonmetallic flashlight for battery inspection, and follow the "one-hand-in-pocket" rule (see Section 6.16.2).

Never lay any conductive object on top of a battery. Avoid work methods that could cause battery circuit interruption, short circuits, or arcing in the battery vicinity.

Post "No Smoking" and "No Open Flame" signs where they are clearly visible to anyone entering the battery room area. Keep doors leading out of the battery room clear at all times.

Mount a 10-lb, Class C fire extinguisher just inside the battery room door.[9] Carbon dioxide (CO_2) extinguishers are not recommended because the cold temperature can cause thermal shock and crack cell containers resulting in a spill hazard, adding to the original fire problem and leaving an even larger mess to clean up.

Vented lead–acid batteries generate a highly explosive mixture of hydrogen and oxygen when gassing, and sparks, open flame, or lighted cigarettes never should be permitted near any kind of battery. Although VRLA batteries are sealed and use recombinant techniques, they can generate and release explosive gasses during normal and overcharge conditions. Hydrogen concentration in the battery room or area must be kept below 2% by volume at all times.

Battery rooms must be ventilated regardless of the battery technology used. In small enclosed battery installations, vents or louvers that provide natural air circulation through the battery room or enclosure are sufficient. Larger installations require forced air ventilation (fans) that runs continuously or periodically.

Periodically measure airflow and total combustible gas in the battery areas to ensure there is adequate air movement for diffusing hydrogen gas.

Battery cells and modules are very heavy and should be handled with a lifting device such as a small crane, cherry picker, or elevator lift. Certain types of cells require special lifting devices (Fig. 6.34).

6.17.5 Acid Electrolyte Spill Management

Spill management applies to both VLA and VRLA batteries. The electrolyte in VRLA batteries is immobilized, but it still can leak out through faulty post seals and container cracks and pinholes. However, the magnitude of acid spills from VRLA batteries seldom is of the same magnitude as spills from VLA batteries.

All battery installations should have a spill management kit for safely neutralizing, cleaning up, and disposing of spilled electrolyte and should include personal protective gear (Fig. 6.35). Battery system manufacturers and other manufacturers can provide complete kits. A typical kit consists of:

- Personal protective gear
  - Acid-resistant clothing
  - Acid-resistant gloves
  - Acid-resistant boots or socks
  - Face shield or goggles
- Equipment and material to neutralize and clean up electrolyte
  - Booms and pillows
  - Disposal bags and ties
  - Acid-absorbent towels and pads
  - Salvage drum

The absorbent material, disposal bags, and drum must be large enough to hold the amount of spilled liquid, which in the worst case will equal the electrolyte volume

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[9] Class C fires involve electrical equipment, and the agent used in Class C extinguishers is not electrically conductive. A circle containing the letter "C" identifies Class C extinguishers.

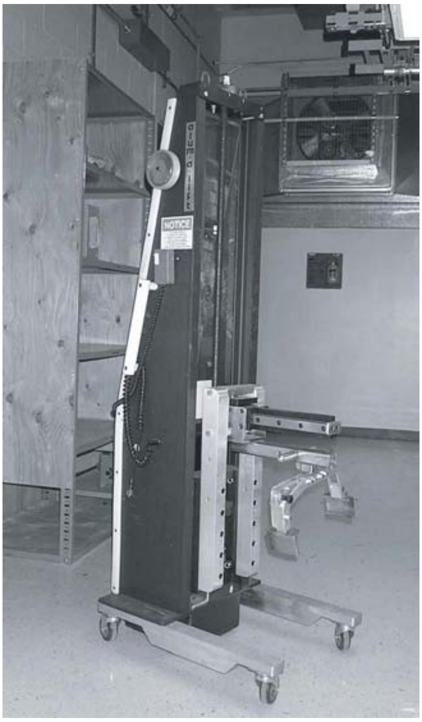

Fig. 6.34 Lifting device for round cells.

(quarts, gallons, or liters) in each cell, as determined from the battery data sheets, times the number of cells. Generally, one kit is provided per battery string.

6.17.6 Electrical Connections

All electrical connections must be properly torqued, including battery terminals, cell interconnecting straps, and bus and terminal fasteners. Some VRLA modules are marked with the correct torque values (Fig. 6.36). Particular care must be taken to prevent overtightening fasteners at battery posts as these are made from relatively soft material that can be crushed and deformed (Fig. 6.37). If the fasteners loosen because of temperature cycling or slow compression (cold flow) of the lead terminal posts, the interconnecting strap resistance will increase over time. A high resistance is apparent on discharge because the straps will get very hot.[10]

Regular examination of the cell interconnecting straps and hardware is essential. If corrosion is apparent (usually around the positive post), the connections need to be disassembled and cleaned. The corrosion may be severe enough to crack the hardware, partic-

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[10] In the early 1980s at a site in Alaska, the author had checked the torques on all cell interconnect straps on a new 24-cell battery string installed by others. About 6 months later, there was a commercial power outage and the batteries started to discharge. When the site technician walked into the darkened battery room, he was surprised to see the cell interconnect straps glowing red. The connections had loosened in 6 months and the high resistance produced enough heat to glow.

Fig. 6.35 Spill management kits. (Upper photo (Whitham D. Reeve; lower photo courtesy M.W. Migliaro.)

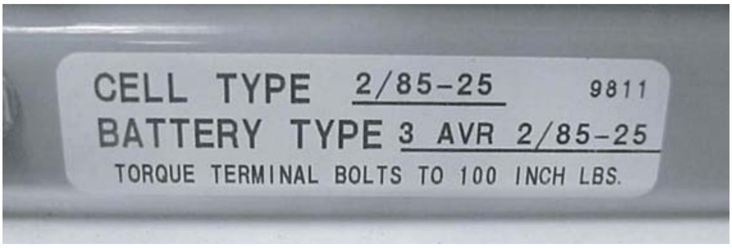


Fig. 6.36 Terminal torque label on VRLA module.

Fig. 6.37 Battery post deformation caused by fastener overtorque. Note that the battery post is deformed in the shape of an anvil (and is called “anviling”). (Photo courtesy M.W. Migliaro.)

ularly the fastener nuts, or the cell cover (Fig. 6.38). A coating of antioxidant compound should be applied to the posts and straps after they are cleaned. A stiff, nonmetallic scrub-brush should be used to clean battery components (a metallic brush, steel wool, and emery cloth should not be used as they may leave incompatible material that will corrode even further).

6.17.7 Cell Ground Faults

Over the life of a VLA or VRLA battery, cells can develop cracks in the container or at the seam of the cover and container, or the containers may have pinholes from the manufacturing process. Also, containers can be cracked during shipping, handling, and installation. Any electrolyte that leaks out through the openings can provide a conductive fault path to ground via the battery frame or directly to the concrete floor for large, freestanding cells (Fig. 6.39). The resulting fault may cause the cell containers to slowly burn at first, but the smoldering fire may easily escalate into a major fire.

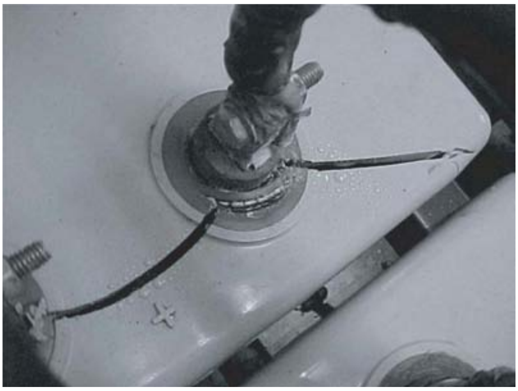


Fig. 6.38 Cracked cell cover caused by corrosion in the post seal. (Photo courtesy M.W. Migliaro.)

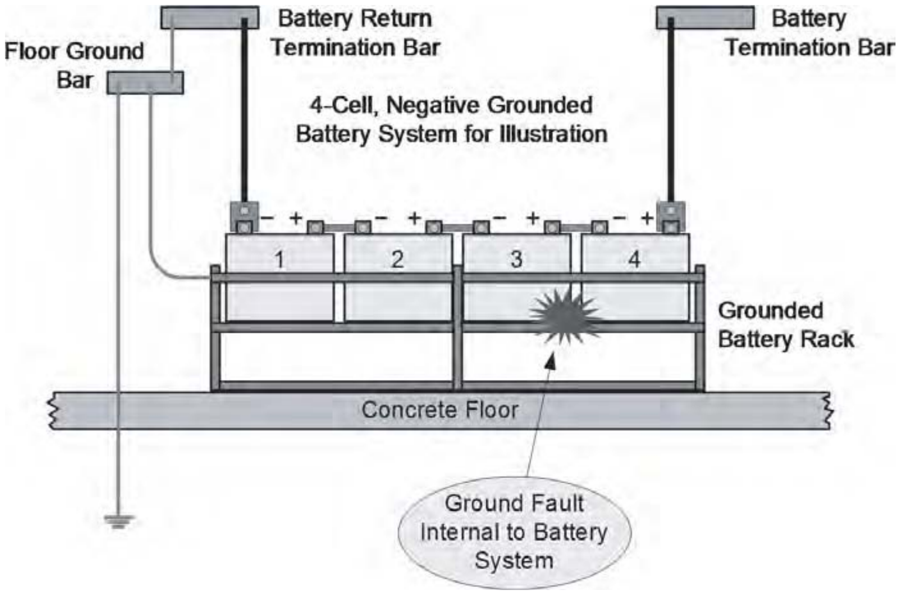


Fig. 6.39 Battery internal faults. In this illustration, a simple 4-cell battery system with a negative ground experiences a ground fault in cell 3, possibly due to a cracked case or other problem that causes electrolyte to leak out and provide a current path to ground.

Since one terminal of all telecommunications battery systems is connected to ground, a cell ground fault cannot be detected unless each individual cell is connected to a monitoring system. Cell ground fault currents normally are not large enough to trip battery circuit overcurrent protection devices (if equipped). Battery circuit overcurrent devices only protect against faults external to the battery system, whereas cell ground faults are internal to the battery system. Battery strings that are connected through a one-pole disconnect or overcurrent device may be opened manually by a push-button operated shunt-trip mechanism if a fault is discovered, but the one-pole device will do nothing to interrupt the ground fault path. The only way to manually interrupt the ground fault is to have a two-pole disconnect or molded case circuit breaker with a shunt trip mechanism in the battery circuit that disconnects both battery terminals, including the grounded terminal (Fig. 6.40).

6.17.8 Measurements

6.17.8.1 Voltage Measurements Battery and cell voltage readings should be taken on a regular basis. Rectifier output voltage also must be measured on a regular basis and whenever changes have been made to the ac electrical service or building wiring. For example, if the building electrical service voltage is changed or if the electric utility changes taps on its service transformers or voltage regulators, rectifier voltage may need adjustment. In the case of service voltage change, the input transformer taps in older rectifiers may need to be changed. Most modern rectifiers operate over a wide input voltage range and do not have transformer taps.

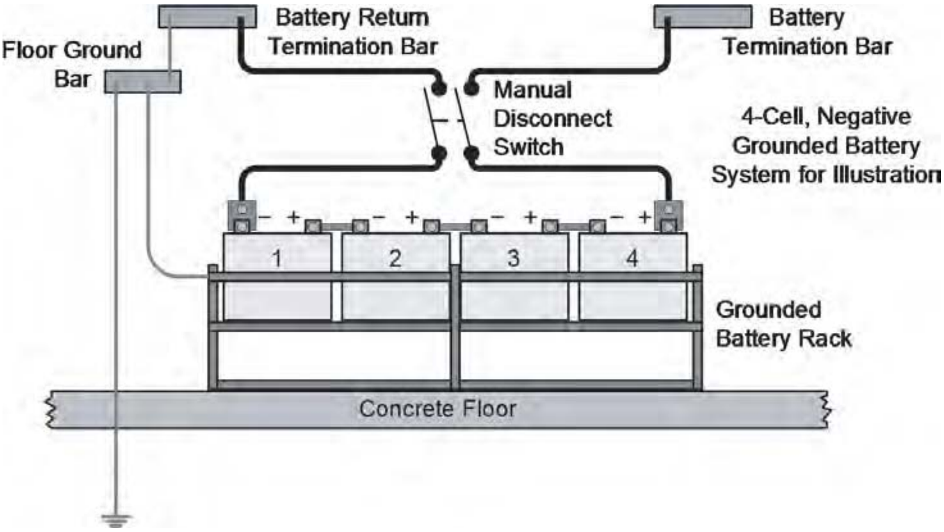


Fig. 6.40 Two-pole battery disconnect. Either a manual disconnect switch or molded case circuit breaker with shunt trip mechanism can be used to disconnect both battery terminals during maintenance or to isolate a battery with an internal ground fault.

When measuring cell voltages, the probes should be placed directly on the cell posts or terminals and not on the cell interconnect straps. When measuring battery terminal voltage, the probes should be placed directly on the terminal plates or lugs.

6.17.8.2 Temperature Measurements All cells of a VLA battery should be at approximately the same temperature—a 3°C (5°F) spread from the coldest to the warmest is acceptable. Heat sources such as sunlight and portable heaters must be blocked or moved so they do not raise the temperature of individual cells. If the temperature spread of the cells exceeds 3°C (5°F) (e.g., if the upper row of a two-tier VLA battery rack is warmer), the room ventilation or air circulation may be inadequate. Never intentionally allow electrolyte temperature to exceed 38°C (100°F). Record the room ambient temperature before measuring cell temperatures.

Battery installations with several tiers, such as many VRLA installations, may exhibit a wider temperature spread from bottom to top. In this case, the warmest tier (usually the highest) should never exceed 28°C (82°F).

If an accurate IR thermometer is available, measure the temperature of the battery connections (terminals and cell-interconnecting straps) when load current is flowing such as during a discharge test or when the battery discharges during a commercial ac power outage. The temperature of loose or improperly torqued connections will be higher than the other connections.

6.17.8.3 Connection Resistance Measurements Cell interconnecting straps are made of lead-coated copper. Connections include the strap as well as the contact to the cell terminal post and typically are designed for 20- to 30-mV drop at the anticipated range of discharge currents. The connection resistance can be calculated from Ohm's law, or

$$R_{\text{Connection}} = \frac{V_{\text{Drop}}}{I_{\text{Discharge}}} \text{ ohms} \tag{6.5}$$

Example 6.1 The 3-h discharge current for a 620-Ah battery is 170 A. If the interconnecting straps are designed for 20-mV drop, determine their resistance.

Solution Using Ohms's law

$$R_{\text{Connection}} = \frac{V_{\text{Drop}}}{I_{\text{Discharge}}} = \frac{0.020\text{ V}}{170\text{ A}} = 118 \times 10^{-6}\,\Omega = 118\,\mu\Omega$$

Connection resistance measurements can be dangerous; people making the measurements must be alert, methodical, and cautious. Connection resistances are very small, measured in microohms. To obtain meaningful measurements it is important to use consistent and proper methods. Measurements are made from post to post of connected cells and from the post to the terminal lug on the first and last cells. The microohmmeter scale should be set to the lowest resistance scale and the probes should be held perpendicular to the terminal or post. There are many manufacturers of instruments designed to measure very small resistances, and some are specifically designed for battery applications.

NEVER place the probes across a cell or cells (across positive and negative posts or terminals of a given cell) with the meter set to measure resistance. This may damage the meter and the cell and may cause injury.

Cell post and terminal configurations vary. Figure 6.41 shows some common configurations and the recommended measurement points. Proper and improper methods for connection resistance measurements are shown in Figures 6.42 and 6.43. Some VRLA cells have a plastic cover over the cell post that makes measurement difficult if not impossible (Fig. 6.44). In this case it is tempting to measure from bolt head to bolt head, but the measurement so obtained is useless because the measurement includes the high-resistance stainless steel bolt and is not a true cell-to-cell measurement.

Measurements should start at the battery terminal connected to cell No. 1, which in many telecommunications installations is the cell at the positive end, and move to the opposite end of the battery. Ensure the battery is on float charge before beginning the measurements and not on equalize or being discharged. Record all measurements on Form 3 at the end of this chapter.

1. Take the first measurement on cell No. 1 between the terminal lug and the first post [Figs. 6.41(a) to 6.41(d)]. This measurement will be about one-half of the cell interconnecting strap readings in steps 2 and 3 below.
2. Take the second measurement between *opposite* polarity *posts* of cells No. 1 and No. 2 (do not put the probes on the interconnecting straps). This measurement will include the resistance of two bolted connections (one on each post) and the cell-interconnecting strap or straps [Figs. 6.41(e) to 6.41(h)] and will be about twice the value of the first and last measurements at the battery terminals (steps 1 and 4).

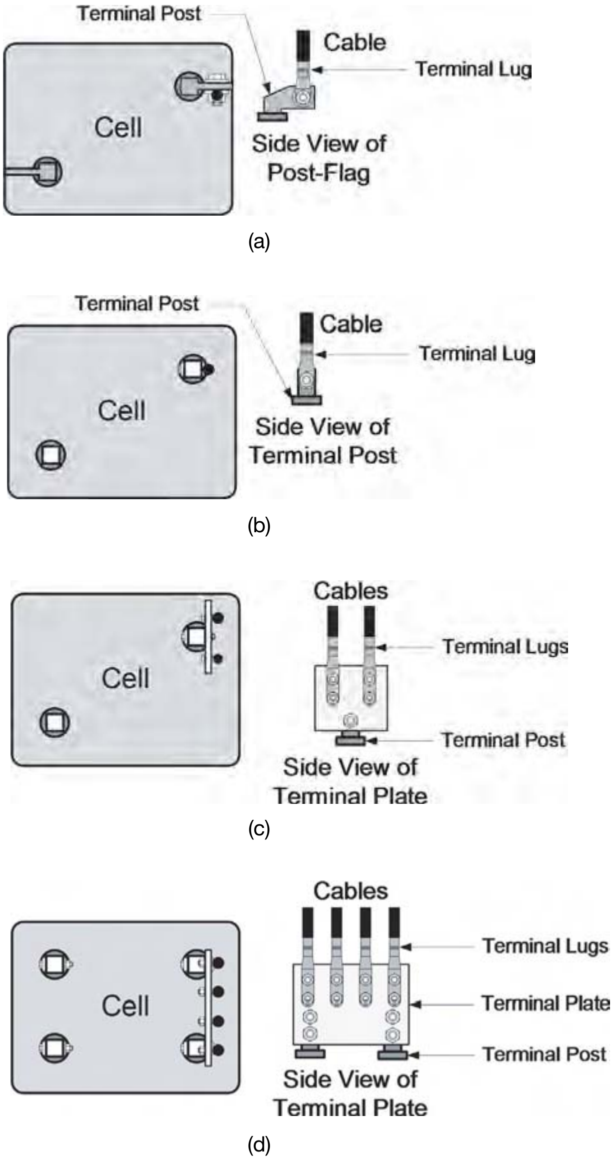


Fig. 6.41 Battery cell post and terminal configurations and associated resistance measurements. (a) *Post–flag terminal*—Each post has an offset plate (flag) mounted on it or part of it for fastening interconnection straps or terminal conductors. Measure resistance from terminal lug to terminal post. (b) *Single terminal*—Terminal conductors are fastened directly to each battery terminal. Measure resistance from terminal lug to terminal post. (c) *Single post plate terminal*—Each battery terminal has a plate for fastening terminal conductors. Measure resistance from each terminal lug to the cell post. (d) *Cable–plate–post*—Each battery terminal has two parallel posts with one large plate mounted on them for fastening terminal conductors. Measure resistance from each terminal lug to plate and from plate to each cell post.

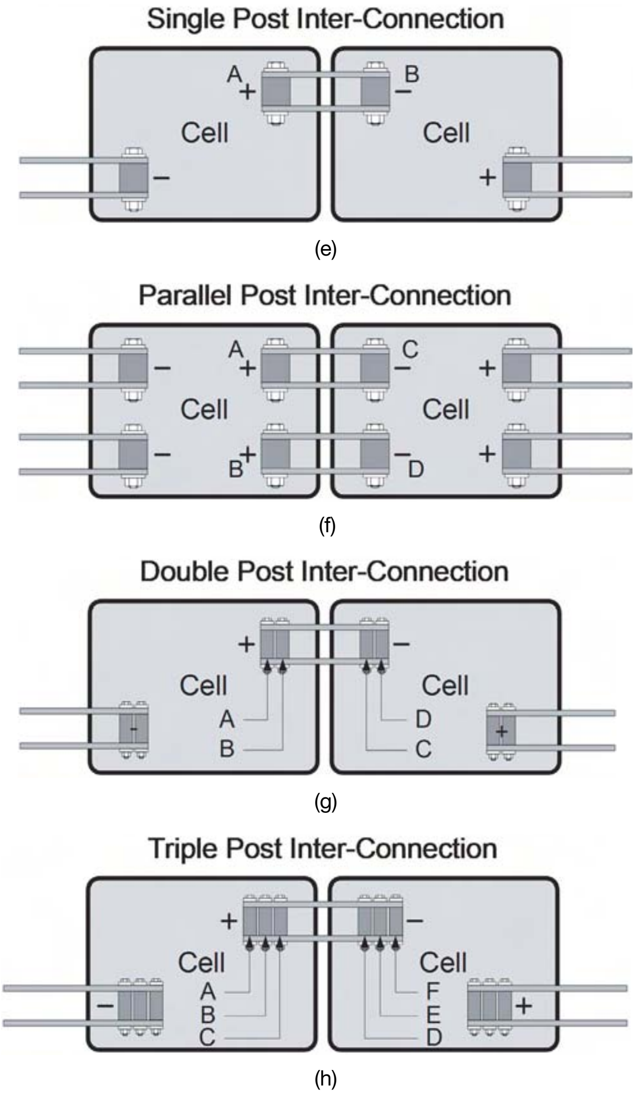
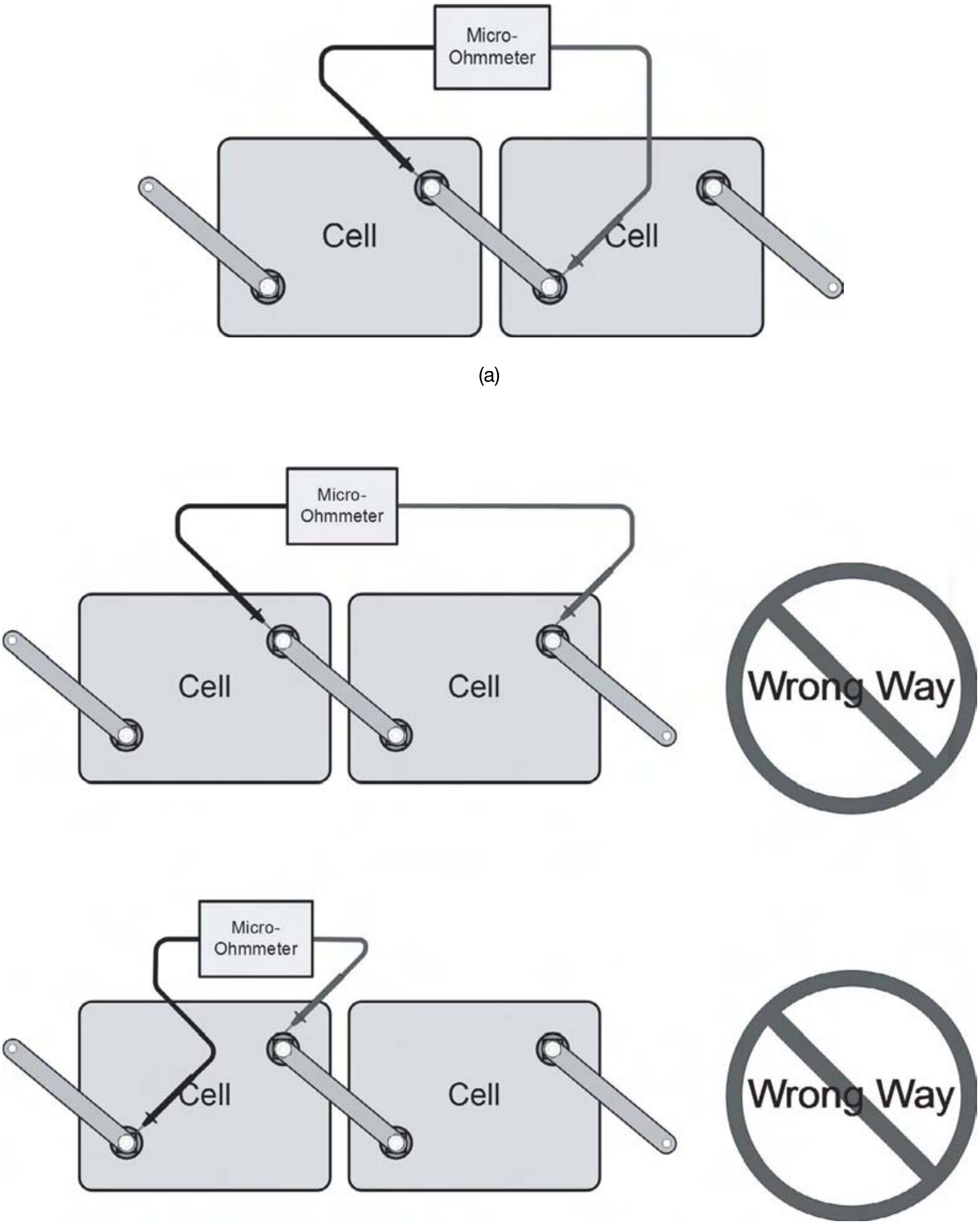


Fig. 6.41 Battery cell post and terminal configurations and associated resistance measurements. (e) *Single post*—One or two parallel interconnection straps (two shown) may be equipped depending on cell capacity. Measure resistance from the positive terminal post *A* of one cell to the negative terminal post *B* of the adjacent cell. (f) *Parallel post*—Each cell polarity has two posts internally connected in parallel. Measure resistance from the positive terminal post *A* of one cell to the negative terminal post *C* of the adjacent cell and from positive terminal post *B* to the negative terminal post *D* of the adjacent cell. The two resistances should be approximately the same. (g) *Double Post*—Each cell polarity has two closely spaced posts internally connected in parallel, and each post has a set of fasteners for the interconnection straps. Measure resistance from the positive terminal post *A* of one cell to the negative terminal post *C* of the adjacent cell and from positive terminal post *B* to the negative terminal post *D* of the adjacent cell. The two resistances should be approximately the same. (h) *Triple Post*—Each cell polarity has three closely spaced posts internally connected in parallel, and each post has a set of fasteners for the interconnection straps. Measure resistance from the positive terminal post *A* of one cell to the negative terminal post *D* of the adjacent cell, from positive terminal post *B* to the negative terminal post *E* of the adjacent cell, and from positive terminal post *C* to the negative terminal post *F* of the adjacent cell. The three resistances should be approximately the same.



(a)

(b)

Fig. 6.42 Connection resistance measurement methods. (a) *Proper method*—Probes should be placed on the cell post and not on the interconnection strap. See also Figure 6.43. (b) *Improper method*—Connecting the meter across the cell may result in cell or meter damage and injury.

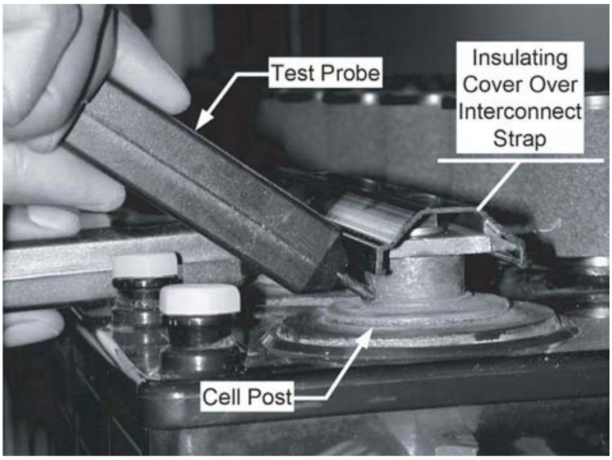


Fig. 6.43 Correct test probe connection at cell post. Note that the probe is touching the lead metal on the cell post. The second probe is visible behind the labeled test probe. (Photo courtesy of M.W. Migliaro.)

3. Make subsequent measurements between positive and negative *posts* of adjacent cells in a manner similar to step 2, moving from cell to cell.
4. Take the last measurement between the last post on the last cell and the battery terminal lug fastened to it.
5. Analyze the measurements as follows: The positive and negative battery terminal resistances should be no higher than approximately one-half of the cell interconnection strap resistances. The higher of the two terminal measurements should be no

Fig. 6.44 Plastic cover on VRLA cells. When the cell interconnect strap is in place, the lead metal on the cell post is completely covered and not accessible for resistance measurements. A measurement from bolt head to bolt head, if attempted, is useless. (Photo courtesy of M.W. Migliaro.)

more than 20% higher than the lower measurement. The resistance of any interconnection strap should not be 20% higher than the lowest resistance, as in

$$R_{\text{High}} \leq 1.2R_{\text{Low}} \tag{6.6}$$

6. If a high resistance is found, measure from each post to its cell-interconnecting strap to determine which of the two connections is bad. Mark all high-resistance connections for repair (step 7).
7. Retorque problem connections to the manufacturer's specifications. If the resistance still does not meet the requirements of step 5, disassemble, clean, and apply corrosion inhibitor compound and reassemble. Retest the repaired connection and record the resistance in the "as-left" column on Form 3. Disassembly of connections on an active battery string must be done with caution and planning so as to not jeopardize network equipment operation.

The resistances of the interconnection straps and battery terminals should be on the order of 100 μΩ or less; actual values will depend on the amount of contact area and size of the inter-connection straps (smaller battery installations will have higher resistances than larger installations). Measurements taken upon completion of the original installation will be used as a baseline for comparison to later measurements. See Section 6.18.6 (VLA) and 6.19.5 (VRLA).

6.17.8.4 Cell Internal Impedance Measurements Internal impedance, resistance, or conductance can indicate cell internal condition and applies to both VLA and VRLA batteries. Measuring the internal impedance of a VRLA cell allows the user to monitor two important failure modes, which are grid corrosion and dry out. Battery manufacturer's literature should list the normal expected values. If a manufacturer is reluctant to provide this information or says it is not available, batteries should not be purchased from them.

Internal impedance, resistance, or conductance measurements should not be made until after the cell interconnection resistances are checked (and repaired if necessary). Depending on how the measurements are made, a high connection resistance may falsely indicate a high internal cell resistance.

There is some disagreement in the industry as to exact values and tolerances of cell internal measurements, but Table 6.16 may be used to establish a reference program for tracking trends. A cell reference value (CRV) is determined and then used as a benchmark for future measurements. It is important that written records be kept starting on the installation date and periodically thereafter. Initial values are as important as trends throughout the battery system life.

Although it is possible to measure cell internal impedance while the battery is being discharged (by dividing the cell voltage by the discharge current), this type of test may not provide repeatable results. Commercial test sets are available to measure internal impedance, resistance, or conductance and provide repeatable results during normal float operation.

6.17.9 Monthly, Quarterly, and Yearly Inspections

Inspections are required to determine the general condition of safety equipment and are in addition to specific inspections and measurements of power system components (batteries and rectifiers) listed in respective sections that follow.

Table 6.16 Cell Internal Impedance, Resistance, or Conductance Measurements

Description	Conductance	Resistance or Impedance
Cell reference value (CRV)	Average of 10 highest (24-cell battery) or 5 highest (12-cell battery) cells	Average of 10 lowest (24-cell battery) or 5 lowest (12-cell battery) cells
For a battery string that is new or only a couple years old	Measurements of all cells should fall within ±5% of the CRV	Measurements of all cells should fall within ±5% of the CRV
For an older, fully functional battery string	Measurements of all cells should fall within ±10% of the CRV	Measurements of all cells should fall within ±10% of the CRV
Battery string is in good condition if	All cells are above 80% of the CRV	All cells are below 125% of the CRV
Additional testing may be required on a suspect cell if	The cell is 60–80% of the CRV[a]	The cell is 125–167% of the CRV[b]
Cell is unserviceable and requires replacement if	The cell is $\leq$ 60% of the CRV	The cell is $\geq$ 167% of the CRV

[a] This range is for guidance. It is possible that a cell measuring < 70% of the average conductance has < 80% rated capacity and should be replaced.

[b] This range is for guidance. It is possible that a cell measuring > 130% of the average resistance or impedance has < 80% rated capacity and should be replaced.

- Check for availability and condition of all safety equipment, including gloves, aprons, and face shields.
- Check for a full gallon (4 liters) of labeled acid-neutralizing solution.
- Check operation of the eyewash station or portable eyewash equipment.
- Check operation and cleanliness of the body wash station.
- Check that a Class C fire extinguisher is available and that it has been inspected and tested according to schedule.
- Check that insulated tools and utensils are available.
- Check the hydrometer for cleanliness and cracked rubber parts (VLA installations only).

6.18 VENTED LEAD–ACID BATTERIES

6.18.1 General

This section outlines the requirements for operating and maintaining vented lead–acid (VLA) batteries. The battery manufacturer and industry standards are the best places to get detailed operation and maintenance information; however, this section provides sufficiently detailed information for most VLA batteries.[11]

6.18.2 Specific Gravity Measurements

6.18.2.1 Instruments Three types of hydrometers are available for measuring the electrolyte specific gravity in VLA cells—float type, syringe type, and electronic display

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[11] See also IEEE Std 450 [5].

(Fig. 6.45). The float type can be installed in the sampling port in one corner of the cell cover. The syringe type has a rubble nozzle, weighted float, glass tube, and a rubber bulb at the top. Both hydrometers have a weighted float with divisions marked off on the upper portion. The float sinks into the electrolyte far enough to displace a volume of electrolyte equal in weight to the weight of the float itself. The higher the specific gravity, the heavier the electrolyte and the less the float sinks. The marks on the float are graduated in increments of 1 point, or 0.001, over a specific gravity range of 1.100 to 1.300.

At sites with a large number of cells, it is desirable to have two high-accuracy hydrometers and to frequently check them against each other; however, most sites have only one hydrometer. Bulb-type hydrometers should be replaced every 2 or 3 years.

Specific gravity in a cell can vary with depth and is known as *stratification.* Stratification occurs when the sulfuric acid that is formed by high initial charging currents settles to the bottom because it is heavier than water. Gassing upon full charge tends to mix the electrolyte and reduce stratification.

The electrolyte level in a cell is lowered by evaporation and water electrolysis. The sulfuric acid in the electrolyte does not evaporate, so the specific gravity increases as the level decreases. For small VLA cells, a small difference in level can make a several-point difference in specific gravity. To avoid dry-out, the electrolyte level should never be allowed to decrease below the low-level mark on the cell. Electrolyte should not be added to a cell unless directed to by the manufacturer.

The loss of water from the electrolyte due to evaporation and charging affects the specific gravity. In a fully charged cell, if the electrolyte level is $\frac{1}{4}$ in. (6 mm) below the high-level mark, the specific gravity will be approximately 6 points (0.006) higher than with the electrolyte at the high mark (the lower electrolyte level has a higher concentration of acid because it is less diluted with water). Therefore, when measuring specific gravity, the electrolyte level with respect to the high mark should be noted so that the specific gravity can be properly evaluated. Battery manufacturers can provide a more accurate correction for each battery type.

The electrolyte level is affected by the charging rate and amount of gassing. Gassing electrolyte has a slightly higher volume and will show a higher level. If the electrolyte

Fig. 6.45 Electronic display specific gravity measurement. (Photo courtesy of M.W. Migliaro.)

level is at the high-level mark during float, it will rise above that mark when the battery is being equalized. Such a rise is not a problem unless the level is so high that the electrolyte overflows.

When measuring VLA electrolyte specific gravity, the electrolyte level should be at the high-level mark on the cell. If water needs to be added, specific gravity measurements should not be made for at least 72 h to allow the water to mix with the electrolyte (some cell types require longer mixing times). Tap water should not be used to adjust electrolyte level as it contains impurities that could damage the plates.

Specific gravity measurements require very little practice to perform correctly. Cells used in telecommunications applications usually are marked with the rated specific gravity and temperature. The main problem will be accidentally spilling or dripping electrolyte from the hydrometer nozzle. Any spilled electrolyte must be neutralized and cleaned up.

The specific gravity changes 1 point inversely with each 1.67°C (3°F) change in temperature. The reference temperature for specific gravity measurements is 25°C (77°F), so all measurements must be corrected to this temperature. Every VLA battery room should be equipped with a thermometer for measuring room ambient temperature and another for measuring cell electrolyte temperature. Two types of cell thermometers are available for measuring electrolyte temperature—floating and nonfloating. The floating type can be installed in the sampling port in one corner of the cell cover. The nonfloating type is installed in the cell vent. The temperature of a cell rises very little during discharge but rises rapidly during recharge.

The battery room ambient temperature ideally is 25°C (77°F) but a range of 16 to 27°C (60 to 80°F) is acceptable. When the ambient temperature is consistently above 32°C (90°F), due to inadequate air conditioning and it is not possible to install better air conditioning equipment, the battery manufacturer may recommend the specific gravity be reduced.

To minimize measurement errors, use a long nozzle syringe and take samples about one-third down from the top of the plates if possible. Some cells have an electrolyte withdrawal tube for this purpose. Bubbles in the hydrometer electrolyte cause errors, and readings should not be taken sooner than 15 min after gassing has stopped.

6.18.2.2 Specific Gravity Measurement Procedures

1. Clean the hydrometer glass barrel and float with soap and water if necessary. Rinse thoroughly with clean distilled or demineralized water and dry so the hydrometer components do not contaminate the electrolyte. Because of possible contamination, never use a hydrometer on lead–acid cells that has been used on nickel–cadmium (NiCd) cells.
2. Hold the hydrometer vertically and squeeze the rubber bulb before immersing it in the electrolyte. Insert the nozzle into the electrolyte withdrawal tube or opening and release the bulb. Draw enough electrolyte into the hydrometer barrel so the float freely floats without touching the sides or top of the syringe. To avoid spilling the electrolyte, do not remove the nozzle from the electrolyte withdrawal tube while reading it.
3. Read the specific gravity on the hydrometer scale at the flat surface of the electrolyte (Fig. 6.46).
4. Slowly squeeze the rubber bulb to release the electrolyte back into the cell. Be sure to completely empty the barrel; otherwise, the electrolyte from one cell may affect the measurement of the electrolyte from another cell.

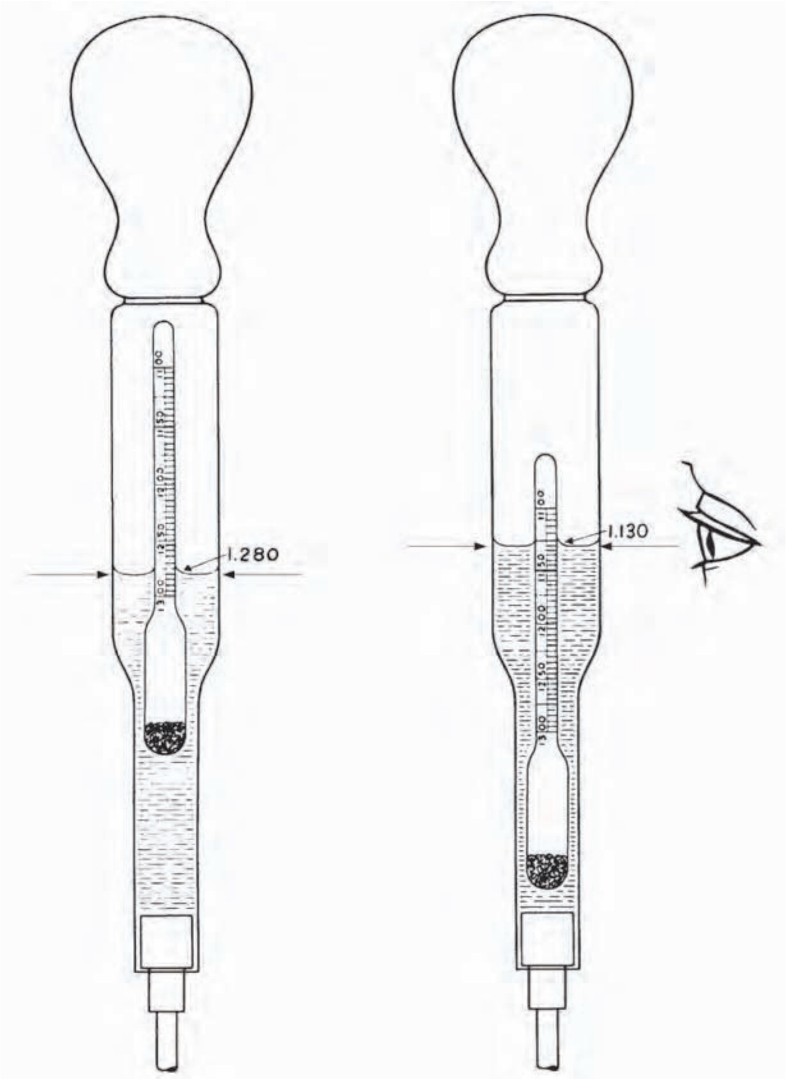

Fig. 6.46 Hydrometer: Read the specific gravity at the flat surface of the electrolyte, not on the raised edges at the float or inside of tube.

5. If the hydrometer is a different temperature than the cell electrolyte, repeat steps 2 to 4 several times until the float reaches the same temperature as the electrolyte.
6. Correct the specific gravity measurements to 25°C (77°F) before recording (Table 6.17). When temperature readings are in Celsius, add 0.6 points (0.0006) to the reading for every 1°C the pilot cell temperature is above 25°C, and subtract 0.6 points from the reading for every 1°C the pilot cell temperature is below 25°C. When temperature readings are in Fahrenheit, add one point (0.001) to the reading for every 3°F the pilot cell temperature is above 77°F, and subtract one point from the reading for every 3°F below 77°F. If an electronic hydrometer is used, the instrument may automatically correct the specific gravity measurement for temperature, but this must be confirmed before recording the measurement.

Table 6.17 Specific Gravity Temperature Correction Factors

Electrolyte Temperature	Correction	Electrolyte Temperature	Correction
32.2°C (90°F)	+0.004	23.3°C (74°F)	–0.001
31.7°C (89°F)	+0.004	22.8°C (73°F)	–0.001
31.1°C (88°F)	+0.003	22.2°C (72°F)	–0.001
30.6°C (87°F)	+0.003	21.7°C (71°F)	–0.002
30.0°C (86°F)	+0.003	21.1°C (70°F)	–0.002
29.4°C (85°F)	+0.002	20.6°C (69°F)	–0.002
28.9°C (84°F)	+0.002	20.0°C (68°F)	–0.003
28.3°C (83°F)	+0.002	19.4°C (67°F)	–0.003
27.8°C (82°F)	+0.001	18.9°C (66°F)	–0.003
27.2°C (81°F)	+0.001	18.3°C (65°F)	–0.004
26.7°C (80°F)	+0.001	17.8°C (64°F)	–0.004
26.1°C (79°F)	0.000	17.2°C (63°F)	–0.004
25.6°C (78°F)	0.000	16.7°C (62°F)	–0.005
25.0°C (77°F)	0.000	16.1°C (61°F)	–0.005
24.4°C (76°F)	0.000	15.6°C (60°F)	–0.005
23.9°C (75°F)	0.000	23.3°C (74°F)	–0.006

7. Record all readings (Form 1 at the end of this chapter) and keep them for the life of the battery. The spread in specific gravity across all cells in a battery string (the difference between the highest and the lowest) normally should not exceed 0.020 (the tolerance on nominal specific gravity is ±0.010) with the electrolyte level at the high mark.
8. Rinse the hydrometer with clean distilled or demineralized water and return it to its holder.

Example 6.2 Determine the temperature-corrected specific gravity if the measured specific gravity is 1.207 at 21°C (70°F).

Solution From Table 6.17, the correction factor is –0.002 so the corrected specific gravity is 1.207 – 0.002 = 1.205.

Example 6.3 Determine the temperature-corrected specific gravity if the measured specific gravity is 1.212 at 31°C (87°F).

Solution From Table 6.17, the correction factor is +0.003 so the corrected specific gravity is 1.212 + 0.003 = 1.215.

6.18.3 Periodic Measurements and Inspections

Some measurements, such as cell temperature, are based on a pilot cell. The pilot cell serves as a proxy or representative for the other cells in the battery and its use saves time measuring battery systems with large number of cells; each battery string will have its own pilot cell (Fig. 6.47). The pilot cell is chosen from one of the cells with the lowest specific gravity and lowest voltage, a new pilot cell is chosen at least once a year.

6.18.3.1 Initial Installation Initial installation measurements can be made coinci-

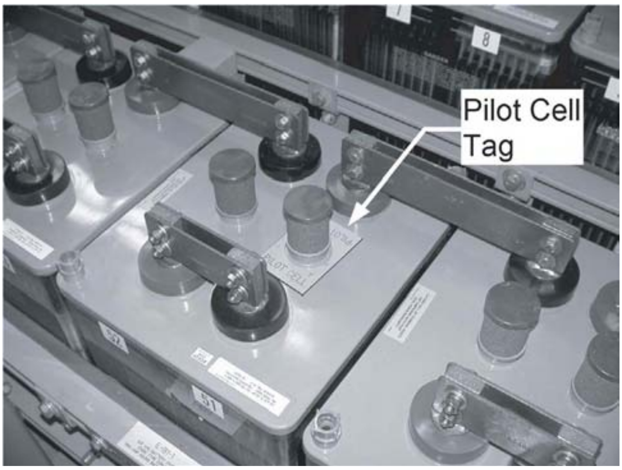

Fig. 6.47 Battery string pilot cell. Note the engraved plastic tag slipped over the vent in the middle of the picture. When a new pilot cell is chosen, the tag is moved to the new cell. (Photo courtesy of M.W. Migliaro.)

dentally with the acceptance tests (Section 6.18.6) and should be performed no sooner than one week after the battery has had its initial freshening charge. A complete set of measurements should be taken to establish a baseline for a new installation including:

- Ambient temperature.
- Internal impedance, resistance, or conductance of each cell. Note: Some users consider this an optional test unless the cells have factory-made connections that are inaccessible for maintenance, such as a three-cell monobloc with internal lead-burned connections between the cells.
- Specific gravity and temperature of each cell.
- Voltage of each cell and voltage across the battery terminals.
- Cell interconnecting strap resistances and battery terminal resistances.
- Battery float current.

6.18.3.2 Monthly Measurements

- Check the ambient temperature and ensure ventilation devices (fans and vents) are operable.
- Measure and record pilot cell specific gravity, voltage, and temperature.
- Examine electrolyte level in all cells and add water if necessary.
- Measure and record float voltage at battery terminals.
- Examine the overall battery, battery rack, and battery room or area for appearance and cleanliness. Remove combustible materials such as empty boxes from the room.
- Measure and record rectifier output voltage and current.
- Examine cell containers and covers for cracks, distortion, and electrolyte leaks.
- Examine cell and battery terminals and connections for corrosion.
- Examine racks and fasteners for corrosion and overall structural integrity (shake test).

- Measure and record float charging current.
- Check battery monitoring system operation, if equipped.

6.18.3.3 Quarterly Measurements

- All monthly work items.
- Measure and record the specific gravity and temperature of 10% of the total number of cells; rotate these cells so that readings are taken on different cells each quarter.
- Measure and record voltage of each cell.

6.18.3.4 Yearly Measurements

- All quarterly work items.
- Measure and record the voltage, specific gravity, and temperature of every cell.
- If equipped with clear containers, examine every cell for internal condition, plate and separator deterioration and distortion, excessive sediment at the bottom of cells, proper plate color (positive plates normally are a deep chocolate brown to black color and negative plates are a medium gray color), post distortion or lifting, and any other visual attributes considered out of the ordinary. Note: Some plate growth is normal over time but it normally should not exceed 5%.
- Examine cell interconnections and terminal connections to ensure they are clean and are coated with a thin layer of corrosion inhibiter.
- Verify that all cells are properly numbered (in telecommunications applications, the cell closest to the positive end of the battery normally is No. 1).
- Verify that all cells are equipped with flame arrester vents and plastic dust caps. Examine vents and clean or replace if clogged (see Section 6.18.7).
- For seismic installations, examine the battery to ensure a spacer is present between each cell and that the spacer is in good condition and not broken, distorted, or cracked.
- Measure and record cell interconnection and terminal resistances and compare values to those obtained on initial installation. If any connection resistance has increased more than 20%, disassemble, clean, apply corrosion inhibiter, reassemble, retorque, and remeasure.
- Measure and record the internal impedance, resistance, or conductance of each cell and compare to initial and previous measurements (some users consider this optional).

Table 6.18 Typical Float and Equalize Voltages at 25°C (77°F)—Vented Lead–Acid Batteries

Type	Cell Voltage (V/cell)	24-V, 12-Cell System (V)	48-V, 24-Cell System (V)
Float			
VLA (lead–antimony)—1.215 SG	2.15–2.17	25.80–26.04	51.60–52.08
VLA (lead–calcium)—1.215 SG	2.17–2.25	26.04–27.00	52.08–54.00
Equalize			
VLA (lead–antimony)—1.215 SG	2.24–2.39	26.88–28.68	53.76–57.36
VLA (lead–calcium)—1.215 SG	2.24–2.39	26.88–28.68	53.76–57.36

6.18.4 Battery Charging and Measurement Procedures

6.18.4.1 Initial Freshening Charge New batteries and batteries that have been stored for 3 months or more should be given an initial freshening charge. Unless the manufacturer specifies a different voltage, normal equalizing voltage should be used (Table 6.18). If the battery is connected to a power system, care must be taken to ensure the charge voltage used does not exceed the maximum rated voltage of the load equipment.

The initial charge voltage should be applied until each cell gasses freely and equally and the specific gravity and cell voltage stops rising. Gassing can be determined easily by examining cells that have transparent or clear translucent containers but is not possible with opaque cell containers (such as hard rubber). In the latter case, specific gravity, cell voltage, or charge current measurements are used to determine the end of charge condition.

Just before the end of the initial charge, record the cell voltages and then change to the normal float voltage. Allow the cells to stabilize for 72 h, measure the cell specific gravities, correct them to 25°C (77°F), and record the corrected value.

6.18.4.2 Float Charge Batteries are continuously float charged at a constant voltage during normal operation. Use Table 6.18 to determine the appropriate float voltage unless the manufacturer specifies a different value. Measure the voltage across the battery terminals with an accurate digital voltmeter or multimeter and compare the reading with the rectifier and powerboard bus voltmeters. If necessary, adjust the rectifier output voltage to provide the required float voltage at the battery terminals, and adjust the rectifier and powerboard voltmeters (if adjustable) to agree with the digital voltmeter. Do not rely on the rectifier voltmeter to set the battery voltage because the voltmeters on rectifiers usually do not have the required accuracy and resolution; the voltage at the battery terminals is the important parameter and not the voltage at the rectifier.

6.18.4.3 Equalizing Charge Equalizing charges should not be performed on a routine basis; however, if one of the conditions below is met, apply an equalizing charge at the recommended voltage (Table 6.18 unless recommended otherwise by the manufacturer). Failure to equalize cells when needed can lead to problems such as overdischarge and internal physical damage or cell polarity reversal when the battery is discharged. Ensure that the electrolyte level in all cells is near the high-level mark before beginning the equalizing charge. Lead–calcium batteries normally do not require periodic equalizing if floated between 2.20 and 2.25 V per cell.

Conditions for equalizing charge:

- Following a discharge that reduces the battery capacity by 10% or more.
- If the temperature-corrected specific gravity of any cell is more than 10 points (0.010) below the nominal full charge value when the battery is on float.
- If the voltage of any cell is more than 0.05 V (lead–calcium) or 0.03 V (lead–antimony) below the average cell voltage when the battery is on float. The average cell voltage is found by dividing the float voltage measured at the battery terminals by the number of cells in the battery string.
- If the electrolyte level in any cell falls to or below the minimum fill line, distilled or demineralized water must be added to restore the level to the maximum fill line, and an equalizing (mixing) charge can be performed to restore specific gravity. A mixing charge is important where low temperatures may cause the water in the cells to freeze.

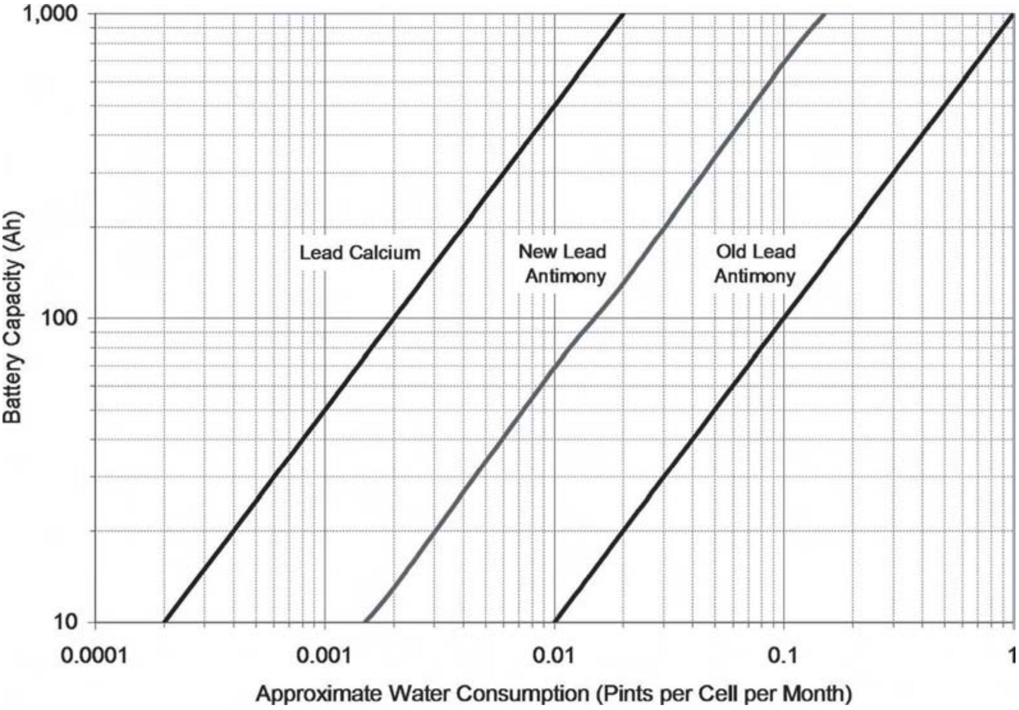

Fig. 6.48 Typical water consumption at 25°C (77°F). To convert from pints per cell per month to liters per cell per month, multiply by 0.473.

- If a cell is undercharging, it will not consume water at the same rate as normal cells. In this case, an equalize charge should restore it to normal. Figure 6.48 shows typical water consumption.

Terminate the equalize charge when all conditions below are met.

- Every cell gasses freely and equally.
- The specific gravity of all low cells has stopped rising as determined by two consecutive specific gravity measurements over the last one-eighth of the charging period.
- The voltage difference between the highest and lowest cells is no greater than recorded for the initial charge.

The equalizing charge may be started and stopped by an automatic equalize timer if the powerboard is so equipped. Use the battery manufacturer's recommended charge time for the cell type or, if that information is not available, use Table 6.19. Take care to ensure the equalizing voltage does not exceed the maximum equipment voltage.

When an equalizing charge is stopped and float voltage is reapplied to a battery, heavy gassing will end shortly thereafter. About 15 or 20 min afterwards measure and record the specific gravity of every cell. If two cells with the lowest specific gravity (checked over the last one-eighth of the charging period) have not stopped rising, continue the equalizing charge.

Table 6.19 Typical Equalize Charge Duration for Various Charge Voltages

Type	Cell Voltage (V/cell)	24-V, 12-Cell System (V)	48-V, 24-Cell System (V)	Time (h)[a]
VLA (lead–antimony)—1.215 SG	2.24	26.88	53.76	80
	2.27	27.24	54.48	60
	2.30	27.60	55.20	48
	2.33	27.96	55.92	36
	2.36	28.32	56.64	30
	2.39	28.68	57.36	24
VLA (lead–calcium)—1.215 SG	2.24	26.88	53.76	222
	2.27	27.24	54.48	166
	2.30	27.60	55.20	105
	2.33	27.96	55.92	74
	2.36	28.32	56.64	50
	2.39	28.68	57.36	34

[a] If the battery temperature is in the range 4–16°C (40–60°F), the duration should be doubled and if below 4°C (40°F), the duration should be quadrupled.

If some cells are worn out or otherwise faulty, an equalize charge may not bring them to the rated specific gravity, and it may be incorrectly assumed that additional electrolyte is needed to raise the specific gravity in that cell. However, battery manufacturers generally do not recommend that electrolyte be added to in-service cells. If in doubt about the cell's condition, contact the manufacturer for guidance.

6.18.4.4 Check Charge A check charge may be used at unattended sites to determine if a full equalizing charge is necessary. With a check charge, the battery is manually placed on equalize charge. After 15 or 20 min, the battery voltage should be stable at which point the individual cell voltages are measured. If the highest and lowest cell voltages (while on equalize) differ by no more than 0.04 V, the battery does not require equalizing. The battery should be equalized if the voltage differences exceed 0.04 V. Measurements should be made with a digital voltmeter accurate to at least 0.01 V. Alternately, the charge current can be measured at 2-h intervals to see if it has stabilized.

The check charge is effective in determining the *equality* of cell charge. However, the test should not be substituted for specific gravity or float current measurements that determine the *state* of cell charge. All cells must be within 3°C (5°F) and the ambient temperature must be above 13°C (55°F).

6.18.5 Troubleshooting Battery Problems

6.18.5.1 General This section describes VLA troubleshooting principles and how to determine if the care is adequate and correct. Correct charging is critical for long battery life and reliable service, and the most important part of battery care is a proper charging program. Accurate records of physical condition and electrical measurements are required to determine if the charging program is correct.

The following discussion describes cell conditions with both proper and improper operation and maintenance. Manufacturers should be consulted to confirm diagnoses before action is taken to replace a battery or cell. Table 6.20 summarizes various problems that

Table 6.20 Battery Problems and Possible Causes

Problem	Possible Cause
Gassing	
• Lack of gassing while on charge	• Internal short between plates causing the cell to discharge internally as fast as it is being charged
Specific Gravity or Voltage	
• Lower specific gravity or voltage than other cells	• Excessive internal losses resulting from consistent undercharging
• Loss of capacity over time is shown by a gradual decrease in specific gravity of the cells	
Color	
• Patches of white lead-sulfate either on the positive or negative plates	• Cells standing idle or undercharging for extended periods
• Antimony deposits (dark-slate patches on the negative plates, usually near the terminal)	• Charging at too high a rate or an aged cell nearing the end of its service life
• White top layer of sediment	• Undercharging
• Lumpy brown sediment	• Overcharging, cycling, or high temperature
• All white sediment with no visible layers	• Overcharging after prolonged low float voltage
• Large flaking on the interplate collector bar	• Battery on float charge for extended periods at insufficient float voltage and without equalizing charge
Plate Problems	
• Cracks on the edges of the positive plate grids	• Cell at end of life
• Light-colored sulfating spots on edges of plates below the cracks mentioned above	• Cell at end of life
• Excessive sediment in the bottom of the case	• Cell at end of life
• "Mossing" on the tops of negative plates	• Cell at end of life
• Buckling of positive plates	• Excessive sulfating caused by undercharging or excessive temperature
Water Problems	
• Excessive water consumption	• Excessive charging rates, high operating temperatures, or a leaking cell
• Unusually low water consumption	• Insufficient charging
Capacity Problems	
• Failure to supply rated ampere-hours	• Discharged condition, excessive sulfating, or loss of active material from positive plates • Cells may be worn out or active material may be gone from positive plates

may be encountered in the field. Additional detailed descriptions are provided in the following sections.

6.18.5.2 Surface Charge Phenomenon When a battery has been on float charge for a long time and then is discharged under load, the voltage initially drops rapidly (so-called *coupe de fouet*) because plugged pores on the surface of the plates partially block ion transfer. The voltage may drop below the low-voltage alarm threshold and in severe cases may drop below the low-voltage disconnect (LVD) setting, if equipped. If the LVD does not trip, the battery voltage usually will increase to above the low-voltage alarm threshold. The battery will then operate normally until its capacity is exhausted.

If the battery is exercised (partially discharged) on a routine basis, the voltage dip can be reduced or eliminated. Turning off the rectifiers for at least 15 min and allowing the battery to discharge into the load exercises the battery. The first few times this procedure is performed, disable the LVD to prevent an inadvertent trip and be sure to reenable the LVD after the test. The first time the battery is exercised, the procedure should be performed several times in succession until the voltage stays above the alarm setting. Always allow the battery to fully recharge (the charging current reduces to the normal float value) before turning off the rectifiers again for the next cycle. A battery should not be exercised too often because even 15-min discharge will affect its life.

Each battery has its own characteristics, and the exercise frequency should be adjusted so the voltage drop does not cause the low-voltage alarm. Start at a monthly cycle and experiment with increasing the time between exercises. The proper time between exercises exists when the voltage drop is just above the alarm threshold. Some alarm systems may be equipped with a time delay and may be set to ignore a low-voltage alarm for a preset time period giving the battery time to recover. The time delay will have to be determined experimentally for each installation.

6.18.5.3 Initial Troubleshooting If any cells seem to be in trouble, give the whole battery an equalizing charge, and then measure the specific gravity of all cells. If all cells gas evenly and the specific gravity of every cell is normal, all the battery needed was the equalizing charge. Otherwise, record all low specific gravities and give an extra thorough equalizing charge.

Measure and compare the temperature of all cells. Excessively sulfated cells can run hot enough to cause damage if not corrected. Investigate for impurities and measure for internal short circuits any cells that still do not gas with the extra equalize charging.

6.18.5.4 Cell Replacement If a faulty cell is to be replaced, replace it with one in good condition and of the same make, type, rating, and approximate age (the latter is difficult with an older battery because spare cells of the same age seldom, if ever, are available). Avoid installing a new cell in series with older cells unless no other alternative is available. A 12- or 24-cell battery may be operated temporarily without one cell by removing the cell and installing temporary jumpers between the adjacent cells. The float and equalizing voltages must be reduced to that required by an 11- or 23-cell battery. If the installation uses parallel battery strings, operating with one cell removed from only one string cannot be done; instead, a cell must be removed from all battery strings.

The capacity of the battery with one cell removed will be reduced due to the lower discharge voltage range. For example, say load equipment stops operating when the battery terminal voltage reaches 42.0 V (the voltage at the load equipment will be somewhat lower due to voltage drop from the battery to the load). For a 24-cell battery, this corresponds to a final cell voltage of 1.75 V/cell, or the voltage at which a telecommunications battery is considered fully discharged. If one cell is temporarily removed, the 23-cell battery will be fully discharged when its voltage reaches 40.25 V (23 cells × 1.75 V/cell). However, the equipment will have stopped operating at 42.0 V (1.83 V/cell) so the 23-cell battery never fully discharges to 1.75 V/cell. In this case, increasing the end-of-discharge (final) cell voltage from 1.75 to 1.83 V/cell decreases the overall capacity by approximately 10 to 15% (this reduction corresponds to the recommended design margin used to size the battery; see Chapter 5, System Design).

6.18.5.5 Charging It is important to know when a cell is fully charged. A cell is fully charged when, during equalize, the cell is gassing, specific gravity has stopped rising, and specific gravity, corrected for temperature, remains constant for two successive readings. Hydrometer readings must be corrected for any changes in cell temperature that have occurred between readings. The two successive readings should be taken during the last one-eighth of the charging period (usually 1, 2, or 3 h apart).

Proper Charging If cells are *undercharged,* service will be poor and battery life short. If *overcharged,* service with will be good initially but battery life short. Proper charging means *slight overcharging* just enough to cause the *least possible sedimentation and a minimum of heavy gassing*. This condition requires very little makeup water in lead–calcium VLA cells. No perceptible sedimentation or plate buckling occurs if the charging rate is such that cells are not allowed to gas vigorously. Sedimentation starts with gassing and is proportional to the total amount of gas liberated.

Appearance of Normal Cells The edges of normal positive plates will not show any sulfation, cracks, or plate growth. The edges of negative plates should be uniformly gray. When a normal cell with correct float charging is examined with a flashlight, there should be no sparkling from lead sulfate crystals.

No visible change occurs when the cell is discharged a normal amount (i.e., not overdischarged). If the charging program is correct, sediment accumulates very slowly. It should never be white or lumpy as shown in Figure 6.49. The charging program may produce a very small amount of fine, dark-brown sediment.

Chemical Changes A fully charged cell has brown lead dioxide on the positive plates and gray sponge lead on the negative plates. On discharge, electric current converts active

Fig. 6.49 Sediment at the bottom of the cell due to improper charging. (Photo courtesy of M.W. Migliaro.)

materials in the positive and negative plates to normal lead sulfate. This process leaves the electrolyte weak at the end of the discharge. Lead sulfate is white in color but cannot be seen on plates unless the cell is overdischarged, which produces oversulfating. This condition first makes the plate color lighter and finally mottled white in patches or white all over.

Charging the cell reverses this process, converting lead sulfate in the plates to lead dioxide and sponge lead and producing sulfuric acid, which restores the specific gravity to normal. As the charge nears completion, only a little lead sulfate remains to be converted to lead. The charging current begins to separate water into oxygen and hydrogen (electrolysis), which bubbles to the top of the electrolyte and forms a mixture of very explosive gases.

A detailed description of the chemical reactions is given in Chapter 4 (Telecommunications Batteries).

Effect of Impurities on Float Voltage Compared to lead–antimony, lead–calcium cells have the advantage of low internal losses, which remain constant for the life of the cell. Fully charged lead–antimony cells discharge internally by an action between the active material and the grid. Impurities may hasten this action and may result in visible or invisible changes on the plates, depending on the types of impurities present.

No metal objects should be put into the cell electrolyte at any time, except a cadmium or other compatible reference electrode. Impurities may prevent a proper float voltage from maintaining float charge and may prevent an equalizing charge from equalizing the cell.

High-Rate Overcharging After a battery is fully charged, continuation of charging current at a high rate damages the positive plates. Violent gassing forms bubbles in the interior of the active material. The resulting pressure forces gasses through the porous active material breaking off particles. These particles rise with the bubbles and may result in a muddy red or brown electrolyte color (although it is rare to see this). Some of this fine sediment settles on and, if allowed to accumulate, short circuits the negative plates. The sediment is converted to gray sponge lead and results in a growth of mosslike sediment on the top edges of the negative plates. The “mossing” indicates that a high-rate overcharging previously occurred and can cause the cell to overheat during charging.

Low-Rate Overcharging At lower overcharge rates, bubbling is reduced and sediment falls to the bottom of the cell. Overcharging at a very slow rate disturbs electrolyte so little that fine brown sediment falls in a vertical line, forming tiny ridges on top of the sediment. Ridged sediment is a good indication that the recent overcharging was not at high rates. Overcharging should be kept at a minimum, and ridges should be small.

Undercharging If the battery is undercharged, unconverted sulfate remains on the plates too long and hardens. The longer the plates stay in the undercharged condition, the harder the sulfate becomes and the more difficult it is to reconvert. When new, the sulfate is easily converted back to soft active materials by a normal charge, but a long overcharge is required to remove it after becoming hard. Sulfate accumulates unnoticed, a little on each charge, if charging is not enough to eliminate all sulfate. This residue buildup continues until a substantial portion of the cell capacity is lost. The remedy is to slightly increase float voltage to give a *slight overcharge.* This procedure must be put into practice while the battery is new and followed for the life of the battery. Prolonged undercharging also leads to large flaking on the internal interplate connection strap.

The pressure of expanding active material due to sulfate buildup can break plate separators and cause shorts inside the cell. If charged at too low a rate, the hardened sulfate is thrown out of plates and settles in white ridges on the cell bottom. At higher rates, the gassing distributes the sediment evenly without ridges. An oversulfated cell has high internal resistance and requires extra voltage across the cell, which also causes it to develop higher temperatures on charge. Buckled or cracked plates cannot be repaired by sulfate removal, but the cell may be used as long as it has satisfactory capacity.

6.18.5.6 Overdischarge The plates suffer greatly when overdischarged. The cell voltage should not be allowed to drop below 1.75 V. Specific gravity should not be allowed to decrease below the limit given by the manufacturer, which is different for various types and sizes of cells. Normal discharge converts active materials to *normal* lead sulfate, which requires only slightly more space than active materials. Overdischarge forms *more* lead sulfate in the pores of the active material than they are able to hold. This process may expand and bend or buckle the plates or crack the grids. In some instances, sufficient pressure is created to crack or puncture separators. Overdischarge may lead to cell polarity reversal, which permanently damages the cell.

6.18.5.7 Sediment The history of each cell is shown by the sedimentation because successive layers are laid down in colored strata at the bottom of the cell. These layers can be seen edgewise against the inside of the cell container. Fine, dark brown or black layers indicate periods of excessive charging (current too high or charge too long). Lumpy gray layers indicate times the battery was overdischarged. A layer of white sulfate from subsequent charges generally covers these layers. A considerable amount of sediment and slivers will be found initially in some batteries. This condition is a normal result of the forming process. Some additional sediment and slivers will be dislodged in shipment and will accumulate at the bottom of the case of these batteries during the first few equalizing charges. With this exception, a perfectly charged battery should have little fine brown or gray-white sediment and no lumps. If some experimenting is done with the charging program, slight undercharging may result in a white sulfate layer. This layer indicates that the float voltage should be slightly increased.

6.18.5.8 Battery Watering

Water Requirements As cells are charged, a small quantity of water in the electrolyte is broken down into hydrogen and oxygen by the charging current. The gases are dissipated through the vents. As this process takes place, the electrolyte level gradually falls until water must be added. Commercially available "demineralized" water is equal to commercial or locally distilled water and may be substituted for it. Do not add water above the maximum level mark. Specific gravity readings will be inaccurate until the water has had time to mix with the rest of the electrolyte, which can take weeks in some cells. Generally, at least 72 h should elapse from the time water is added to a cell to the time specific gravity measurements are made on that cell.

Always use glass, plastic, or rubber containers to store battery water; never store it in any kind of metallic container. Keep records of water consumption and compare the long-term average with Figure 6.48.

Water Replacement Rate for Lead–Antimony Cells Lead–antimony cells begin their lives with low water consumption, but water consumption increases as much as five times toward the end of their lives. Very little water evaporates from capped cells; loss is caused by gassing and is proportional to the amount of charge the battery receives. Heavy gassing requires frequent water additions. When equalizing a battery, the water should be added just before or at the beginning so that gassing will ensure thorough mixing before specific gravity readings are taken. Proper charging minimizes excess gassing and the need for adding distilled water.

Water Replacement Rate for Lead–Calcium Cells Water additions two or three times a year should be sufficient if the lead–calcium cells are properly charged. Frequent water additions to lead–calcium cells indicate improper charging. The electrolyte in all cells should be maintained within $\frac{1}{4}$ in. (6 mm) below the high-level mark. Because of greater purity of their components, lead–calcium cells require only about one-tenth the water needed by equivalent size lead–antimony cells. This low requirement remains constant during the entire battery life.

6.18.5.9 Specific Gravity Adjustments Specific gravity should not be adjusted until it is definitely established to be wrong and, even then, only upon recommendation by the battery manufacturer. Before adjusting for low specific gravity, make sure that it cannot be raised by equalize charging. Continue the charge until the specific gravity shows no rise and then charge for 3 more hours. Do not adjust specific gravity on a cell that does not gas on charge—the cell probably has failed.

To *increase* specific gravity, remove some electrolyte from the cell and replace it with pure, 1.300 specific gravity sulfuric acid (30% concentrated acid and 70% water by volume, or 39% concentrated acid and 61% water by weight). Recharge until all cells gas for an hour. Repeat the procedure if the gravity is still not normal. To *lower* the gravity, remove some of the electrolyte and replace it with distilled or demineralized water. Specific gravity measurements should be made after waiting at least 72 h for the acid or water to mix in the cell.

6.18.5.10 Internal Short Circuits A short circuit through a separator may be caused by:

- Sulfated plates—Insufficient charging causes material in the plates to become mostly lead sulfate. The lead sulfate expands and, if the grid does not crack to relieve the strain, the plate will distort or buckle. The buckling is most pronounced, and shorts are most likely to occur, at the four corners of the positive plates.
- Impurities in the electrolyte caused by using contaminated water or dirty utensils.
- Plate contact—Excessive overcharging causes the grid to be partially converted to lead dioxide, which reduces its mechanical strength and allows positive and negative plate contact.

A short in a cell can be detected by falling specific gravity and falling cell voltage over time. In some cases, a gray discoloration occurs at the point of the short. If a short is longstanding, disintegration of the positive plate will occur at the point of contact with the negative plate because of the conversion of positive plate material to negative.

6.18.5.11 Sulfation

Normal and Oversulfation During cell discharge, “normal” sulfate is formed, which is required to produce current. If recharging is not performed in a reasonable time, the sulfate fills the pores of the plates and makes the active material dense and hard. This condition is referred to as "oversulfated."

Normal lead sulfate formed on discharge is in a form that a charge will easily reconvert. When a battery is oversulfated, plates are less porous than normal and absorb a charge with difficulty. With this condition, an ordinary charge will not reconvert the entire sulfate and specific gravity remains below normal. The active material of oversulfated negative plates is light in color and either hard and dense or granular and gritty and easily disintegrated. Oversulfated negative plates require a prolonged charge to restore. The plates in an individual cell may become oversulfated by external grounding, by an internal short, or by exposure to air because electrolyte level was neglected and water was not added. Prolonged low float charging may also cause oversulfation.

Treating Oversulfation A battery or cell that is oversulfated should be fully equalize charged in the regular way until specific gravity stops rising. Then, one of the weakest cells should be discharged through a load bank at the normal 8-h discharge rate to a final voltage of 1.75 V. The battery is not oversulfated if the representative cell gives normal capacity—that is, about 100% rated capacity for a fairly new battery or down to 80% for a battery nearing the end of its expected life.

If the required capacity is not obtained, possible oversulfation should be treated as follows:

1. In cases where one or more individual cells have become oversulfated and the rest of the battery is in good condition, these cells should be treated separately after removing them from the circuit.
2. Recharge the removed cells at half the 8-h discharge rate. Record specific gravity readings and temperature at regular intervals (3 to 5 h) during the charge to determine if the specific gravity has peaked. Maintain constant electrolyte level by adding water after each reading. Do not add water before taking readings.
3. Continue the charge and record the specific gravity readings until no further rise occurs in any cell for 10 h. If the temperature reaches 38°C (100°F), reduce the current or temporarily interrupt the charge so as not to exceed this temperature. When the specific gravity has peaked, terminate the charge and record the specific gravity reading of each cell.
4. Replace the cells if they again fail the capacity check.

6.18.6 Vented Lead–Acid Battery Testing

The following information does not replace specific instructions by the battery manufacturer. Follow the manufacturer's information in case of a conflict between these guidelines and the manufacturer's information.

6.18.6.1 Acceptance Testing Acceptance tests should be performed at least one week after the battery has been operating at the proper float voltage or given an initial charge according to the manufacturer's instructions. Factory tests do not replace on-site acceptance tests because there may be shipping and handling damage to the battery prior to installation. The acceptance test should be at least a 3-h and preferably an 8-h discharge test and should discharge at least 90% of rated capacity.

Maintain accurate records of the acceptance test, including make, model, and serial number of all equipment used and the test results. These initial records will be used as a baseline for later comparisons.

1. Conduct the test only after all terminal and cell interconnection resistances have been measured and any discrepancies corrected.
2. Install an accurate ammeter, voltmeter, and thermometer, and use an accurate stopwatch to record elapsed time.
3. Record the following parameters just prior to the test.
    - Specific gravity and voltage of each cell
    - Temperature of the electrolyte of 10% or more of the cells to establish an average temperature (an IR thermometer may be used)
    - Battery terminal voltage
4. Disconnect the battery from the rest of the dc power system and connect it to a load bank (Fig. 6.50) so that constant current can be maintained equal to the 3- or 8-h rating of the battery at the initial battery temperature.
5. Using the average temperature from step 3, calculate the end-of-discharge voltage. An end-of-discharge voltage of 1.75 V/cell applies to an average cell temperature of 25°C (77°F). If the average cell temperature is not 25°C (77°F), determine the new end-of-discharge voltage as follows: For each 10°C above 25°C, add 0.006 V to 1.75 V, and for each 10°C below 25°C, subtract 0.006 V from 1.75 V. Similarly, for each 10°F above 77°F, add 0.01 V to 1.75 V, and for each 10°F below 77°F, subtract 0.01 V from 1.75 V.
6. Measure and record individual cell voltages and the battery terminal voltage. The measurements should be taken after applying the load at the beginning of the test. Repeat the measurements at one-half hour intervals until the last hour of the test.

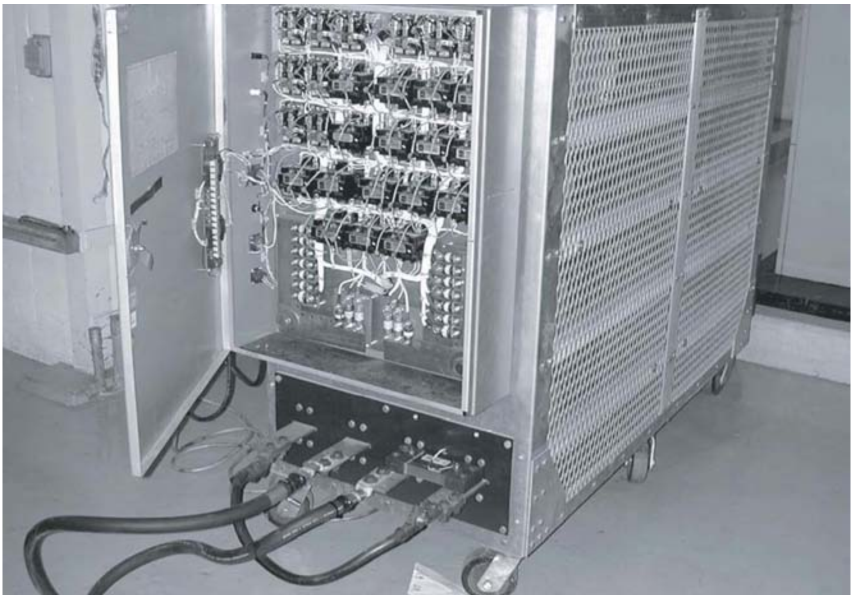

Fig. 6.50 Load bank for capacity testing a battery system. (Photo courtesy of M.W. Migliaro.)

During the last hour take measurements at shorter intervals such as 10 min. Measure individual cell voltage between respective terminals of like polarity (positive to positive) so the voltage drop of the cell interconnection straps are included in the measurement.

7. If an individual cell is approaching reversal of its polarity (voltage drops to 1.0 V/cell or less), terminate the test and consult the manufacturer.
8. Maintain the discharge rate until the battery terminal voltage decreases to 1.75 V/cell times the number of cells (21.00 V for a 12-cell and 42.00 V for a 24-cell battery).
9. Calculate the capacity from

$$\text{Capacity}_{25°\text{C}}(\%) = \frac{\text{Actual Time}}{\text{Rated Time} \times K_T} \times 100 \tag{6.7}$$

where K_T is the temperature correction factor (Table 6.21 or 6.22).

6.18.6.2 Capacity Testing Capacity tests are very similar to acceptance tests described above. Frequent VLA capacity tests are not recommended (each discharge/charge cycle wears out the battery). However, a capacity test on initial installation will establish a baseline for a new battery, and capacity tests at 5-year intervals will indicate if the battery is aging normally. Additional capacity tests may be needed to determine if a battery is nearing the end of its useful life or for warranty claim purposes. Absent specific procedures from the manufacturer, use the following test procedures. Perform yearly tests when the measured capacity drops below 90% of rated capacity, and replace the battery when it has reached 80% of rated capacity. Although capacity tests are very similar to acceptance tests previously described, capacity tests are separately described in this section because they could involve network equipment that is in operation and extra precautions are necessary to ensure that equipment operation is not jeopardized.

1. Equalize the battery and then return it to float service for between 3 and 30 days.
2. Take precautions to ensure that a battery failure will not jeopardize other equipment. Disconnect the battery to isolate it from the rest of the dc power system.
3. Install an accurate ammeter, voltmeter, and thermometer, and use an accurate stopwatch to record elapsed time.
4. Check all battery connections visually and with a microohmmeter to ensure connections are clean and low resistance. An IR thermometer may be used to check the connections just after the discharge test has begun. The temperature will be higher on poor connections. If poor connections are found, stop the test and repair them before continuing.
5. Record the following parameters just prior to the test:
   - Specific gravity and voltage of each cell
   - Temperature of the electrolyte of 10% or more of the cells to establish an average temperature (an IR thermometer may be used)
   - Battery terminal voltage
6. Use the average temperature measured in step 5 to calculate the end-of-discharge voltage. An end-of-discharge voltage of 1.75 V/cell applies to an average cell temperature of 25°C (77°F). If the average cell temperature is not 25°C (77°F), determine the new end-of-discharge voltage as follows: For each 10°C above 25°C, add

0.006 V to 1.75 V, and for each 10°C below 25°C, subtract 0.006 V from 1.75 V. Similarly, for each 10°F above 77°F, add 0.01 V to 1.75 V, and for each 10°F below 77°F, subtract 0.01 V from 1.75 V.

7. Connect the battery to a load bank. Discharge the battery through the load bank for 3 h at the rated 3-h discharge current (or for 8 h at the rated 8-h discharge current) until it reaches the end-of-discharge voltage determined in step 6. Record the voltage of each cell every half-hour during discharge. Watch closely during the last hour to determine the exact time when the end-of-discharge voltage is reached. If the end-of-discharge voltage is reached before 3 (or 8) h has elapsed, the test should be stopped and the capacity should be computed. If the measured capacity is between 80 and 90% of rated capacity, the battery should be tested again in one year. The entire battery should be replaced as soon as possible after capacity drops below 80%.
8. Calculate the capacity from

$$\text{Capacity}_{25^\circ\text{C}}(\%) = \frac{\text{Actual Time}}{\text{Rated Time} \times K_T} \times 100 \tag{6.8}$$

where K_T is the temperature correction factor (Table 6.21 or 6.22).

As with acceptance tests, maintain accurate records of all capacity tests, including make, model, and serial number of all test equipment used and the test results. These records should be compared to the baseline records and previous tests to determine the battery performance trend.

6.18.7 Flame Arrester Vents

Article 480.9 of the National Electrical Code [6] requires each vented cell to be equipped with a flame arrester designed to prevent destruction of the cell by ignition of gases inside the cell by an external spark or flame. The diffuser material in flame arresters can become

Table 6.21 Temperature Correction Factors for Battery Capacity Tests (Celsius)[a]

Initial Temperature (°C)	Temperature Correction Factor K_T	Initial Temperature (°C)	Temperature Correction Factor K_T	Initial Temperature (°C)	Temperature Correction Factor K_T
5	0.684	22	0.966	30	1.045
10	0.790	23	0.977	31	1.054
15	0.873	24	0.986	32	1.063
16	0.888	25	1.000	33	1.072
17	0.902	26	1.006	34	1.081
18	0.916	27	1.015	35	1.090
19	0.929	28	1.025	40	1.134
20	0.942	29	1.036	45	1.177
21	0.954				

[a] These factors apply to batteries with 1.215 specific gravity (consult the manufacturer for batteries with different specific gravities).

Source: IEEE Std 450-2002 [5].

Table 6.22 Temperature Correction Factor for Battery Capacity Tests (Fahrenheit)[a]

Initial Temperature (°F)	Temperature Correction Factor K_T	Initial Temperature (°F)	Temperature Correction Factor K_T	Initial Temperature (°F)	Temperature Correction Factor K_T
40	0.670	73	0.975	85	1.040
45	0.735	74	0.980	86	1.045
50	0.790	75	0.985	87	1.050
55	0.840	76	0.990	88	1.055
60	0.882	77	1.000	89	1.060
65	0.920	78	1.002	90	1.065
66	0.927	79	1.007	95	1.090
67	0.935	80	1.011	100	1.112
68	0.942	81	1.017	105	1.140
69	0.948	82	1.023	110	1.162
70	0.955	83	1.030	115	1.187
71	0.960	84	1.035	120	1.210
72	0.970				

[a] These factors apply to batteries with 1.215 specific gravity (consult the manufacturer for batteries with different specific gravities).

Source: IEEE Std 450-2002 [5].

partially clogged from electrolyte spray if cells are overfilled with water or have been excessively overcharged.

Flame arresters should have dust caps and be in good condition. Examine them annually and replace those having clogged pores or clean them as follows:

1. Immerse the flame arrester vent several times in a plastic bucket full of fresh clean water.
2. Remove the water from the vent after each immersion by vigorous shaking or using compressed air.
3. Refill the bucket with clean water for every 15 flame arresters that are cleaned.
4. Do not use any cleaning or neutralizing agents in the water because dry residue may clog the pores of the diffuser materials.
5. Thoroughly dry the flame arresters so that the plain water used to clean them cannot drip into the cells and contaminate them.

6.19. VALVE-REGULATED LEAD–ACID BATTERIES

6.19.1 General

This section outlines the requirements for operating and maintaining valve-regulated lead–acid (VRLA) batteries. As with VLA, the battery manufacturer and industry standards are the best place to get detailed operation and maintenance information; however, this section provides sufficiently detailed information for most VRLA batteries.[12]

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[12] See also IEEE Std 1188 [7].

6.19.2 Basic VRLA Characteristics

Valve-regulated lead–acid (VRLA) batteries are built in multicell assemblies (modules) or blocs (monoblocs). Because the cases are usually made of opaque plastic material, visual inspection of the internal components is impossible. The hydrogen and oxygen normally are not vented but are recombined, and the cells are sealed, making specific gravity readings and water addition impossible. These cells are typically lead–calcium pasted-plate-type cells with the electrolyte immobilized in gel form (gel-cells) or in fiberglass mats (absorbed glass matt, AGM, cells).

These cells are not flooded and do not dissipate heat as effectively as VLA cells. This characteristic can lead to thermal runaway if ambient and cell temperatures are not carefully controlled. Numerous cases have occurred in which a battery has burst into flame or cracked and spewed electrolyte throughout the room. Maintaining the cells as close as possible to 25°C (77°F) is imperative. Ambient temperature should be maintained so as to not exceed 22°C (72°F).

Air circulation must be sufficient to eliminate cell temperature differences. Do not allow sunlight or other heat sources to raise the temperature of individual cells. The maximum cell temperature spread (warmest to coldest cell) should not exceed 3°C (5°F), and the hottest cell should not be more than 3°C (5°F) above ambient. Lower temperatures reduce capacity, and higher temperatures reduce service life and increase the chances of thermal runaway. As a rule of thumb, battery capacity will be decreased by about 10% for every 10°C (18°F) below 25°C (77°F), and battery service life will be decreased by about 50% for every 8°C (15°F) a battery is continuously operated above 25°C (77°F).

6.19.3 Battery Charging and Measurement Procedures

6.19.3.1 Initial Freshening Charge

Valve-regulated lead–acid batteries and modules are typically shipped fully charged and do not require an initial charge unless recommended by the manufacturer. If VLRA batteries are stored for more than a couple months before installation, they should be given a “freshening” charge immediately after the installation is completed.

Unless the manufacturer specifies a different voltage, normal equalizing voltage should be used (Table 6.23). If the battery is connected to a power system, care must be taken to ensure the voltage used does not exceed the maximum rated voltage of the load equipment.

The initial charge voltage should be applied until the cell voltages stop rising. Just

Table 6.23 Typical Float and Equalize Voltages at 25°C (77°F)—Valve Regulated Lead–Acid Batteries

Type	Cell Voltage (V/cell)	12-Cell System (V)	24-Cell System (V)
Float			
VRLA—1.300 SG	2.25–2.27	27.00–27.24	54.00–54.48
Equalize[a]			
VRLA—1.300 SG	2.30–2.35	27.60–28.20	55.20–56.40

[a] VRLA batteries should not be equalized or operated at elevated voltages unless recommended by the manufacturer.

before the end of the initial charge, record the cell voltages and then change to the normal float voltage. After allowing the cells to stabilize for 72 h, measure the cell voltages.

6.19.3.2 Float Charge Valve-regulated lead–acid cells are typically floated at the voltages shown in Table 6.23; some variations exist, as indicated. Correct battery float voltage is critical for VRLA cells. To reduce the chance of thermal runaway, the float voltage must be temperature compensated such that the higher the temperature the lower the float voltage.

When VRLA cells are operated on float at normal full charge, no net chemical reaction occurs and almost all the overcharge energy results in heat generation. If the environment is such that the heat produced can be dissipated, no thermal runaway problems occur. If the heat generation rate exceeds the dissipation rate, the battery temperature rises, charge acceptance increases, and more current is required to maintain the float voltage. The higher current results in more heat generation, which raises the battery temperature further, and the cycle continues until the battery destroys itself. Elevated ambient temperature above 22°C (72°F) or cell or rectifier malfunction will aggravate this condition.

As cells approach full charge, charging current decreases. The battery is fully charged when the charging current has not changed more than 10% for more than 3 h. If the charging voltage has been set higher than the required float voltage to reduce the charging time, then the charging voltage must be reduced to normal float value after the charging current has stabilized. Never exceed the manufacturer's recommended maximum charging voltage.

6.19.3.3 Equalizing Charge Equalizing charges are not normally performed on VRLA cells because the cells are sufficiently charged at the normal float voltage; however, an equalizing charge may be necessary if a faster than normal recharge time is needed after a discharge. Manufacturers' data sheets normally provide a recommended voltage range, and the float voltage normally is set to a midrange value. If an equalizing voltage is used, it is set to the high end of the recommended range. The risk of VRLA thermal runaway is higher during equalize charging.

6.19.4 Periodic Measurements and Inspections

Regular visual examinations of VRLA cells are very important to check for bloated or cracked cases (Fig. 6.51), leaking seals (Fig. 6.52), and warped cell interconnection straps.

Where temperature-compensated charging is used, the battery voltage will vary with the temperature, and measurements should be corrected to the baseline temperature of 25°C (77°F). Temperature-compensated charging adjusts rectifier voltage by 2.5 to 4.5 mV/°C (0.7 to 2.5 mV/°F). For example, if the battery temperature (or the cell used to sense battery temperature) is 31°C (88°F) and the rectifiers are set to 4.5 mV/°C (2.5 mV/°F) compensation, the voltage of a 24-cell battery should read 27 mV lower than at 25°C (77°F).

The VRLA battery float current is an important indicator of impending cell failure. The float current in normal cells does not increase appreciably throughout the battery's life. Any significant increase indicates one or more cells that are in the failure mode.

Fig. 6.51 Consequences of excessive plate growth in VRLA cells. (Photos courtesy of M.W. Migliaro.)

Fig. 6.52 Post seal leak on cell 21 of a VRLA battery. (Photo courtesy of M.W. Migliaro.)

6.19.4.1 Initial Installation Measurements Initial installation measurements can be made coincidentally with the acceptance tests (Section 6.19.5) and should be performed no sooner than one week after the battery has had its initial freshening charge. A complete set of measurements should be taken to establish a baseline for a new installation including

- Internal impedance, resistance or conductance of each cell or monobloc
- Voltage of each cell or monobloc
- Battery voltage measured at the battery terminals
- Ambient temperature and temperature of each cell or monobloc
- Cell or monobloc interconnecting strap resistances and terminal resistances
- Battery float current

6.19.4.2 Monthly Measurements

- Examine each cell or module for general appearance and cleanliness, cracked covers and containers, electrolyte leakage, and excessive bloating (some types have a “normal bloat range”).
- Examine the overall battery, battery rack, and battery room or area for appearance and cleanliness. Remove combustible materials such as empty boxes from the room.
- Measure and record pilot cell voltage and temperature.
- Measure and record float voltage at battery terminals.
- Measure and record float current.
- Measure and record rectifier output voltage and current.
- Examine cell or module and battery terminals and connections for corrosion.
- Examine racks and fasteners for corrosion and overall structural integrity (shake test).
- Check the ambient temperature and ensure ventilation devices (fans and vents) are operable.
- Check battery monitoring system operation, if equipped.

6.19.4.3 Quarterly Measurements

- All monthly work items.
- Measure and record the internal impedance, resistance, or conductance of each cell or monobloc and compare the results with the initial records. Changes in the internal resistance of 20% or greater should be considered significant. Contact the battery manufacturer and follow its recommendations.
- Measure and record the temperature of the negative terminal of each cell or module.
- If the battery has a discharge rate of 1 h or less, measure and record the cell interconnecting strap resistances on a minimum of 10% of all connections. If an upward trend is noted from the initial readings, measure all connection resistances and take corrective action. Test different connections each quarter.

6.19.4.4 Semiyearly Measurements In addition to the quarterly work items, measure and record the voltage of each cell or monobloc and compare with previous measurements for trending purposes. Measurements should be from cell post to cell post.

6.19.4.5 Yearly Measurements

- All quarterly and semiyearly work items.
- Measure and record the interconnecting strap resistances of each cell or monobloc and of the battery terminals.
- Measure and record the ac ripple current and voltage at the battery terminals.
- Test the temperature-compensated charging system.
- Measure and record the internal impedance, resistance, or conductance of each cell or monobloc and compare to initial and previous measurements for trends.
- Measure and record the ground fault resistance of each cell or monobloc.

6.19.5 Value-Regulated Lead–Acid Battery Testing

6.19.5.1 Acceptance Testing Acceptance tests for VRLA batteries are very similar to VLA batteries. Acceptance tests should be performed at least one week after the battery has been operating at the proper float voltage or given an initial charge according to the manufacturer's instructions. Factory tests do not replace on-site acceptance tests because there may be shipping and handling damage to the battery prior to installation. The acceptance test should be at least a 3-h and preferably an 8-h discharge test and should discharge at least 90% of rated capacity. The operating temperature of the battery will affect the battery capacity; manufacturers' data sheets must be consulted for correction factors.

Maintain accurate records of the acceptance test, including make, model and serial number of all equipment used and the test results. These initial records will be used as a baseline for later comparisons.

1. Conduct the test only after all terminal and cell interconnection resistances have been measured and any discrepancies corrected.
2. Install an accurate ammeter, voltmeter, and thermometer, and use an accurate stopwatch to record elapsed time.
3. Record the following parameters just prior to the test:
   - Temperature of 10% or more of the cells to establish an average temperature (an IR thermometer may be used)
   - Battery terminal voltage
   - Individual cell or monobloc voltages
4. Disconnect the battery from the rest of the dc power system and connect it to a load bank so that constant current can be maintained equal to the 3- or 8-h rating of the battery at the initial battery temperature.
5. Using the average temperature from step 3, calculate the end-of-discharge voltage. An end-of-discharge voltage of 1.75 V/cell applies to an average cell temperature of 25°C (77°F). If the average cell temperature is not 25°C (77°F), determine the new end-of-discharge voltage as follows: For each 10°C above 25°C, add 0.006 V to 1.75 V, and for each 10°C below 25°C, subtract 0.006 V from 1.75 V. Similarly, for each 10°F above 77°F, add 0.01 V to 1.75 V, and for each 10°F below 77°F, subtract 0.01 V from 1.75 V.
6. Measure and record individual cell voltages and the battery terminal voltage. The measurements should be taken after applying the load at the beginning of the test.

Repeat the measurements at one-half hour intervals until the last hour of the test. During the last hour take measurements at shorter intervals such as 10 min. Measure individual cell voltage between respective terminals of like polarity (positive to positive) so the voltage drop of the cell interconnection straps are included in the measurement.

7. If an individual cell is approaching reversal of its polarity (voltage drops to 1.0 V/cell or less) or the voltage of a monobloc (6- or 12-V module) is more than 2 V lower than the others, terminate the test and consult the manufacturer.
8. Maintain the discharge rate until the battery terminal voltage decreases to 1.75 V/cell times the number of cells (21.00 V for a 12-cell and 42.00 V for a 24-cell battery).
9. Calculate the capacity from

$$\text{Capacity}_{25^\circ\text{C}}(\%) = \frac{\text{Actual Time}}{\text{Rated Time} \times K_T} \times 100 \tag{6.9}$$

where K_T is the temperature correction factor (obtain from battery manufacturer).

6.19.5.2 Capacity Tests As with VLA, frequent VRLA capacity tests are not recommended. However, tests at 1- or 2-year intervals will indicate if the battery is aging normally. Additional capacity tests may be needed to determine if a battery is nearing the end of its useful life or for warranty claim purposes. Absent specific procedures from the manufacturer, use the following test procedures. If the test shows the measured capacity has dropped below 90% rated capacity, then tests should be made every 6 months to 1 year. When the measured capacity has reached 80% of rated capacity, it should be replaced. Although capacity tests are very similar to acceptance tests previously described, capacity tests are separately described in this section because they could involve network equipment that is in operation, and extra precautions are necessary to ensure that equipment operation is not jeopardized.

1. Charge the battery at the high end of its recommended float voltage range and then return it to float service for between 3 and 30 days.
2. Take precautions to ensure that a battery failure will not jeopardize other equipment. Disconnect the battery to isolate it from the rest of the dc power system.
3. Install an accurate ammeter, voltmeter, and thermometer, and use an accurate stopwatch to record elapsed time.
4. Check all battery connections visually and with a microohmmeter to ensure connections are clean and low resistance. An IR thermometer may be used to check the connections just after the discharge test has begun. The temperature will be higher on poor connections. If poor connections are found, stop the test and repair them before continuing.
5. Record the following parameters just prior to the test:
    - Temperature of 10% or more of the cells to establish an average temperature (an IR thermometer may be used)
    - Battery terminal voltage
    - Individual cell or monobloc voltages

6. Use the average temperature measured in step 5 to calculate the end-of-discharge voltage. An end-of-discharge voltage of 1.75 V/cell applies to an average cell temperature of 25°C (77°F). If the average cell temperature is not 25°C (77°F), determine the new end-of-discharge voltage as follows: For each 10°C above 25°C, add 0.006 V to 1.75 V, and for each 10°C below 25°C, subtract 0.006 V from 1.75 V. Similarly, for each 10°F above 77°F, add 0.01 V to 1.75 V, and for each 10°F below 77°F, subtract 0.01 V from 1.75 V.
7. Connect the battery to a load bank. Discharge the battery through the load bank for 3 h at the rated 3-h discharge current (or for 8 h at the rated 8-h discharge current) until it reaches the end-of-discharge voltage determined in step 6. Record the voltage of each cell or monobloc every half-hour during discharge. Watch closely during the last hour to determine the exact time when the end-of-discharge voltage is reached. If the end-of-discharge voltage is reached before 3 (or 8) h has elapsed, the test should be stopped and the capacity should be computed. If the measured capacity is between 80 and 90% of rated capacity, the battery should be tested again in one year. The entire battery should be replaced as soon as possible after capacity drops below 80%.
8. Calculate the capacity from

$$\text{Capacity}_{25^\circ\text{C}}(\%) = \frac{\text{Actual Time}}{\text{Rated Time} \times K_T} \times 100 \tag{6.10}$$

where K_T is the temperature correction factor (obtain from battery manufacturer).

As with acceptance tests, maintain accurate records of all capacity tests, including make, model, and serial number of all test equipment used and the test results. These records should be compared to the baseline records and previous tests to determine the battery performance trend.

6.20 BATTERY FAILURE CASE STUDIES

6.20.1 Cell Explosion in UPS Battery

In Figure 6.53 corrosion in the post connection of cell 38 eventually caused the post to open at the connection between cell 38 and 39. Cell 38 exploded, breaking the partition wall to cell 39, which then exploded as well. This corrosion could not be visually detected because the connection that corroded was made by the manufacturer in a “well” in the jar cover and was encased in epoxy.

6.20.2 Lightning Damage to 12-Cell Wireless Site Battery

Figure 6.54 shows lightning damage to a 12-cell wireless site battery in the southern United States. The lightning currents found their way to the battery causing high overpressures presumably from rapid heating of the internal materials. The vent caps were blown out of seven cells and there was obvious damage to eight cells, exposing the plates. Interestingly, the site was not contaminated with electrolyte and there was no other damage.

Fig. 6.53 Cell explosion in UPS battery. (Photo and description courtesy of M.W. Migliaro.)

6.20.3 Corroded Interconnecting Strap

The corrosion shown in Figure 6.55 occurred adjacent to the cell post and was noticed by a maintenance engineer who said the post had a large amount of "blue-green stuff" on it.

6.20.4 Corrosion Around Terminal Post

The corrosion around the terminal post shown in Figure 6.56 has forced the post seal cover off a cell in a poorly maintained battery. This particular problem was pointed out to maintenance personnel, but when the site was visited 18 months later, there had been no changes.

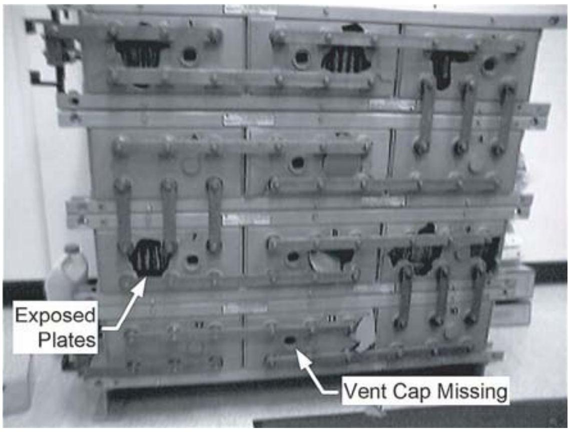

Fig. 6.54 Lightning damage to 12-cell wireless site battery. (Photo courtesy of Gary Trent.)

Fig. 6.55 Corroded interconnecting strap. (Photo and description courtesy of M.W. Migliaro.)

Fig. 6.56 Corrosion around the terminal post. (Photo and description courtesy of M.W. Migliaro.)

Fig. 6.57 Excessive oxidation inhibitor compound. (Photo courtesy of M.W. Migliaro.)

6.20.5 Excessive Oxidation Inhibitor Compound

Thick applications of the compound as shown in Figure 6.57 not only are difficult to clean but also hide potential problems.

Fig. 6.58 Post melting. (Photo and description courtesy of M.W. Migliaro.)

Fig. 6.59 Plate bowing in cell in 19-year-old battery. (Photo and description courtesy of M.W. Migliaro.)

6.20.6 Post Melting

The battery shown in Figure 6.58 was a new telecommunications battery that was being acceptance tested, but the user failed to check the intercell connection resistance and torque before the test. Some connections were loose and a number of cell posts melted.

6.20.7 Plate Bowing in Cell in 19-Year-Old Battery

The associated plate growth shown in Figure 6.59 caused two jars to crack and spill electrolyte.

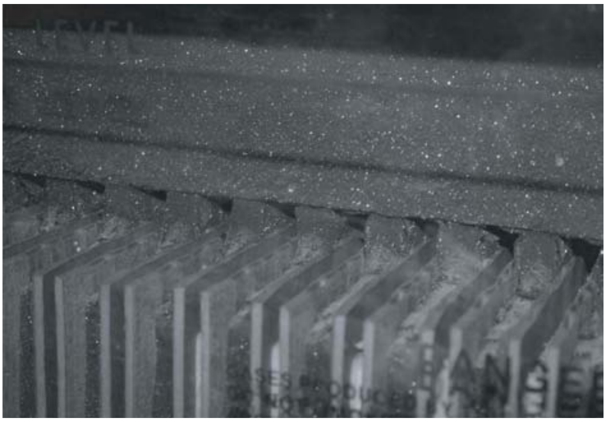

Fig. 6.60 Plate sulfation in shorted cell. (Photo and description courtesy of M.W. Migliaro.)

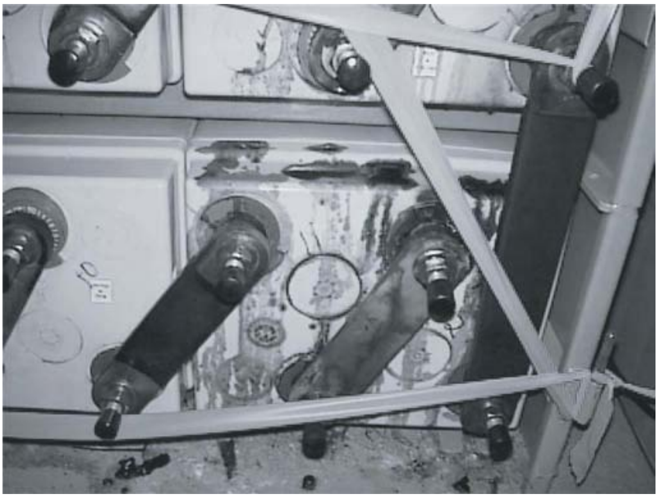

Fig. 6.61 VRLA Thermal runaway. (Photo courtesy of M.W. Migliaro.)

6.20.8 Plate Sulfation in Shorted Cell

The cell in Figure 6.60 was found to have a crack in the separator between two plates.

6.20.9 VRLA Thermal Runaway

Figure 6.61 shows a VRLS battery with thermal runaway, cause unknown.

REFERENCES (PART III)

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2. M. Migiliaro, M., *Stationary Battery Calculations Associated with Maintenance & Testing,* 3rd ed., 1995.
3. Intelec® 2001, *23rd International Telecommunications Energy Conference,* Oct. 14–18, 2001, Edinburgh International Conference Centre, Edinburgh, UK (IEEE catalog number 01CH37336).
4. Intelec® 2002, *24th Annual Telecommunications Energy Conference,* Sept. 29–Oct. 3, 2002, Montreal, Quebec, Canada (IEEE catalog number 02CH37374).
5. ANSI/IEEE 450™-2002, *IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications,* Institute of Electrical and Electronics Engineers, Piscataway, NJ, 2002.
6. NFPA 70-2005, *National Electrical Code®*, National Fire Protection Association, 2005.
7. ANSI/IEEE 1188™-1996, *IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve Regulated Lead-Acid (VRLA) Batteries for Stationary Applications,* Institute of Electrical and Electronics Engineers, Piscataway, NJ, 1996.

VLA BATTERY MAINTENANCE REPORT—FORM 1

Period From: ________________________________ To: ________________________________
Location: ________________________________ Date Installed: ________________________________
String No.: ________________ No. Cells: __________ Specific Gravity: ________________________________
Battery Manufacturer: ________________________________ Model: ________________________________
Type: ________________________________ Amp-Hour Capacity: ________________________________

Notes:
1. Rotate pilot cell yearly
2. All readings taken with battery stabilized on float
3. Do not add water prior to taking readings

Monthly Readings

Date	Charging		Electrolyte Level	Pilot Cell No.			Ambient Temp
	V	I		V	Temp.	SG	

Corrective Action

Water Addition to: (circle cell numbers at right)		
Date:	Qty Added (total):	
Reason for equalize charge:		
Date:	Voltage:	Duration:
Date:	Voltage:	Duration:
Date:	Voltage:	Duration:

Monthly Visual Examination (indicate Y/N)

Positive plates dark brown/free from sulfate crystals ________________
Positive plates/internal hardware free from flaking ________________
Terminal post seals okay ________________
Flame arrester vents and dust caps okay ________________
Connections free of corrosion ________________
Cell containers and covers in good condition ________________
Rack in good condition/free from corrosion ________________
Ventilating fans and vents working ________________
Insulated tools available/in good conditions ________________
Hydrometer and thermometer in good condition ________________
Goggles, face shield, gloves, apron available ________________
Minimum 1-gallon labeled soda solution ________________
Eye wash, body spray clean and working ________________
Class C fire extinguisher available and inspected ________________

Circle one in each column

Sediment			Negative Plates		Grids
Fine	Scarce	Brown	Dark	Mossy tops	Distorted
Coarse	Medium	Gray	Medium	Clean	Cracked
Lumps	Excessive	White	White Spots	Good	

Quarterly Readings

Date:		
Cell	Voltage	Specific Gravity
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24		

Temperatures of 10% of Cells

No.		No.		No.	
No.		No.		No.	

List instruments by type and serial number used to make measurements: ________________________________
____
Comments (if additional space is required, write on back): ________________________________
____
____
____
____
Name: ________________________________ Signed: ________________________________

VRLA BATTERY MAINTENANCE REPORT—FORM 2

Period From: ______________________________ To: ______________________________
Location: ______________________________ Date Installed: ______________________________
String No.: ______________ No. Cells: __________ Specific Gravity: ______________________________
Battery Manufacturer: ______________________________ Model: ______________________________
Type: ______________________________ Amp-Hour Capacity: ______________________________

Notes:

1. Rotate pilot cell yearly.
2. All readings taken with battery stabilized on float.
3. Individual cell voltages should vary no more than 0.03 V from average cell voltage.
4. Cell temperatures should be no greater than 5°F above ambient temperature.

Monthly Readings

Date	Charging			Pilot Cell No.			Ambient Temp
	V	I		V	Temp.		

Corrective Action

Water Addition to: (circle cell numbers at right)		
Date:	Qty Added (total):	
Reason for equalize charge:		
Date:	Voltage:	Duration:
Date:	Voltage:	Duration:
Date:	Voltage:	Duration:

Monthly Visual Examination (indicate Y/N)

Cells not bloated ____________
Terminal post seals okay ____________
Connections free of corrosion ____________
Cell containers and covers in good condition ____________
Rack in good condition/free from corrosion ____________
Ventilating fans and vents working ____________
Insulated tools available/in good conditions ____________
Hydrometer and thermometer in good condition ____________
Goggles, face shield, gloves, apron available ____________
Minimum 1-gallon labeled soda solution ____________
Eye wash, body spray clean and working ____________
Class C fire extinguisher available and inspected ____________

Annual Examination (indicate Y/N)

Cell inter-connection strap torque okay ____________

Quarterly Readings

Date:			
Cell	Voltage	Temperature	Notes
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			

Temperatures of 10% of Cells

No.		No.		No.	
No.		No.		No.	

List instruments by type and serial number used to make measurements: ______________________________
____

Comments (if additional space is required, write on back): ______________________________
____
____
____
____

Name: ______________________________ Signed: ______________________________

CELL IMPEDANCE & INTER-CONNECTION RESISTANCE REPORT—FORM 3

Measurement Date: ______________________________
Period From: ___________________________________ To: ____
Location: _______________________________________ Date Installed: ____
String No.: __________________ No. Cells: ___________ Specific Gravity: ____
Battery Manufacturer: _____________________________________ Model: ____
Type: ____ Amp-Hour Capacity: ____

Notes:

1. See back of this form for instructions and post orientation and numbering.
2. Use additional sheets for double- and triple-post cells.

Meter probes between	Parallel No. 1 As-Found (micro-ohms)	Parallel No. 2 As-Found (micro-ohms)	Parallel No. 1 As-Left (micro-ohms)	Parallel No. 2 As-Left (micro-ohms)	Internal Impedance (ohms)
Lug–Cell No. 1 Post					Cell 1
Post/Cells 1–2					Cell 2
Post/Cells 2–3					Cell 3
Post/Cells 3–4					Cell 4
Post/Cells 4–5					Cell 5
Post/Cells 5–6					Cell 6
Post/Cells 6–7					Cell 7
Post/Cells 7–8					Cell 8
Post/Cells 8–9					Cell 9
Post/Cells 9–10					Cell 10
Post/Cells 10–11					Cell 11
Post/Cells 11–12					Cell 12
Post/Cells 12–13					Cell 13
Post/Cells 13–14					Cell 14
Post/Cells 14–15					Cell 15
Post/Cells 15–16					Cell 16
Post/Cells 16–17					Cell 17
Post/Cells 17–18					Cell 18
Post/Cells 18–19					Cell 19
Post/Cells 19–20					Cell 20
Post/Cells 20–21					Cell 21
Post/Cells 21–22					Cell 22
Post/Cells 22–23					Cell 23
Post/Cells 23–24					Cell 24
Cell No. 24 Post—Lug					
Averages					

List instruments by type and serial number used to make measurements: ____
____

Comments (if additional space is required, write on back): ____
____
____
____
____

Name: ____ Signed: ____

Start at the battery terminal connected to cell no. 1, which normally is the cell closest to ground potential, and move from there to the opposite end of the battery. Ensure the battery is on float charge before beginning the measurements and not on equalize or being discharged. Record all measurements on this form.

1. Take the first measurement on cell No. 1 between the terminal lug and the first post. This measurement will be the resistance between the cell post and battery terminal lug and will be about one-half of the cell interconnecting strap readings in 2 and 3 below.
2. Take the second measurements between *opposite* polarity *posts* (not interconnecting straps) of cells No. 1 and No. 2. The subsequent measurements will be between positive and negative posts of adjacent cells to include the cell interconnecting straps and hardware connections. These measurements will include the resistance of two bolted connections (one on each post) and the cell-interconnecting strap and will be about twice the value of the first and last measurements at the battery terminals. If the cells have two parallel posts for each polarity, measure both and record on the form as “Parallel No. 1” and “Parallel No. 2”.
3. Measure the remaining interconnections as in step 2, moving from cell to cell.
4. Take the last measurement between the last post on the last cell and the battery terminal lug fastened to it.
5. If a comparatively high resistance is found, measure from each post to its cell-interconnecting strap to determine which of the two connections is bad. Mark this and all high-resistance connections for later repair.
6. Configure the test set to measure cell impedance. Measure cell No. 1 between its two posts.
7. Measure the remaining cells as in step 6, moving from cell to cell.

APPENDIX A

COMMENTS ON HISTORIC dc POWER SYSTEM CONFIGURATIONS

A.1 INTRODUCTION

The battery and rectifier configuration described in this book at one time was called a "straight cell system" as compared to two other configurations called a "counter cell system" (also called "counter emf cell system" or "cemf cell system") and an "end-cell system" (also called "emergency cell system").[1] These two configurations were used with electromechanical (step-by-step, or SXS) switching systems. They were replaced when the SXS switching systems were replaced first by stored program-controlled (SPC) and then digital switching systems in the public network in the early 1970s and early 1980s, respectively.

The SXS switching systems operated at a nominal –48 Vdc and required relatively tight voltage regulation (~10%) as compared to the later technologies, which were designed to work over a somewhat wider voltage range (~20%). Although the tighter regulation could be provided by using an extra-large battery and only partially discharging it, in most cases either cemf cells or end cells were used to improve load voltage regulation under all conditions of battery recharge and discharge. Thus, at the expense of higher complexity, the two configurations helped to mitigate two limitations of the straight cell system:

- Relatively poor voltage regulation during battery charging, equalizing, and discharging
- Not fully discharging the battery capacity due to relatively high load minimum voltage limits

A.2 COUNTER emf CELL SYSTEM

The cemf cells originally were an alkaline battery cell with nickel electrodes that developed a relatively constant voltage drop (1.5 to 2 V). The cemf cells were later made from

---

[1] Counter electromotive force (cemf) or counter voltage.

selenium diodes and later still from regular silicon diodes in series and parallel arrangements to achieve the desired voltage drop and current capacity.

The cemf cells were placed in series with the load under normal float conditions, thus "countering" the rectifier voltage, and shorted during battery discharge (Fig. A.1). When the battery was recharging and the bus voltage increasing, the cemf cells were automatically switched in again. In many systems, cemf cells were not inserted in the load circuit to reduce the voltage except when the battery was charged at the equalizing voltage of 56.4 V (2.35 V/cell). The cemf cells also were used in individual load circuits (rather than the main bus) to control the voltage to only certain loads.

A.3 END-CELL SYSTEM

End cells were ordinary lead–acid cells automatically switched in series with the load to add voltage under discharge conditions (Fig. A.2). The end cells usually were switched in steps to avoid exceeding the allowable load upper voltage limit. Thus, a 24-cell battery was increased to 25 cells and then 26 cells when on discharge. A quick calculation shows that a 26-cell battery has an end-of-discharge (final) voltage of 45.5 V (1.75 V/cell). This allowed the SXS equipment to operate while simultaneously deriving maximum discharging capacity from the battery.

A.4 SUMMARY

Neither the cemf nor end-cell configurations are used in modern dc power systems because:

- Both systems required relaying and interlocking schemes that added complexity and were subject to failure.

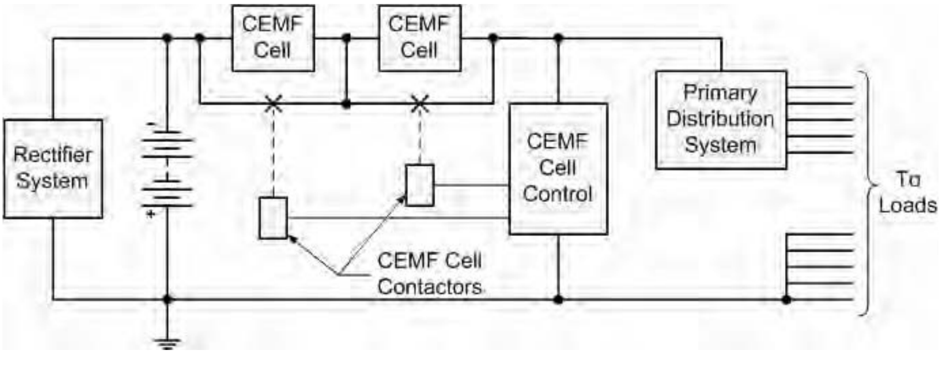

Fig. A.1 The cemf cell system schematic. During normal float operation, the cemf cells are in series with the load circuit and the system output voltage at the primary distribution system is the rectifier float voltage less the voltage drop across the cemf cells (~1.5 V each). When the battery is discharged and its voltage decreases, the cemf cells are shorted by the contactors and the full battery voltage is impressed on the load circuits. A stepped arrangement can be used (shown) to more closely control the voltage delivered to the loads. When the battery is recharged, the cemf cells are automatically switched back into the circuit by opening the contactors.

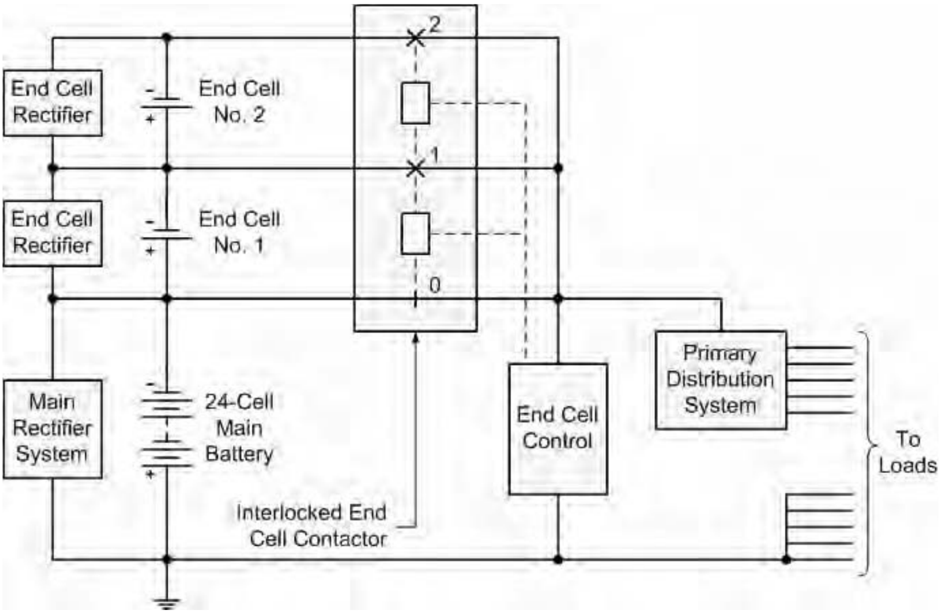

Fig. A.2 End cell system schematic. During normal float operation, the end cells are switched out of the load circuit by open contactors 1 and 2, and the primary distribution system is connected to the main battery through contactor 0. When the battery discharges and its voltage decreases, the end cells are automatically switched in by contactors 1 and 2, thus increasing the load voltage by about 2 V with each step. When the main battery is recharged, the end cells are switched out and independently recharged by end-cell rectifiers. Contactors 0, 1, and 2 are interlocked to prevent shorting the end cells.

- Both systems used break-before-make relay contactors or switches that either momentarily interrupted the dc current or quickly changed the load voltage, which caused transients and noise from the momentary arcing. While acceptable in SXS switching systems, these characteristics were unacceptable in SPC and digital switching systems.
- The relatively tight voltage control required by SXS switching systems was not required by SPC and digital switching systems.

The SPC and digital switching systems were deployed in the network in total replacement and cap-and-grow schemes. In total replacement schemes, the dc power system used with the SXS system was completely replaced with a new straight cell system.[2] In cap-and-grow schemes the old SXS system was retained in service while the access lines were migrated to the new SPC system over a period of years, thus shrinking the SXS and growing the SPC. Meanwhile, the old dc power system (either cemf or end cell) was maintained along side a new straight cell system for the SPC equipment. Eventually, the SXS and its power system were decommissioned.

---

[2] Actually, many SPC switching systems used two battery plants, one for the switching matrix and “talk battery” at 48 Vdc and another at 24 Vdc for the computer and common control equipment. Both were straight cell systems. Some SPC systems used dc–dc converters to derive the 24 Vdc from the main 48-Vdc plant.

APPENDIX B

MATHCAD WORKSHEET EXAMPLES

The following worksheet examples show a few of the many ways to use commercial software, such as Mathcad by Mathsoft Engineering & Education, Inc. (www.mathsoft.com), to perform iterative ampacity calculations. Although the basic calculation procedures are similar for all physical wire configurations, different procedural techniques are used in the examples to show the flexibility available.

These examples are not intended to show the best or most efficient programming method; they are intended to allow the reader to duplicate the calculations and to calculate the ampacities for wire sizes not covered.

B.1 SINGLE WIRE IN FREE AIR

Example shows 4/0 AWG jacketed 1/C with 90°C maximum wire temperature and 30°C ambient temperature.

$\text{Tmax} := 90 \qquad \text{Ta} := 30 \qquad \text{Dc} := 0.528 \qquad \text{tins} := 0.125 \qquad \text{De} := \text{Dc} + 2\ \text{tins}$

$$\text{DeltaT} := \text{Tmax} - \text{Ta} \qquad \rho\text{ins} := 5 \qquad \text{hcr} := \left[\frac{.21}{\left(\text{De}\cdot\frac{25.4}{1000}\right)^{.6}}\right] + 3.94$$

$$\text{Trins} := \frac{\rho\text{ins}\cdot\ln\left(1 + 2\cdot\frac{\text{tins}}{\text{Dc}}\right)}{2\cdot\pi}$$

$$\text{Ka} := \pi\cdot\text{De}\cdot\frac{25.4}{1000}\cdot\text{hcr}\cdot\text{Trins} \qquad \text{err} := 0.00001 \qquad \text{Rw} := 0.06376$$

Ts(err) :=

```
$x \leftarrow 2$
$Diffr \leftarrow .001$
while $|Diffr| > err$
    $DTs \leftarrow x^4$
    $y \leftarrow DTs^{.25}$
    $x \leftarrow \left[\frac{DeltaT}{(1 + Ka \cdot y)}\right]^{.25}$
    $Diffr \leftarrow x - y$

    $y^4$
```

$$Trsa := \frac{1}{\pi \cdot De \cdot \frac{25.4}{1000} \cdot hcr \cdot (Ts(.0001))^{.25}}$$

$$I := \left[\frac{DeltaT}{\frac{Rw}{1000 \cdot 0.3048} \cdot (TRins + TRsa)}\right]^{.5}$$

$$I = 467$$

B.2 TWO BUNDLED WIRES

Example shows 4/0 AWG jacketed 1/C with 75°C maximum wire temperature and 30°C ambient temperature.

$Tmax := 75$ $\quad Ta := 30$ $\quad Dc := 0.528$ $\quad tins := 0.125$ $\quad De := Dc + 2\ tins$

$DeltaT := Tmax - Ta$ $\quad \rho ins := 5$ $\quad hcr := \left[\frac{.29}{\left(De \cdot \frac{25.4}{1000}\right)^{.5}}\right] + 2.35$

$$Trins := \frac{\rho ins \cdot \ln\left(1 + 2 \cdot \frac{tins}{Dc}\right)}{2 \cdot \pi}$$

$Ka := \pi \cdot De \cdot \frac{25.4}{1000} \cdot hcr \cdot Trins$ $\quad err := 0.0001$ $\quad Rw := 0.06081$

Ts(err) :=

```
$x \leftarrow 2$
$Diffr \leftarrow .001$
while $|Diffr| > err$
    $DTs \leftarrow x^4$
    $y \leftarrow DTs^{.25}$
    $x \leftarrow \left[\frac{DeltaT}{(1 + Ka \cdot y)}\right]^{.25}$
    $Diffr \leftarrow x - y$
$y^4$
```

$$Trsa := \frac{1}{\pi \cdot De \cdot \frac{25.4}{1000} \cdot hcr \cdot (Ts(0.0001))^{.25}}$$

$$I := \left[\frac{DeltaT}{\frac{Rw}{1000} \cdot 0.3048 \cdot (TRins + TRsa)}\right]^{.5}$$

$$I = 355$$

B.3 WIRES WITH NO SEPARATION IN ONE OR MORE LAYERS

Example shows 4/0 AWG jacketed 1/C with 90°C maximum wire temperature and 30°C ambient temperature.

$Tmax := 90 \quad Ta := 30 \quad d := .5, 1 \,..\, 7 \quad w := 24 \quad As := 2 \cdot \frac{w}{12} \quad Fdiv := 1 \quad Dw := 0.73$

$\varepsilon := 0.8 \quad \rho eff := 13.13 \quad \sigma := 5.3 \cdot 10^{-9} \quad err := .00001 \quad Rw := \frac{0.06376}{1000} \quad Aw := Dw^2$

```
Wwm(d) :=
    Wwm ← 0
    Diffr ← .0001
    while |Diffr| > err
        Wwm ← Wwm + Diffr · .0
        Wtemp ← Wwm · Fdiv
        $Ts \leftarrow Tmas - \left[\frac{(Wwm \cdot \rho eff \cdot d)}{(8 \cdot w)}\right]$
        $hconv \leftarrow .101 \cdot (ts - Ta)^{.25}$
        $Diffr \leftarrow [hconv \cdot As \cdot (Ts - ta)] + [\sigma \cdot As \cdot \varepsilon \cdot [(Ts + 273.15)^4 - (Ta + 273.15)^4]] - Wtemp$
    Wwm
```

$$qw(d) := \frac{Wwm(d)}{d \cdot w}$$

$$Ww(d) := qw(d) \cdot Aw$$

$$I(d) := \sqrt{\frac{Ww(d)}{Rw}}$$

qw(d) =

	0
0	15.809
1	6.997
2	4.195
3	2.864
4	2.105
5	1.624
6	1.296
7	1.062
8	0.888
9	0.755
10	0.650
11	0.566
12	0.498
13	0.442

I(d) =

	0
0	363
1	242
2	187
3	155
4	133
5	116
6	104
7	94
8	86
9	79
10	74
11	69
12	65
13	61

B.4 WIRES IN ROUNDED BUNDLE

Example shows 4/0 AWG jacketed 1/C with 90°C maximum wire temperature and 30°C ambient temperature.

$\text{Tmax} := 90 \quad \text{Ta} := 30 \quad \text{Dc} := 0.528 \quad \text{tins} := 0.125 \quad \text{Dw} := (\text{Dc} + 2 \cdot \text{tins}) \cdot \dfrac{0.3048}{12}$

$n := 2, 4 \,..\, 16 \quad \text{Dw} := 0.73$

$\text{DT} := \text{Tmax} - \text{Ta} \quad \rho\text{ins} := 16.4 \cdot 0.3048 \quad \rho\text{eff} := 13.12 \cdot 0.3048 \quad \text{Ab}(n) := n \cdot \text{Dw}^2$

$\text{Aw} := \text{Dw}^2$

$\text{Rw} := \dfrac{0.06376}{1000 \cdot .3048} \qquad \text{err} := .0001$

```
Wb(n) := | Deb ← $2 \cdot \sqrt{\frac{n}{\pi}} \cdot \text{Dw}$
         | hcr ← $\frac{.21}{\text{Deb}^{0.6}} + 3.94$
         | Wtemp ← 0.001
         | Diffr ← .001
         | while |Diffr| > err
         |     | Wstemp ← Wtemp + Diffr - .5
         |     | Wb ← Wtemp
         |     | Wtemp ← $\left[\dfrac{\text{DT}}{\left[\dfrac{\rho\text{eff}}{4-\pi} + \dfrac{1}{(\pi \cdot \text{Deb} \cdot \text{hcr} \cdot \text{Wb}^{.25})^{4/5}}\right]}\right]$
         |     | Diffr ← Wb − Wtemp
         | Wb
```

$$\text{Wb}(n) = \begin{pmatrix} 58.400 \\ 69.645 \\ 76.700 \\ 81.867 \\ 85.944 \\ 89.308 \\ 92.167 \\ 94.651 \end{pmatrix}$$

$$\text{qb}(n) := \frac{\text{Wb}(n)}{\text{Ab}(n)}$$

$$\text{qb}(n) = \begin{pmatrix} 7.478 \times 10^4 \\ 4.459 \times 10^4 \\ 3.274 \times 10^4 \\ 2.621 \times 10^4 \\ 2.201 \times 10^4 \\ 1.906 \times 10^4 \\ 1.686 \times 10^4 \\ 1.515 \times 10^4 \end{pmatrix}$$

$$\text{Ww}(n) := \text{qb}(n) \cdot \text{Aw}$$

$$I(n) := \sqrt{\frac{\text{Ww}(n)}{\text{Rw}}} \qquad I(n) = \begin{pmatrix} 374 \\ 289 \\ 247 \\ 221 \\ 203 \\ 189 \\ 177 \\ 168 \end{pmatrix}$$

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