Power Quality

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Overview

1. Introduction:
2. What is Power Quality?
3. Terms and Definitions
4. Voltage Sags and Interruptions
5. Transient Over voltages
6. Harmonics

Introduction

Power Quality (def.)

Any power problem manifested in voltage, current, or frequency deviations that results in failure or misoperation of customer equipment.

Metrics of PQ:

- frequency (50 Hz)
- amplitude (230 V, 150 kV, …)
- symmetry (phase shift of 120 ° in a three-phase system)
- Wave shape

Introduction

There are three major reasons for the increased concern on power quality:

1. Microprocessor-based controls and power electronic devices, is more sensitive to power quality variations than was equipment used in the past.
2. The continued growth in the application of devices such as adjustable-speed motor drives and shunt capacitors which are causing disturbances.
3. Many things are now interconnected in a network. Integrated processes mean that the failure of any component has more important consequences.

Introduction

Power Quality=Voltage Quality

- The power supply system can only control the quality of the voltage; it has no control over the currents that particular loads might draw.
- AC power systems are designed to operate at a sinusoidal voltage of a given frequency [typically 50 or 60 hertz (Hz)] and magnitude. Any significant deviation in the waveform magnitude, frequency, or purity is a potential power quality problem.
- There is always a close relationship between voltage and current in any practical power system.

Introduction

Although the generators may provide a near-perfect sine-wave voltage, the current passing through the impedance of the system can cause a variety of disturbances to the voltage. For example,

1. The current resulting from a short circuit causes the voltage to sag or disappear completely, as the case may be.
2. Currents from lightning strokes passing through the power system cause high-impulse voltages that frequently flash over insulation.
3. Distorted currents from harmonic-producing loads also distort the voltage as they pass through the system impedance.

Introduction

Why are we concerned about power quality? The reasons for the increased interest in power quality can be summarized as follows:

- Downtime: Poor power quality can result in equipment downtime and/or damage, resulting in a loss of productivity.
- Protective relays: Poor power quality can cause protective relays to malfunction.
- Metering: Poor power quality can affect the accuracy of utility metering.
- Electromagnetic compatibility: Poor power quality can result in problems with electromagnetic compatibility.

Introduction

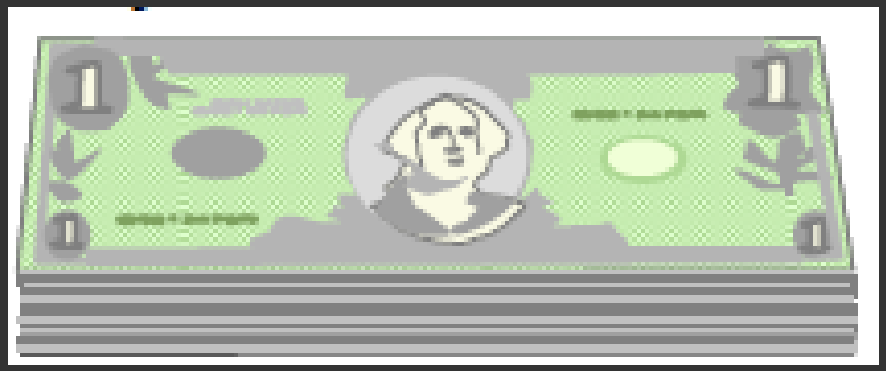
- Voltage quality has to do with what the utility delivers to the consumer, current quality is concerned with what the consumer takes from the utility.
- Voltage and current are strongly related and if either voltage or current deviates from the ideal it is hard for the other to be ideal

Introduction

Power Interruption Cost

- Downtime duration (Hrs.)
- Lost material value ($)
- Canceled orders
- Late delivery / penalty payments
- Lost customer confidence
- Equipment repair/ replacement costs

The Cost of Poor Power Quality



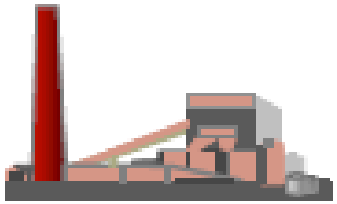
Introduction

Sources of Power Quality Problems in Order of Frequency of Occurrence

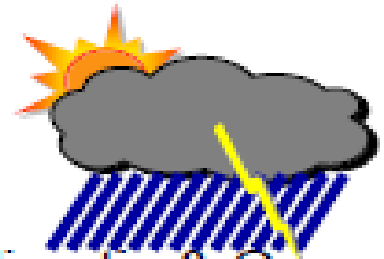
- User loads
- Weather related...lightning, wind, rain, etc.
- Distribution and Transmission System
- Generator.

Introduction

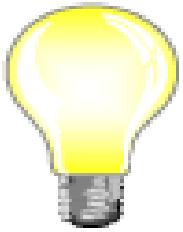
What Determines Electrical Environment Quality?



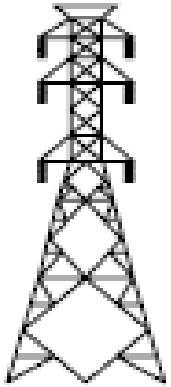
Generation



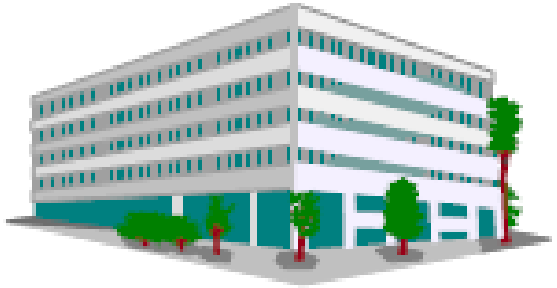
Climatic & Geographic



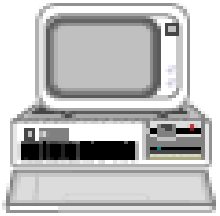
Traditional Loads



T&D



Facility Wiring & Construction

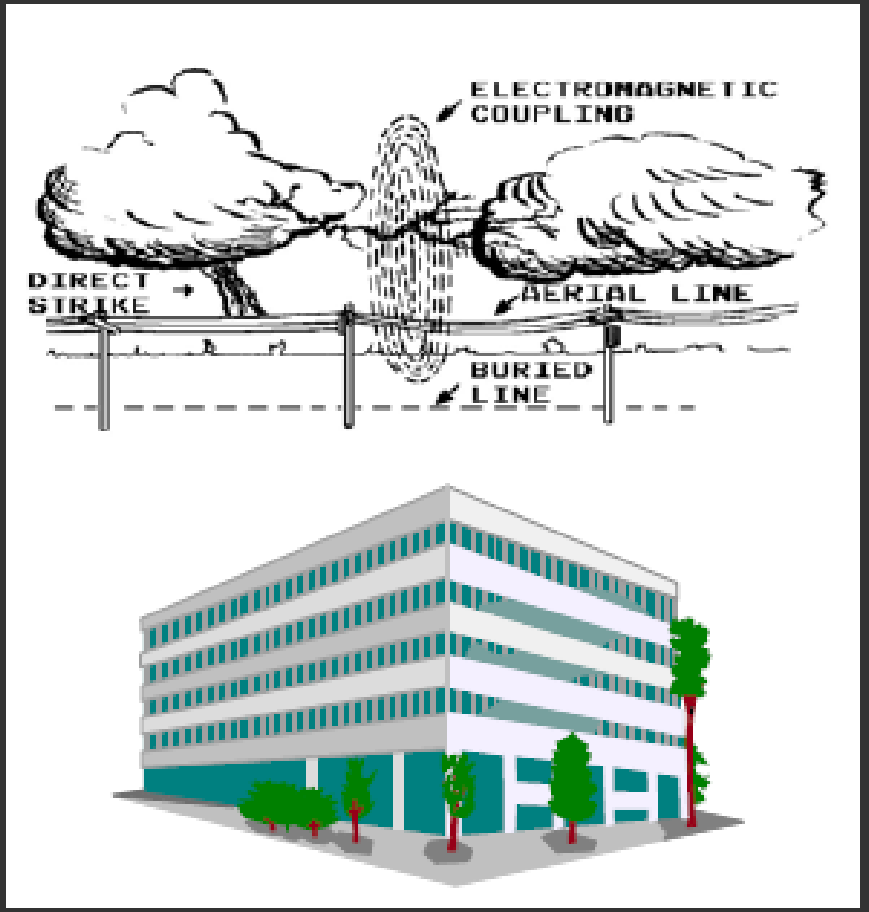


Electronic Loads

Introduction

Sources of Quality Problems

- Internal
  - Loads
  - EMI
  - Wiring errors
- External
  - Utility sources



Ideal Voltages

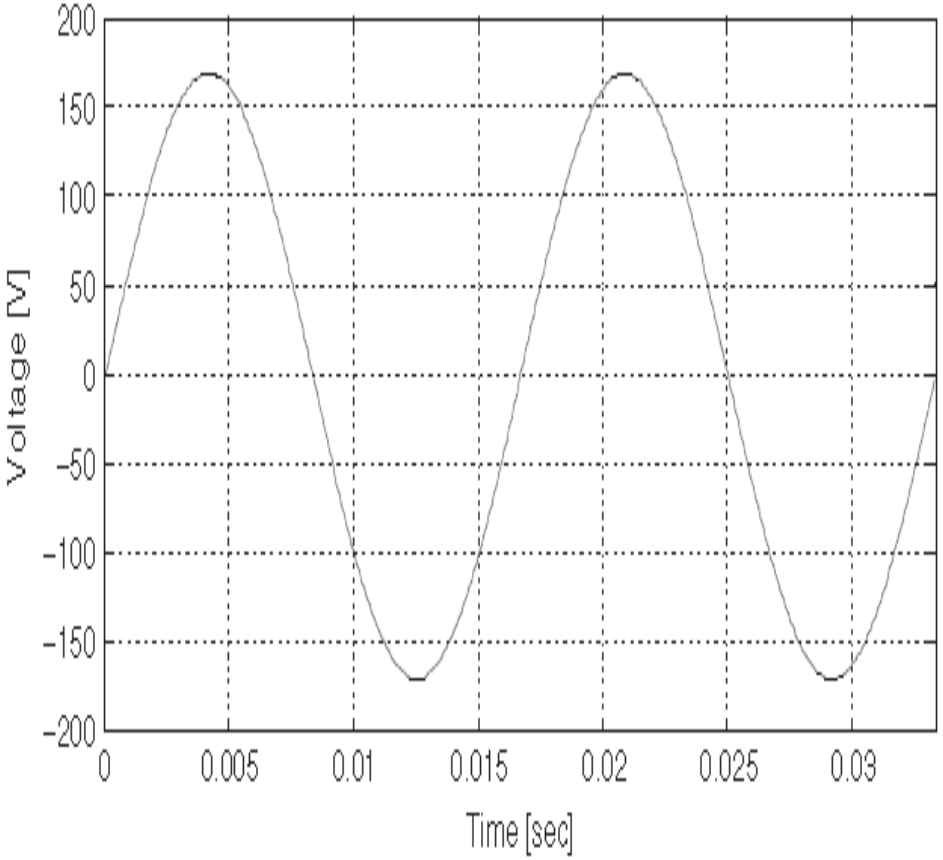


Figure 1.1 Ideal single-phase voltage waveform. The peak value is +170 V, the rms value is 120 V, and the frequency is 60 Hz.

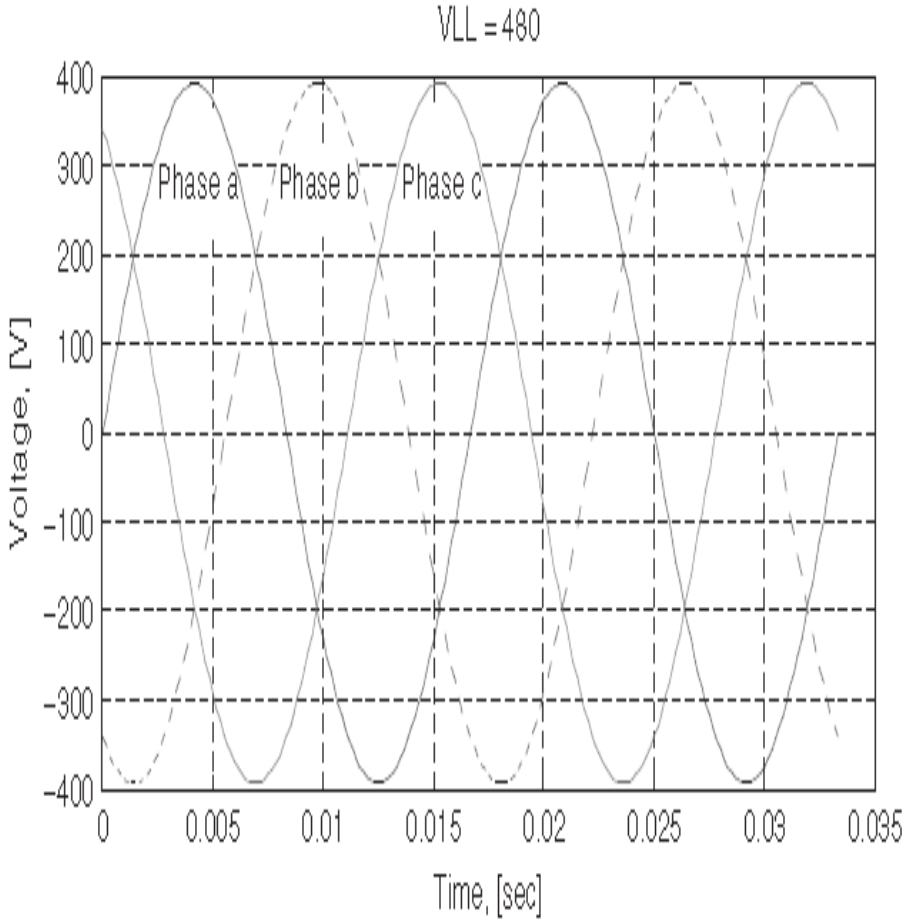
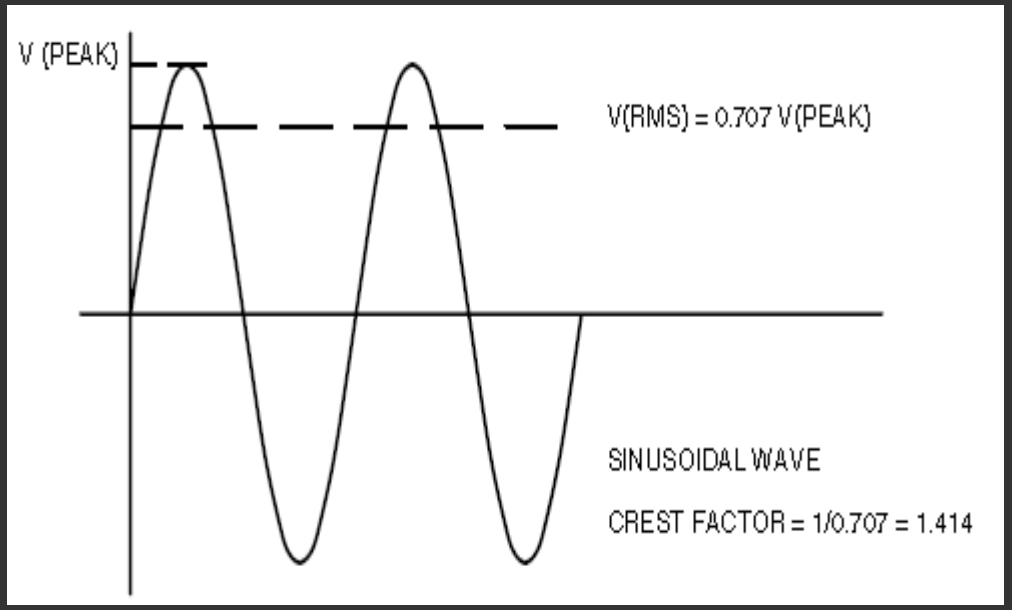
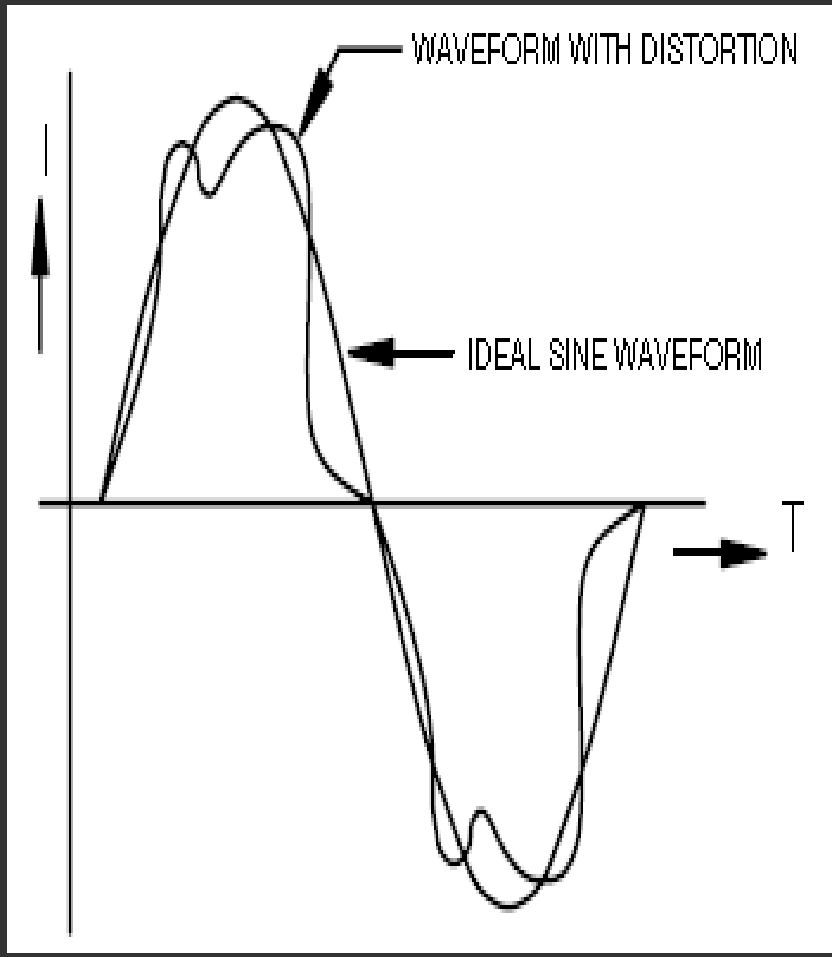


Figure 1.2 An ideal three-phase voltage waveform at 60 Hz with a line-line-voltage of 480 V rms. Shown are the line-neutral voltages of each phase.[2]

Waves


V (PEAK)
V(RMS) = 0.707 V(PEAK)
SINUSOIDAL WAVE
CREST FACTOR = 1/0.707 = 1.414


WAVEFORM WITH DISTORTION
I
IDEAL SINE WAVEFORM
T

Introduction

Equipment immunity is the ability of equipment to operate satisfactorily with the normally expected variations in electricity supply (ie, it's immune to a certain range of variations)

Equipment immunity level:

- **High immunity equipment: motors, transformers, incandescent lamps, heaters, etc.**
- **Moderate immunity equipment: adjustable speed drives, electronic relays, etc.**
- **Low immunity equipment: communication and data processing equipment, electronic medical equipment, etc.**

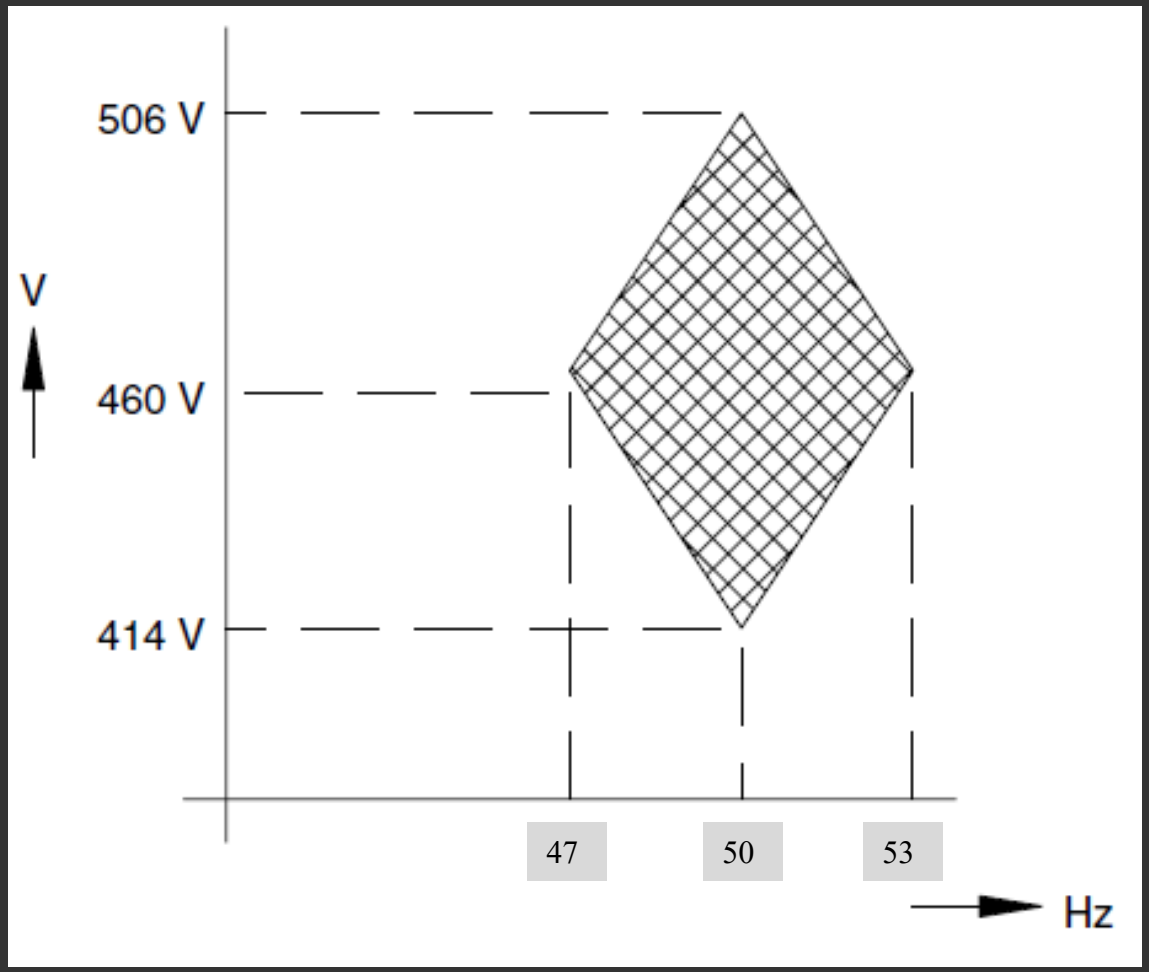
Introduction

Two methods for solving a power quality problem are to either make

- the power quality contour smaller (maintain deviations less) or
- make the immunity contour larger than the power quality contour. (Make equipments tolerant to disturbance)

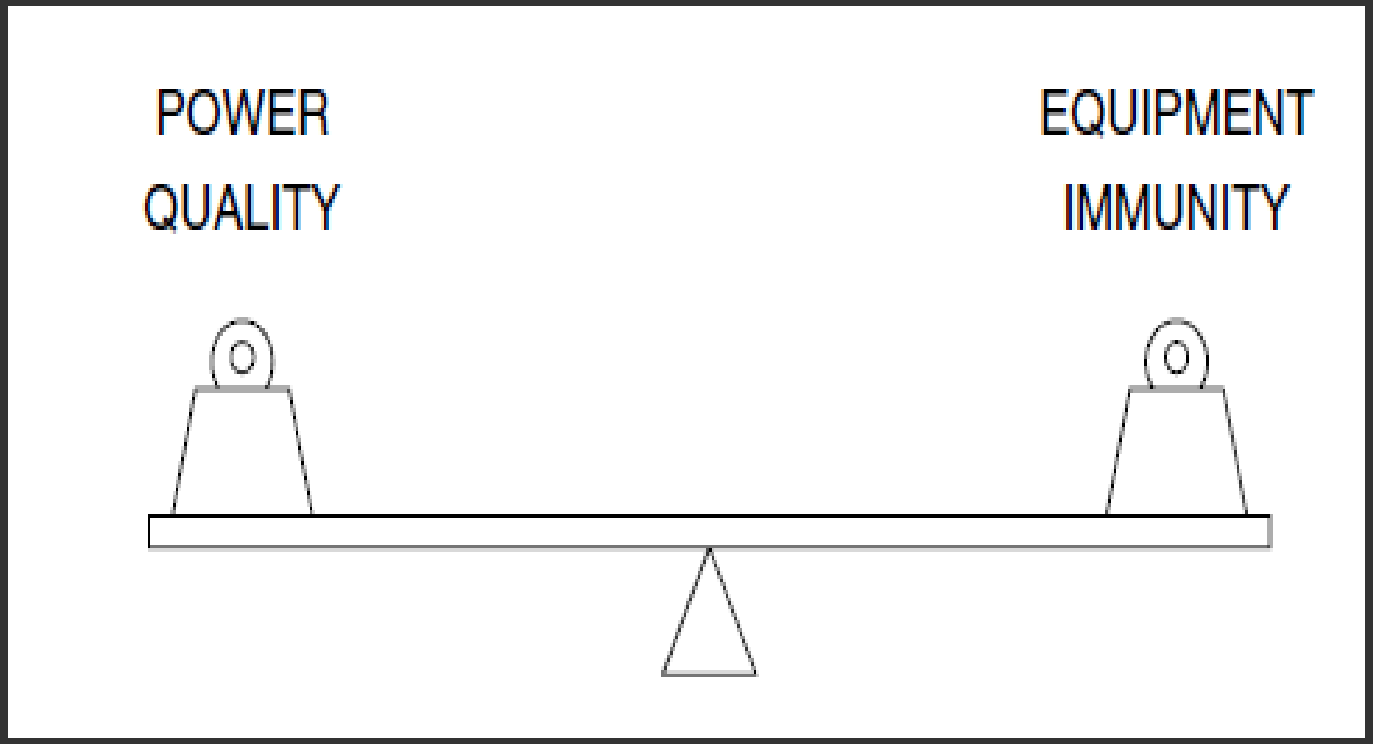
Introduction

Volts–hertz immunity contour for 460-VAC motor

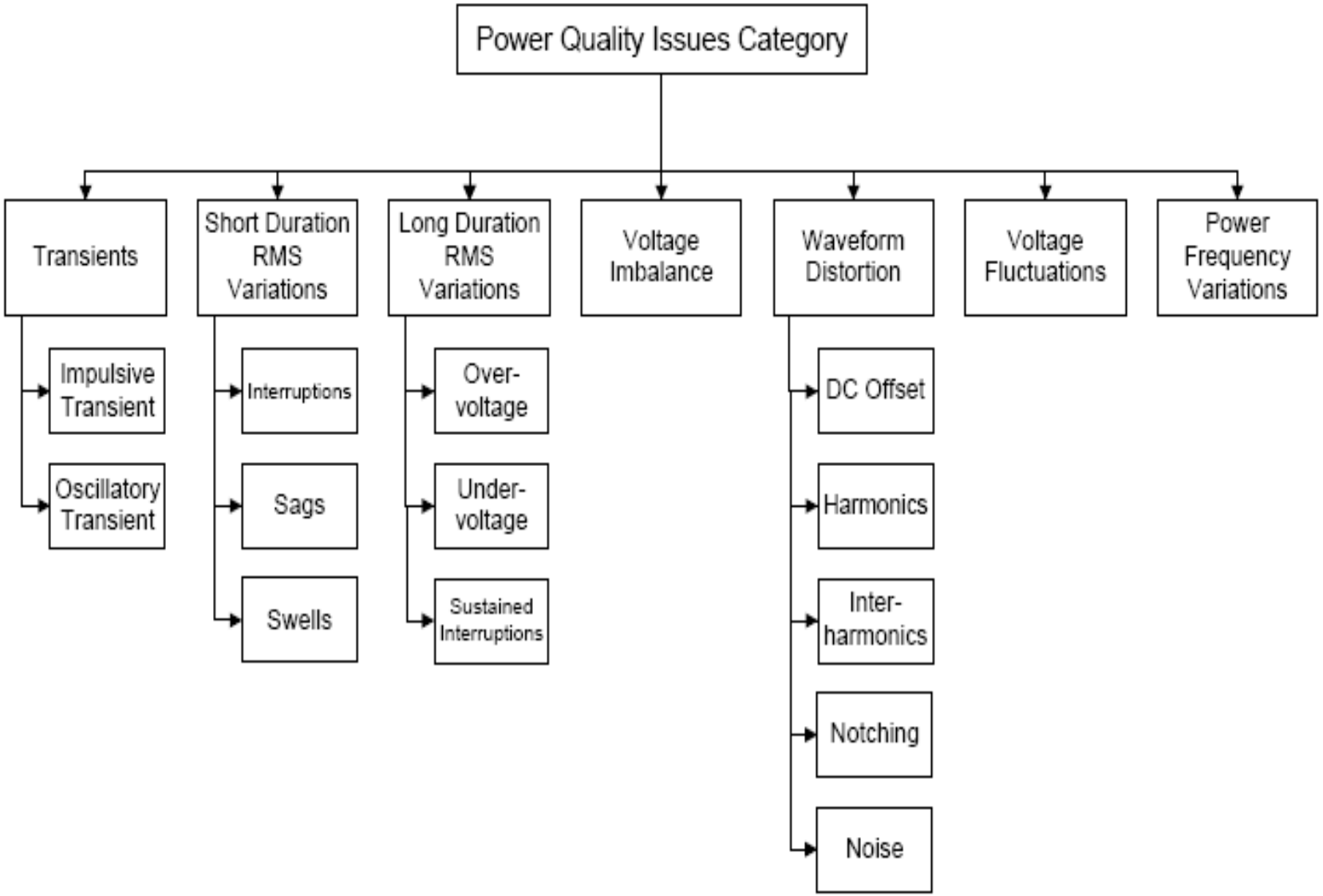


Introduction

Power quality and equipment immunity



Power Quality Categories



Power Quality Category

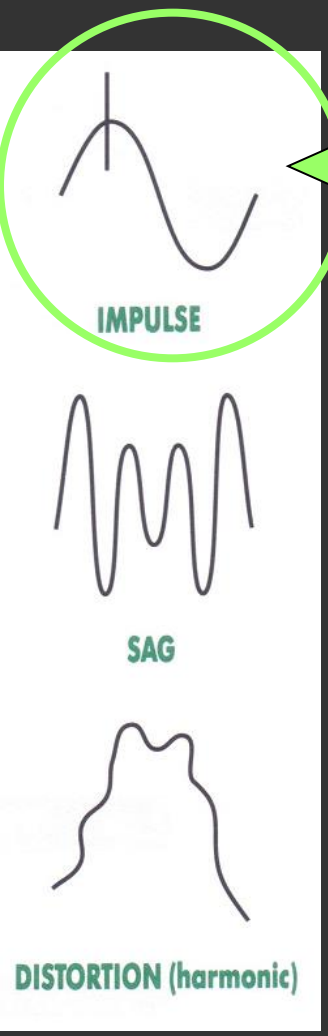
- Tabular indication of voltage magnitude verses duration

Event Magnitude					
	110%	Transients	Swell		High voltage
	90%	Normal operating voltage			
	10%	Transient	Voltage Sag		Under voltage
			Momentary	Temporary	Sustained interruption
		0.5 cycle	3sec		1 min
		Event duration			

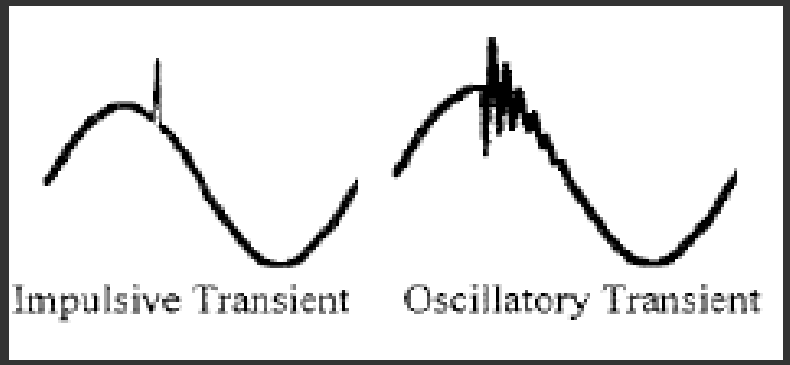
Categories & Characteristics of Power System Electromagnetic Phenomena (IEC)

Categories	Typical characteristics
Overvoltage transients:	
Impulsive:	Nanosecond: 5ns rise time for < 50 ns
	Microsecond: 1us rise time for 50ns-1ms
	Millisecond: 0.1ms rise time for >1ms
Oscillatory:	Low freq.: <5kHz for 0.3-50ms at 0-4 pu
	Med. freq.: 5-500kHz for 20μs at 0-8 pu
	High freq.: 0.5-5MHz for 5μs at 0-4 pu
Short duration voltage variations:	
Interruption	Momentary: < 0.1pu for 0.5 cycles-3 s
	Temporary: < 0.1pu for 3 s-1 min
Sag	Instantaneous: 0.1-0.9pu for 0.5-30 cycles
	Momentary: 0.1-0.9 pu for 30 cycles-3 s
	Temporary: 0.1-0.9 pu for 3 s – 1 min
Swell	Instantaneous: 1.1-1.8pu for 0.5-30 cycles
	Momentary: 1.1-1.4pu for 30 cycles-3 s
	Temporary: 1.1-1.2pu for 3 s-1 min
Long duration voltage variations:	
Interruption	Sustained: 0.0pu for > 1 min
Undervoltages	0.8-0.9 pu for > 1 min
Overvoltages	1.1-1.2 pu for > 1 min
Voltage waveform distortions:	
DC offset	0-0.1%
Harmonics	0-100th H with 0-20% magnitude
Interharmonics	0-6 kHz with 0-2% magnitude
Notching	
Voltage fluctuations:	
Intermittent	< 25 Hz with 0.1-7% magnitude

Transients



- The term *transients* (surge) denote an event that is undesirable but momentary in nature that disappears during transition from one steady state operating condition to another.
- very quick < 1 cycle
  - Normal cause is lightning strike
  - Switching



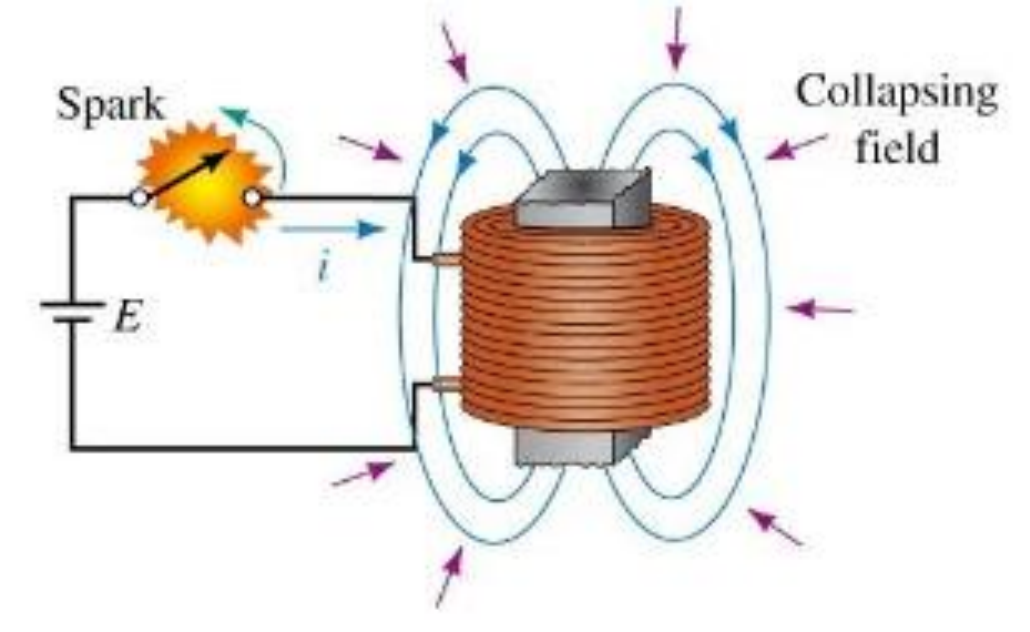
Transients

Transients – surges can have magnitudes of several thousand volts and so can cause serious damage to both the installation and the equipment connected to it.

- Inductive switching transients are the silent killers of semiconductors.

Transients

Opening of inductive circuit may cause voltage spikes of thousands of volts:



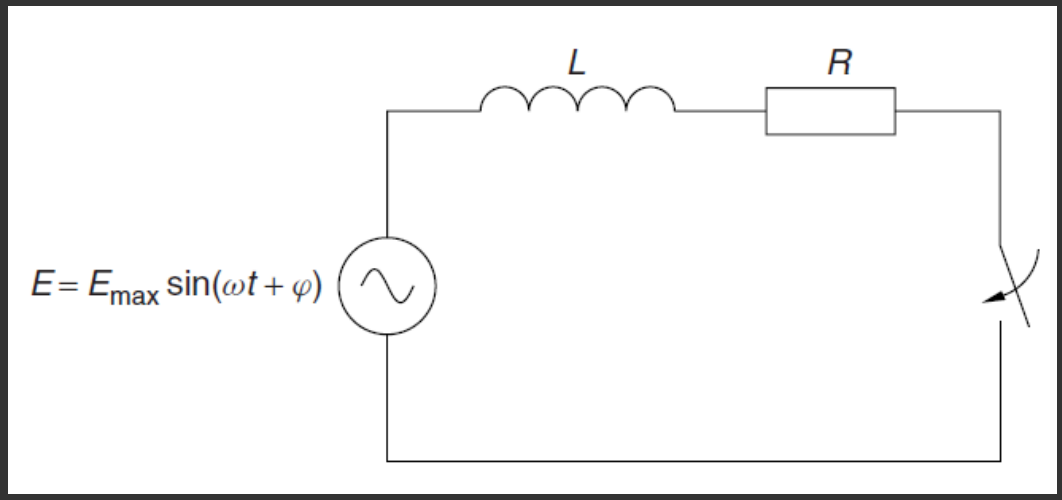
Example: Inductive switching transients occur when a reactive load, such as a motor, solenoid or relay coil, is switched off. The rapidly collapsing magnetic field induces a transient voltage across an inductive load's winding:

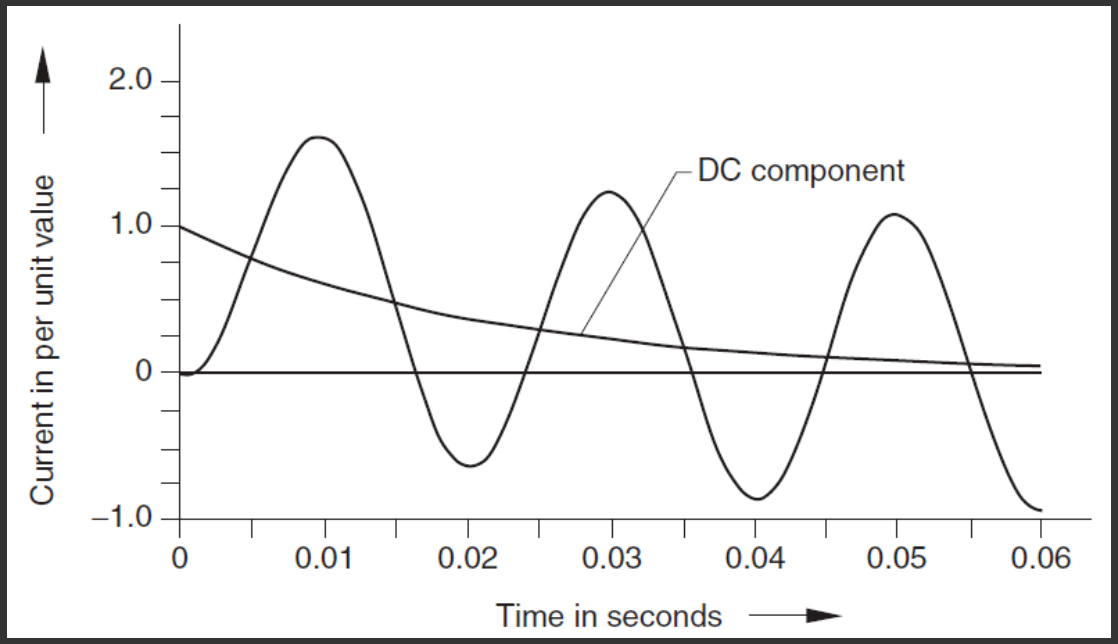
$$V = N (d\Phi/dt)$$

Transients

- Simple transient

$$E_{\max} \sin(\omega t + \varphi) = Ri + L\frac{\mathrm{d}i}{\mathrm{d}t}$$

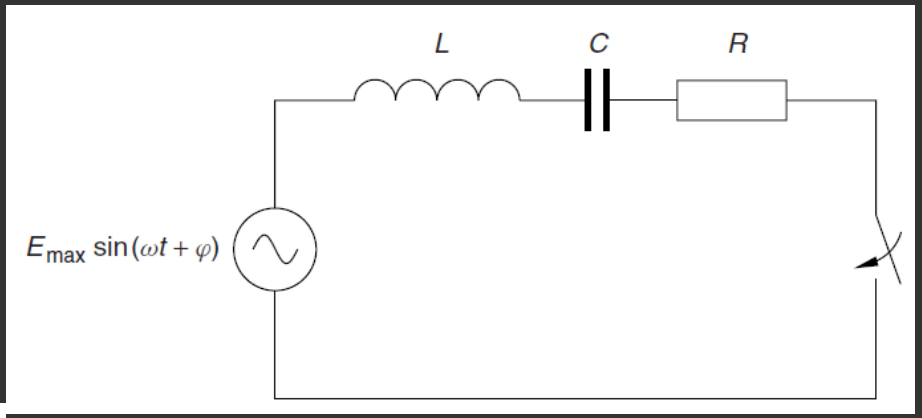


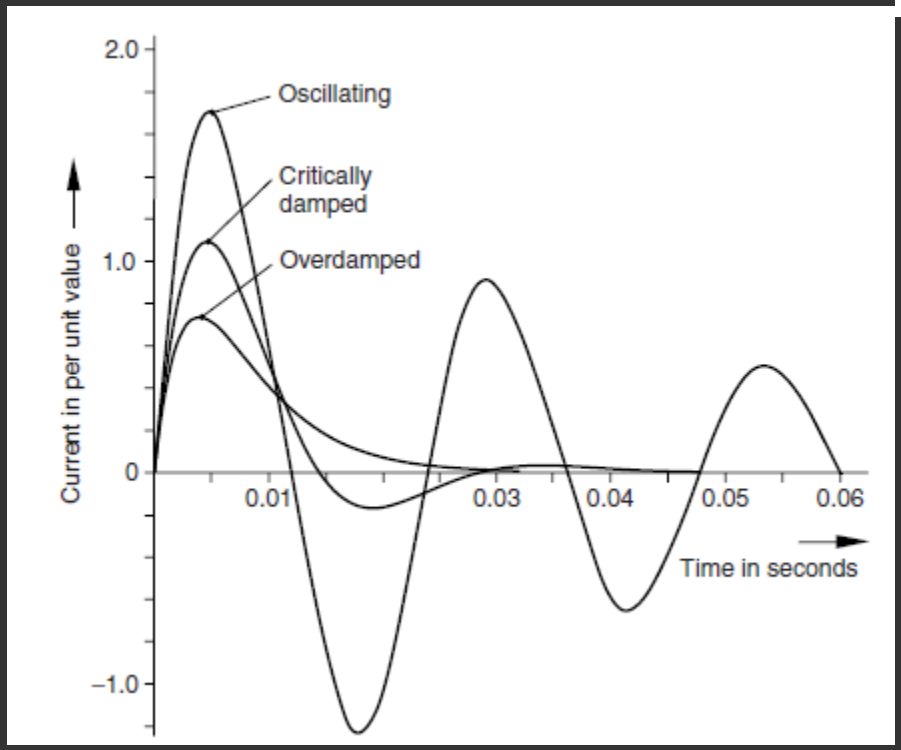


Transients

- Simple transient

$$E_{max}\sin(\omega t+\varphi)=L\frac{di}{dt}+Ri+\frac{1}{C}\int i\,dt$$



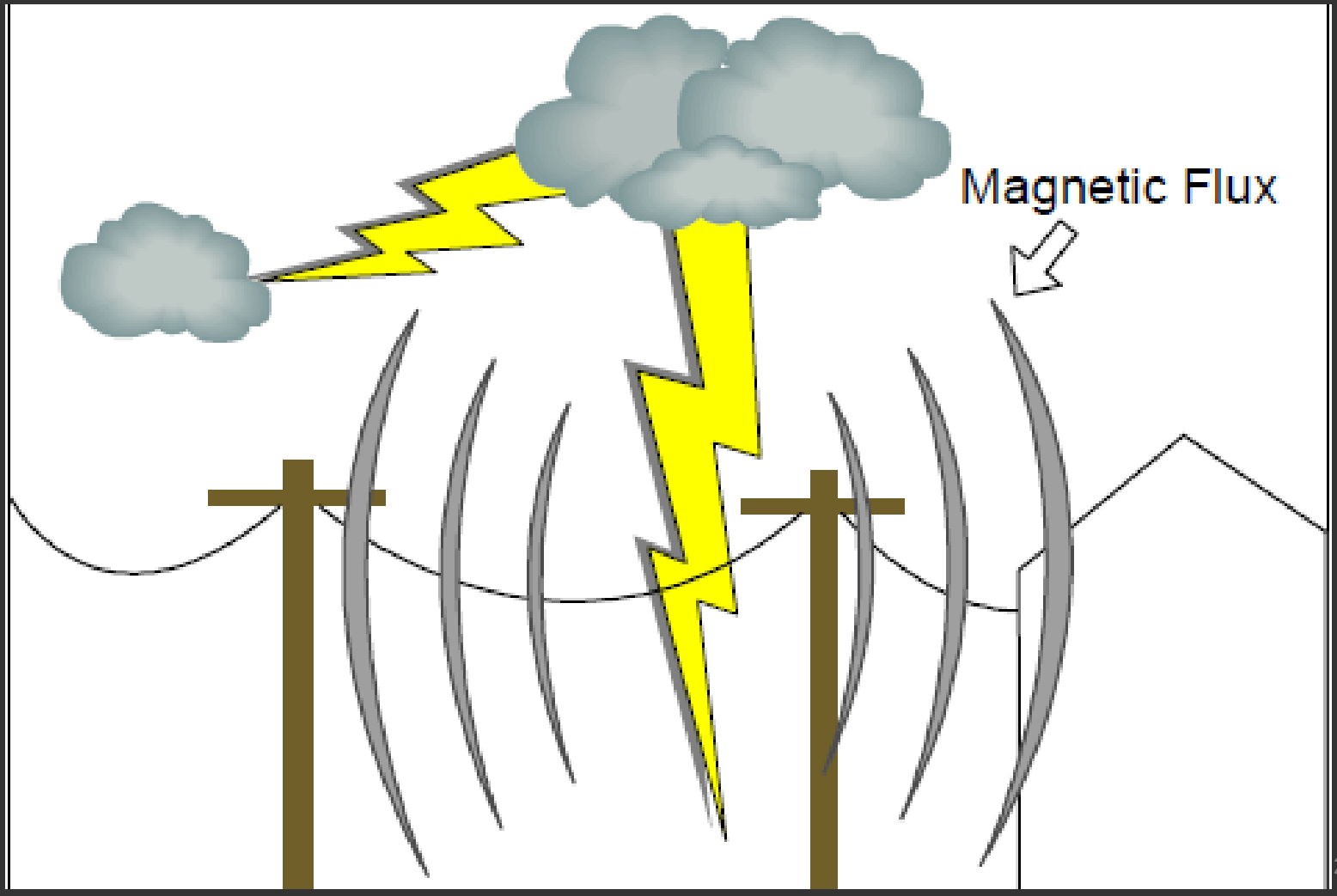


Transients

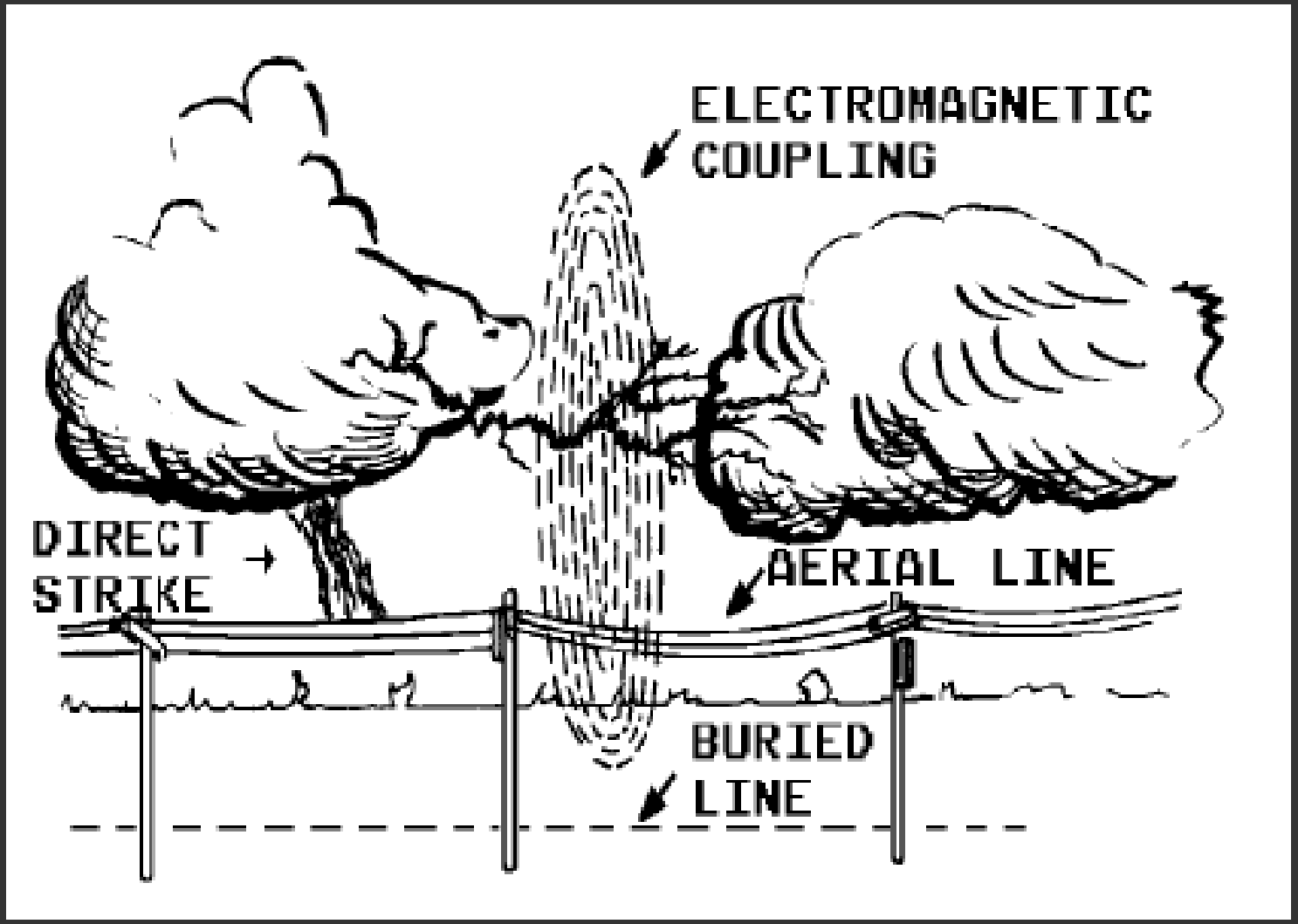
- An *impulsive transient* is a sudden change in the steady state condition of voltage, current, or both, that is unidirectional in polarity (primarily either positive or negative).

- Impulsive transients are normally characterized by their rise & decay times. For example, a 1.2 x50-s 2000-V impulsive transient nominally rises from zero to its peak value of 2000 V in 1.2 s & then decays to half its peak value in 50 s.

Transients

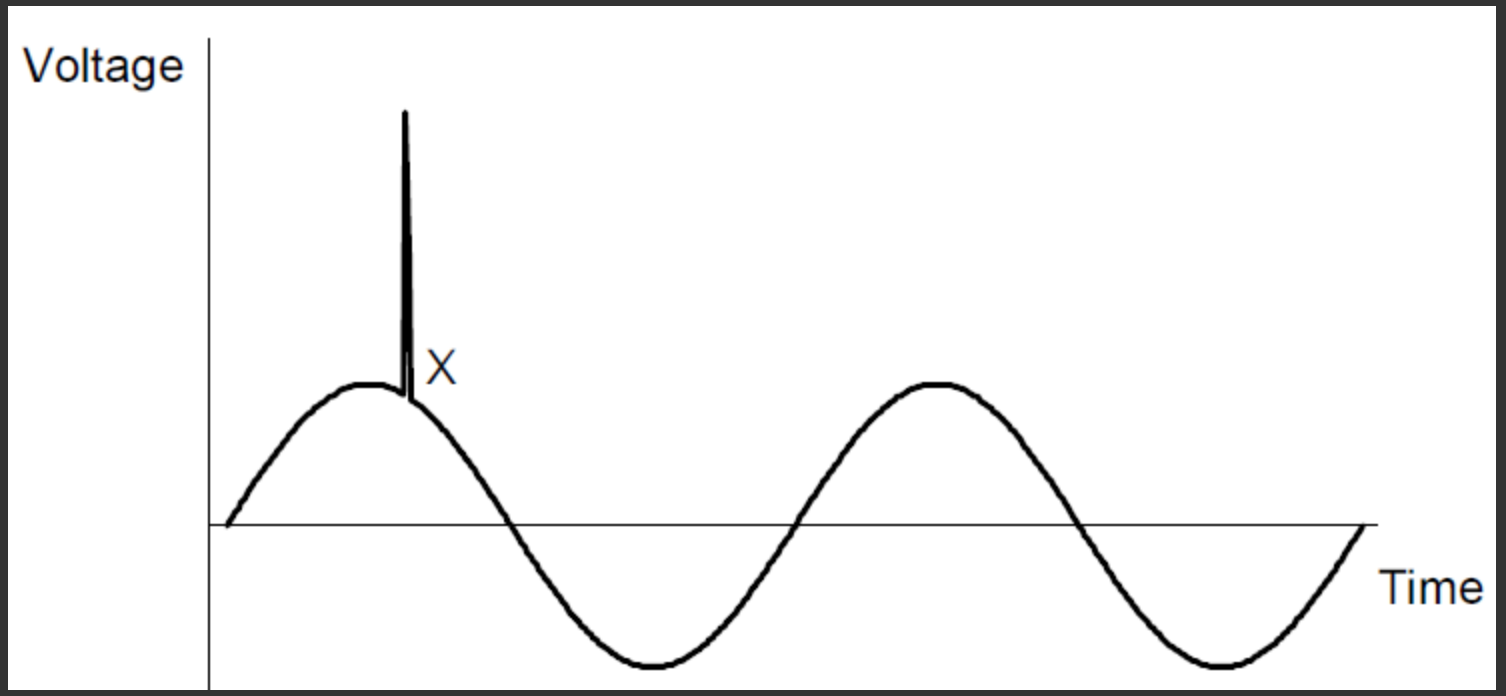


Lightning

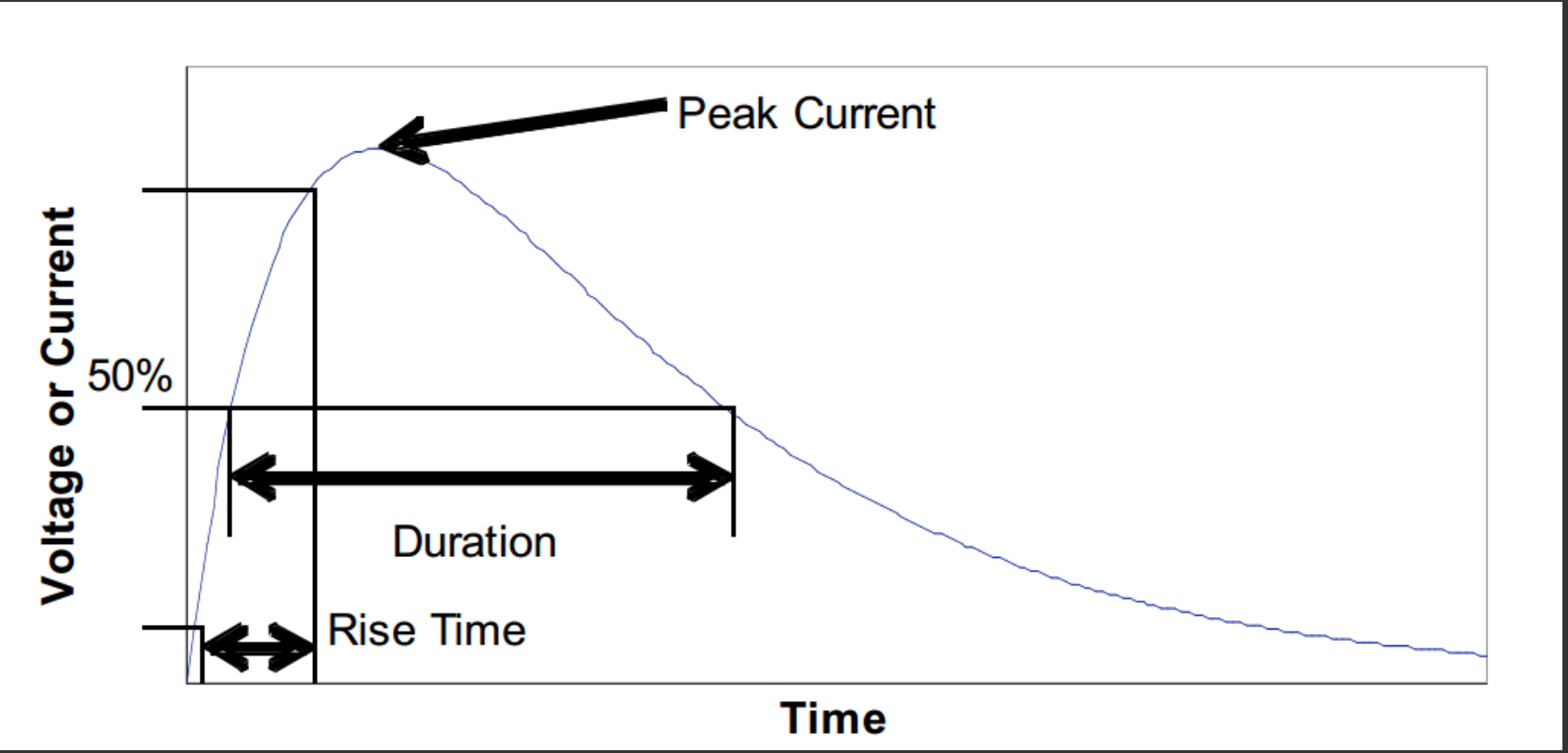

ELECTROMAGNETIC
COUPLING
DIRECT
STRIKE
AERIAL LINE
BURIED
LINE

Lightning

Figure shows a typical impulsive transient (at point X) occurring on a normal voltage waveform. The magnitude of such a transient can be many times larger than the peak value of the normal voltage waveform.



Lightning

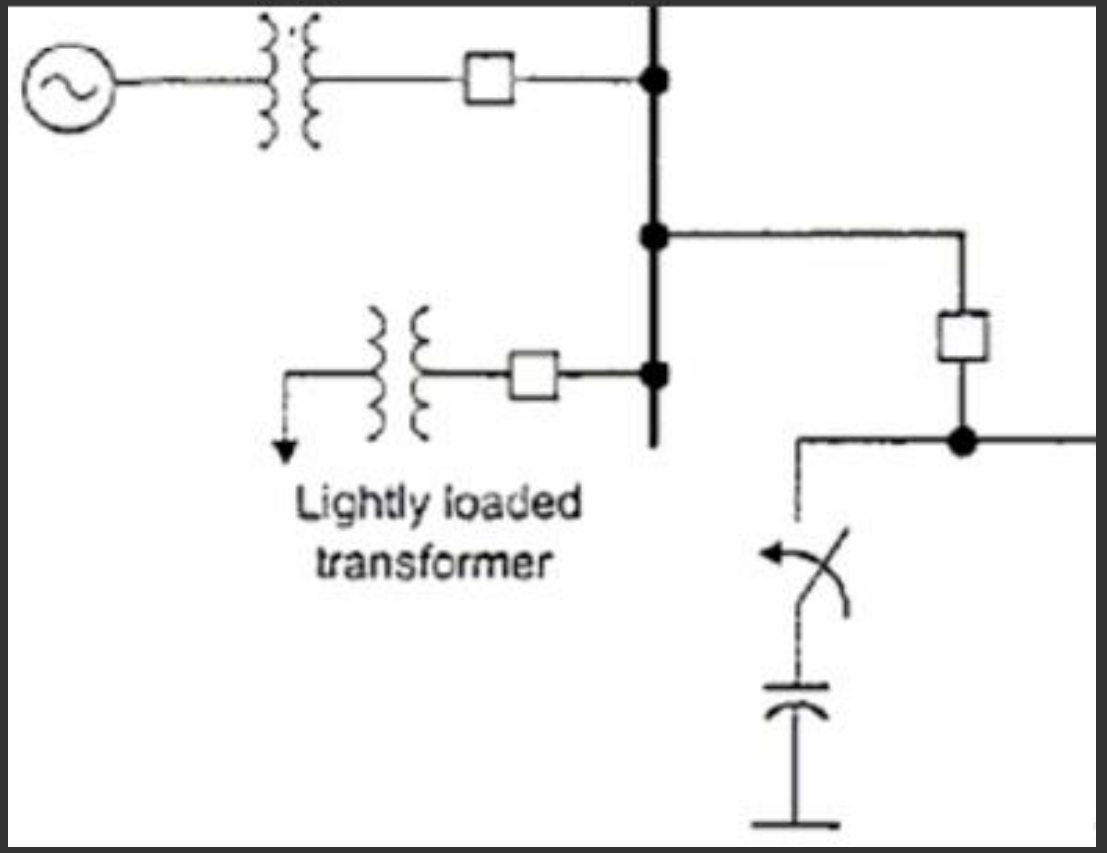


Oscillatory Transient

- An oscillatory transient is a brief, bidirectional variation in voltage, current, or both on a power line. These transients can occur due to resonances during switching.
- Capacitive or inductive load switching is the most common cause of oscillatory transient.
- Capacitor switching can cause resonant oscillations leading to an overvoltage some three to four times of the nominal rating, causing tripping or even damaging protective devices and equipment.

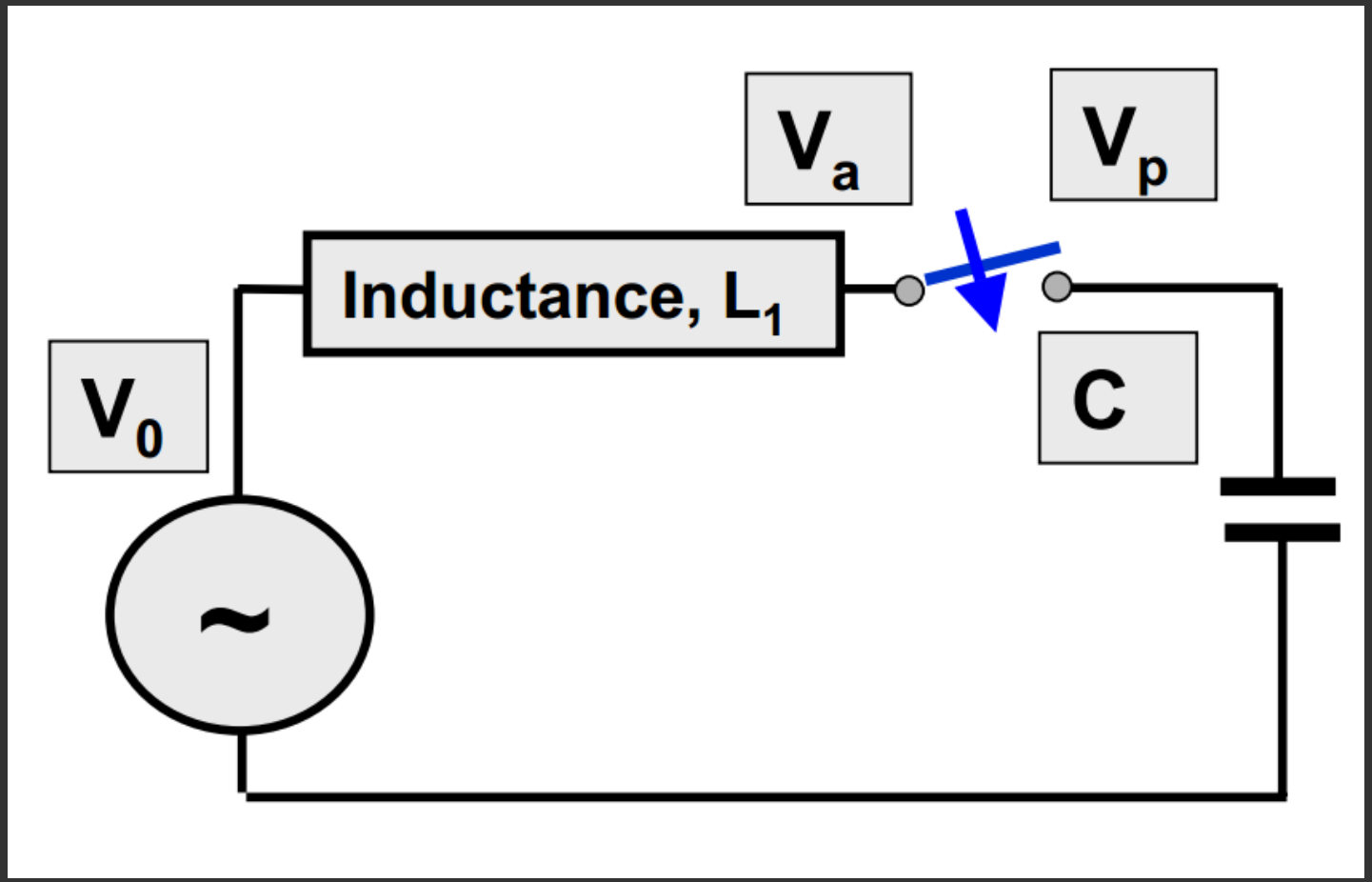
Oscillatory Transient

These transients occur when you turn off an inductive or capacitive load, such as a motor or capacitor bank.

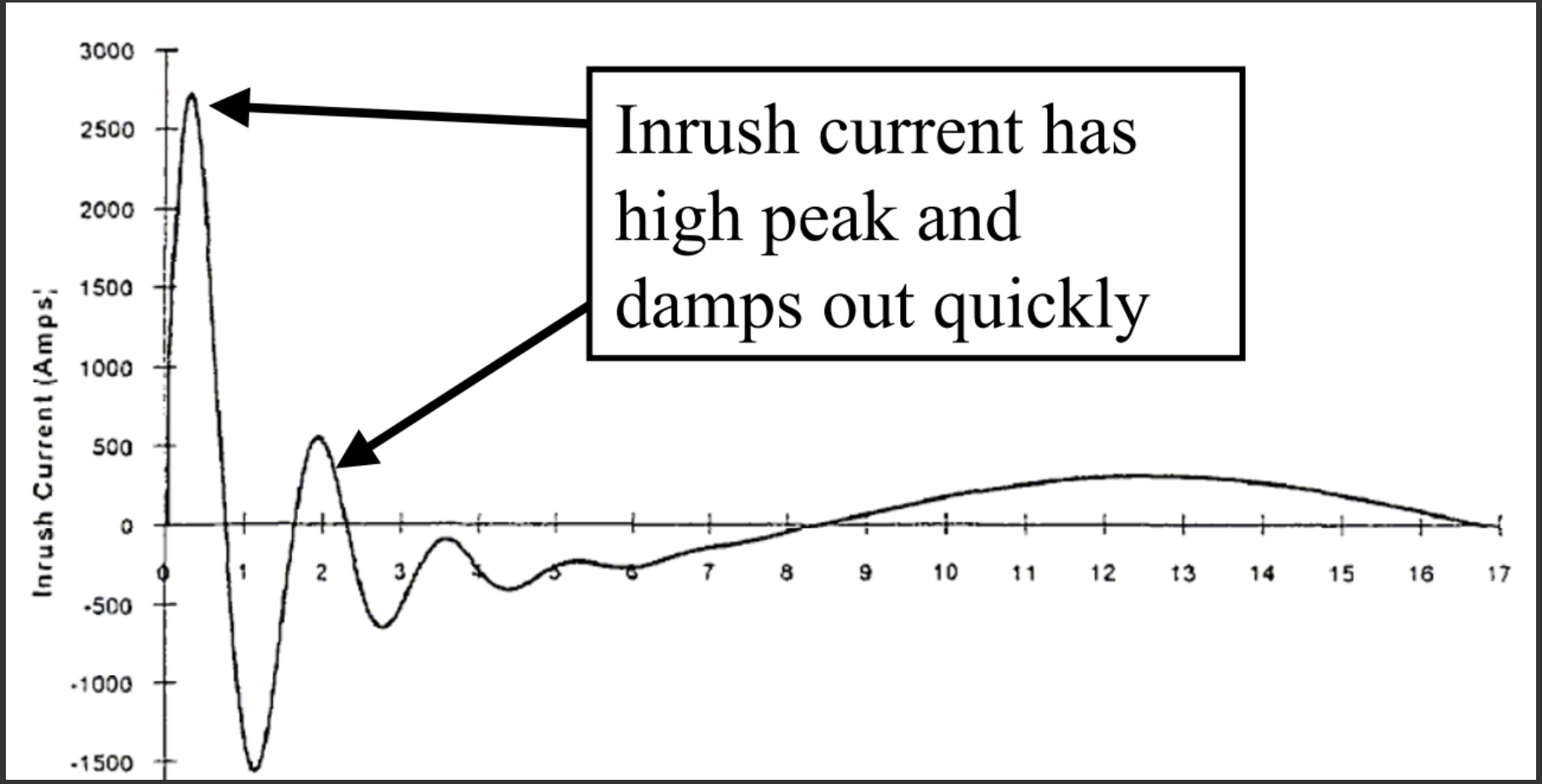


Oscillatory transient

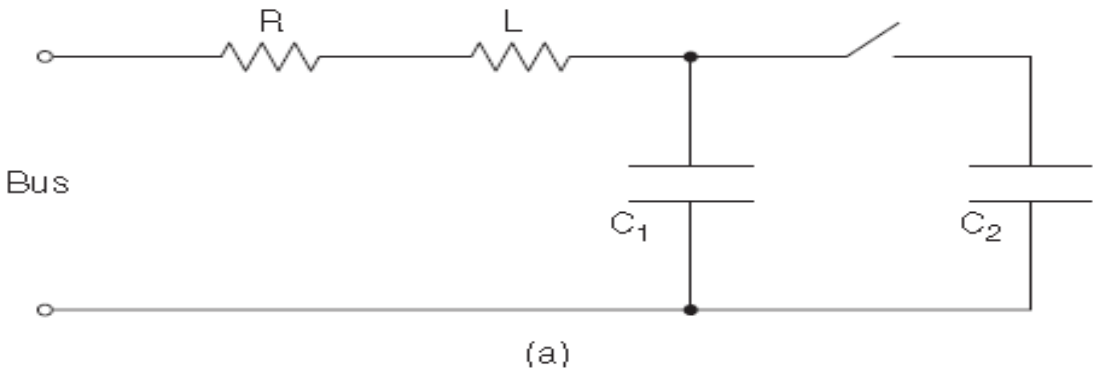
Inrush current flows in the circuit with the natural frequency of the circuit.



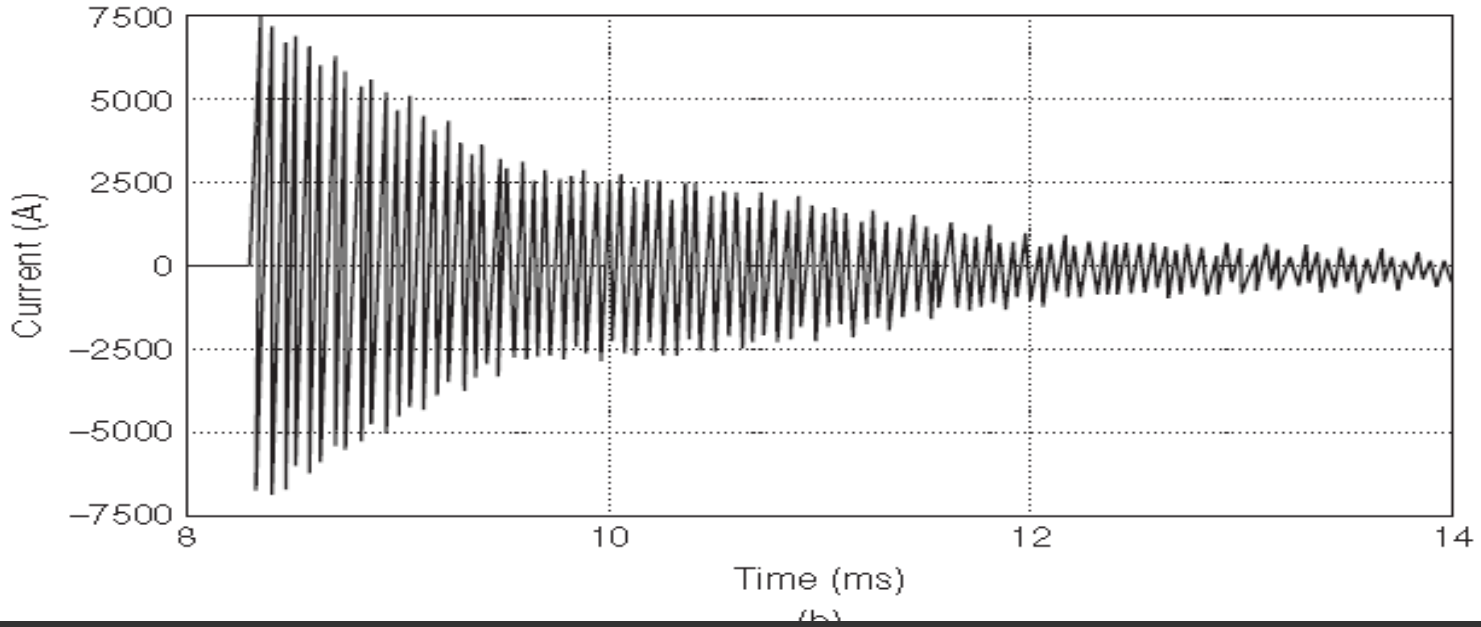
Oscillatory Transient



Oscillatory Transient



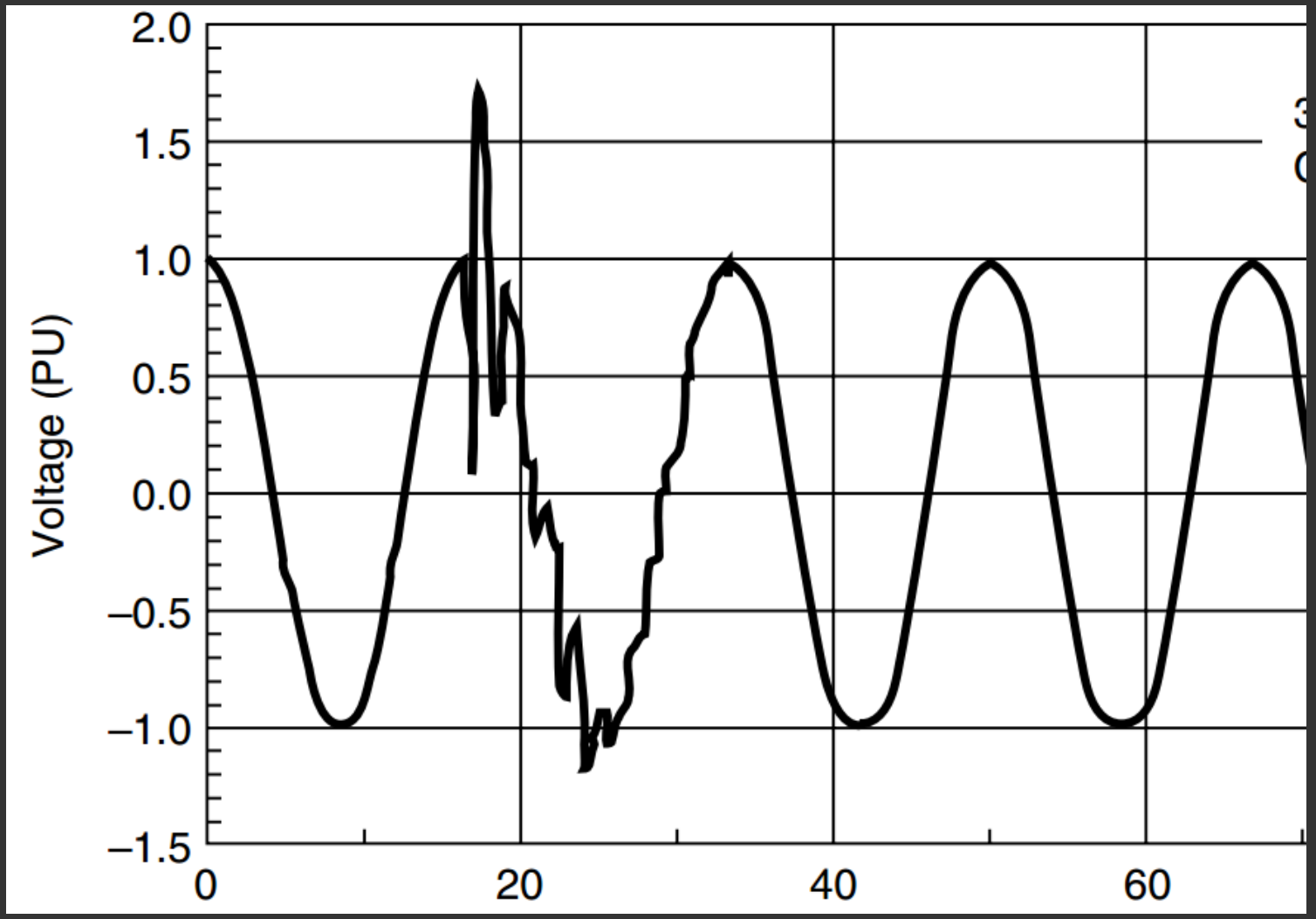
(a)



(b)

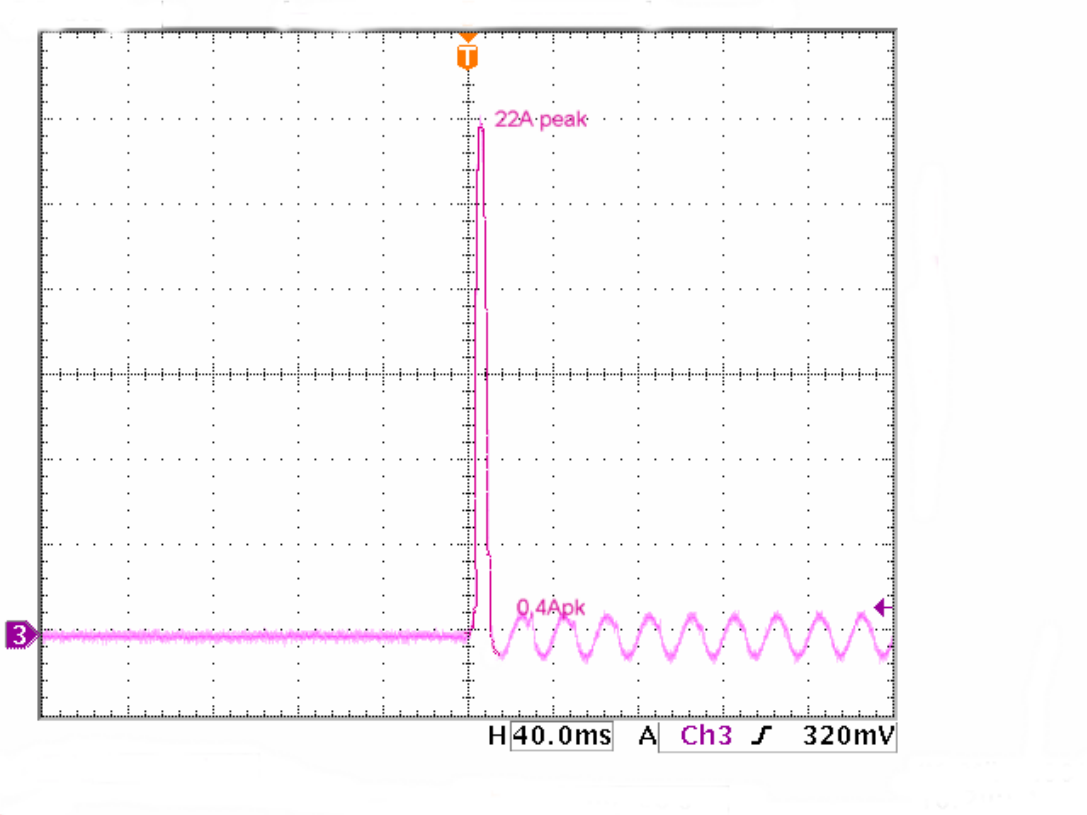
Oscillatory Transient

- Oscillatory transient during capacitor de-energizing



Oscillatory Transient

- When a transformer is first energized, a transient current up to 10 to 15 times the rated current can flow for several cycles.



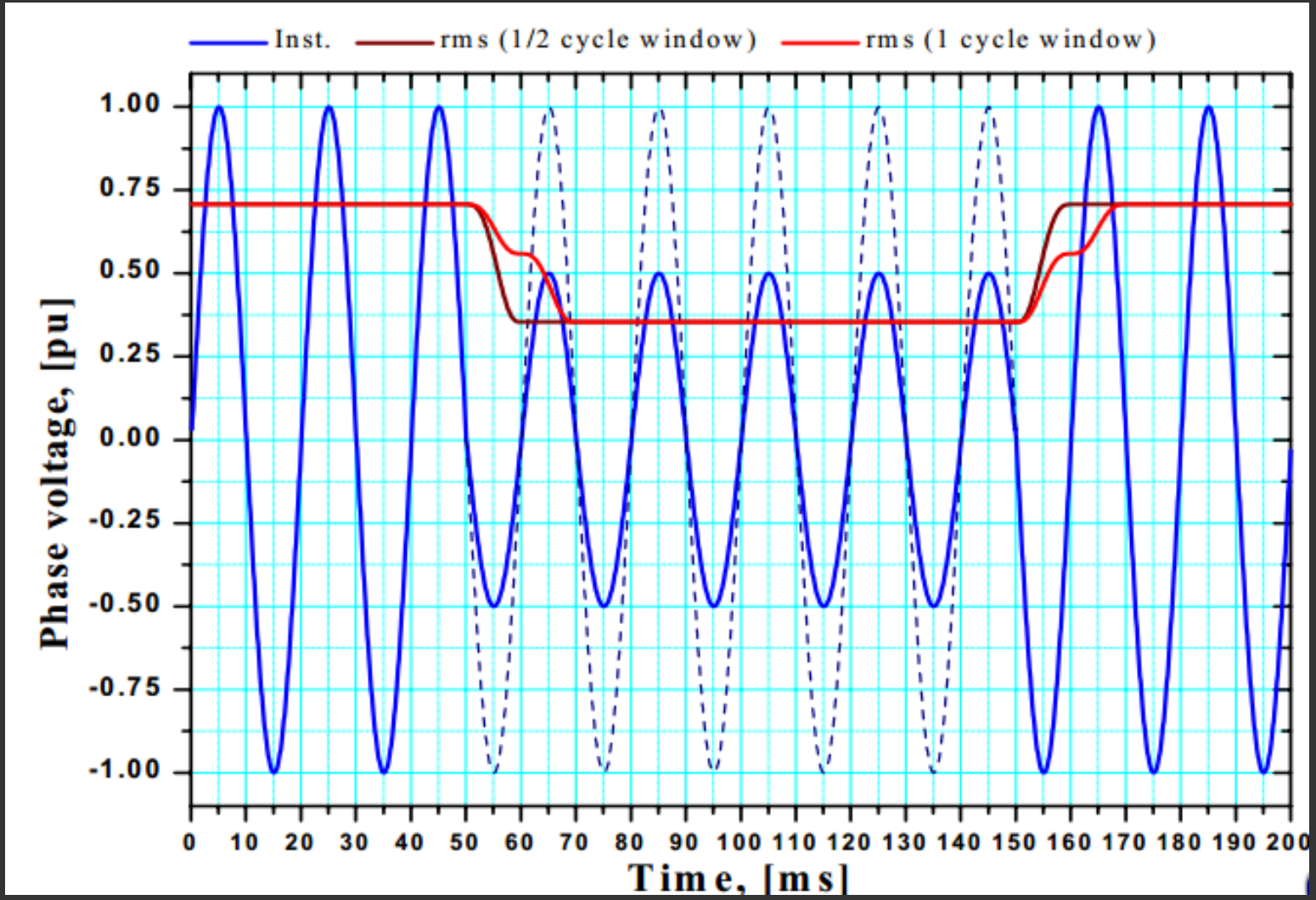
SHORT DURATION VOLTAGE VARIATIONS

- *A voltage sag is a short-duration (typically 0.5 to 30 cycles) reduction (below 90%)* in rms voltage caused by faults on the power system and the starting of large loads, such as motors.

- It is characterized by rms voltage variations outside the normal operating range of voltages.

SHORT DURATION VOLTAGE VARIATIONS

- Voltage sag



SHORT DURATION VOLTAGE VARIATIONS

Causes for voltage sag

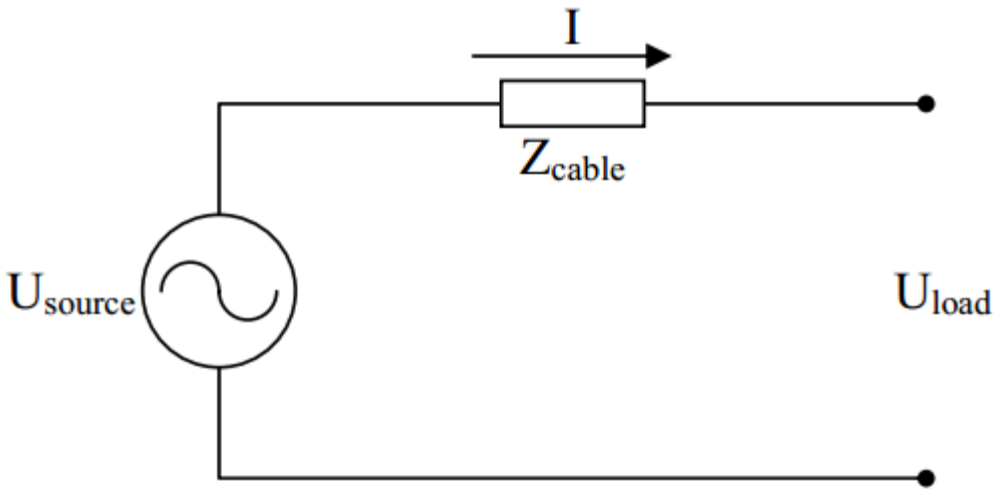
- Starting of an electric motor, which draws more current
- Faults in the power system
- Sudden increase of load connected

SHORT DURATION VOLTAGE VARIATIONS

Voltage sag

If a certain load draws a large current I, the voltage U_{load} will be lower than the source voltage because of the voltage drop across the grid impedance.

$$U_{load} = U_{source} - Z_{cable} \cdot I$$



SHORT DURATION VOLTAGE VARIATIONS

Voltage sag

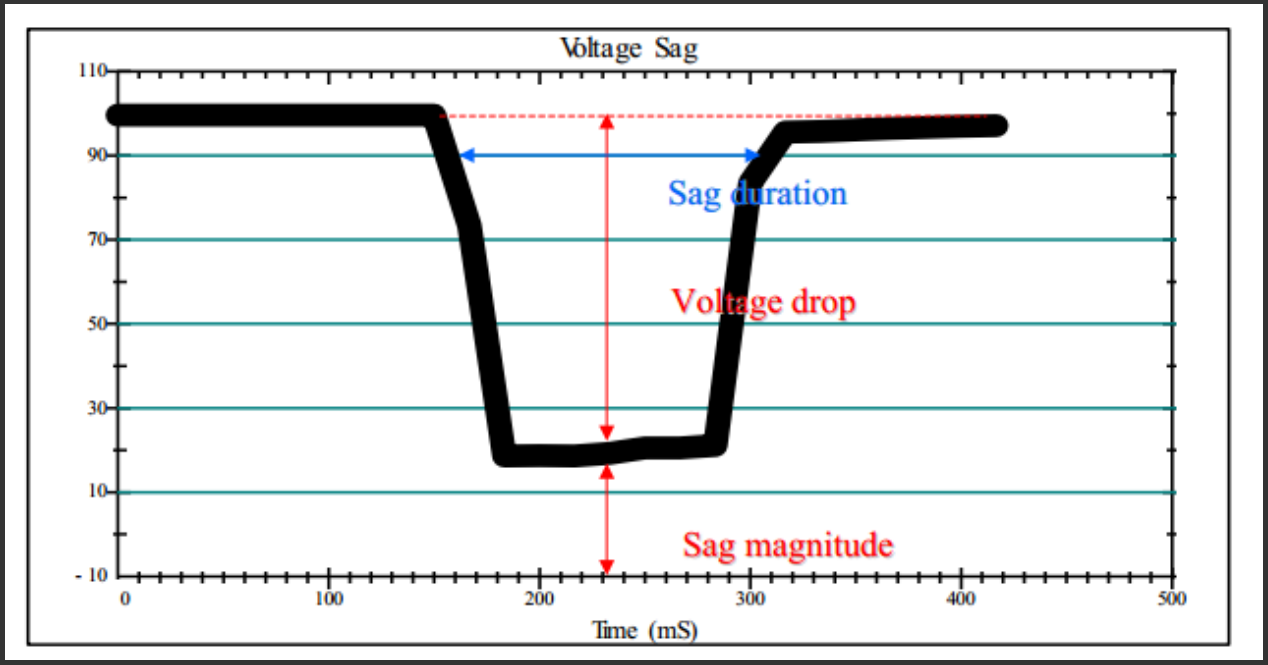
Thus, excessive currents, combined with the grid impedance, result in voltage dips.

SHORT DURATION VOLTAGE VARIATIONS

Voltage sag

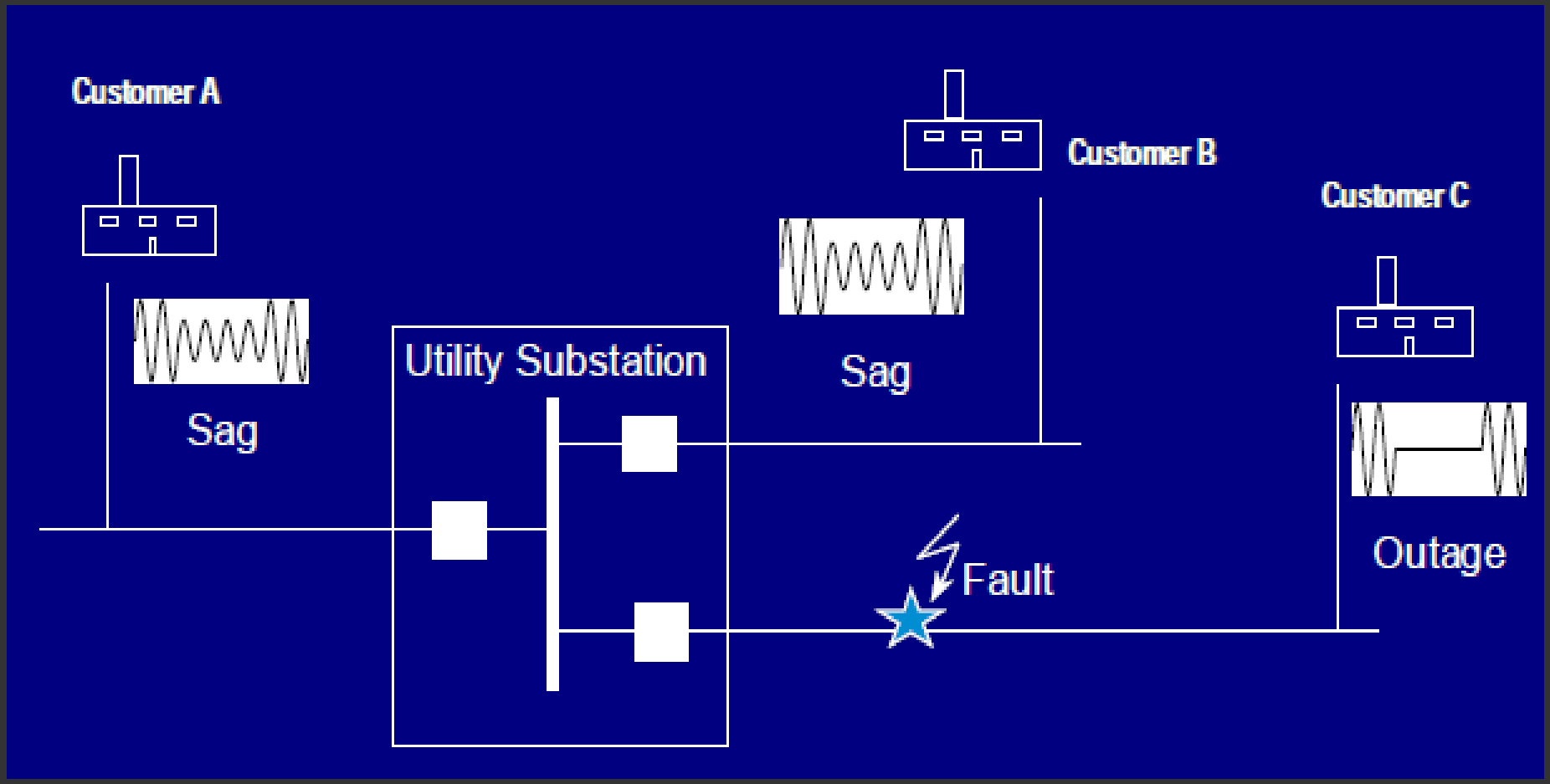
Main characteristics:

- Sag magnitude (remaining voltage in pu during sag)
- Duration of the sag



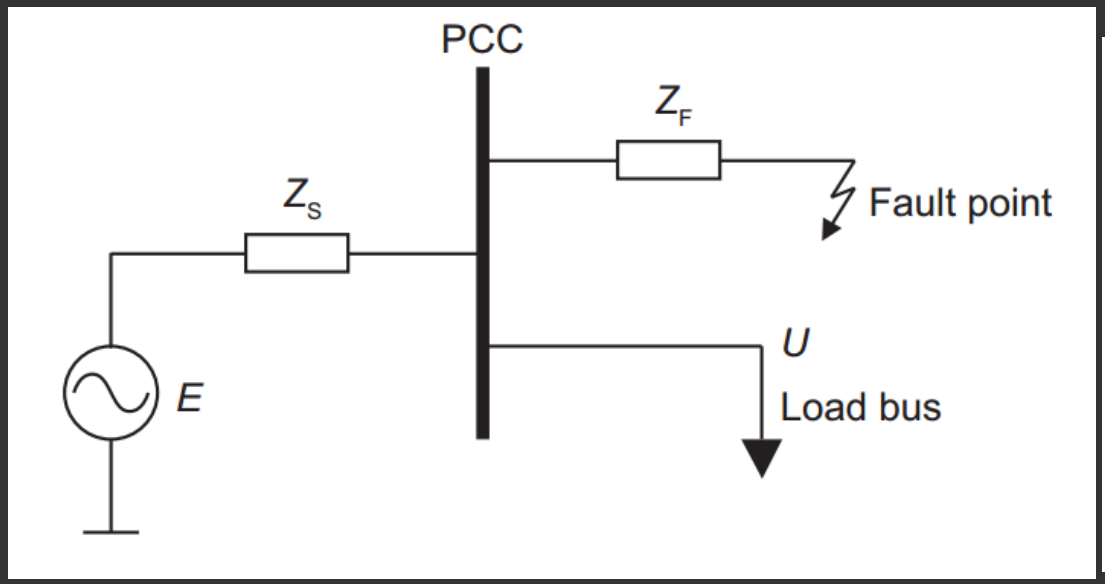
SHORT DURATION VOLTAGE VARIATIONS

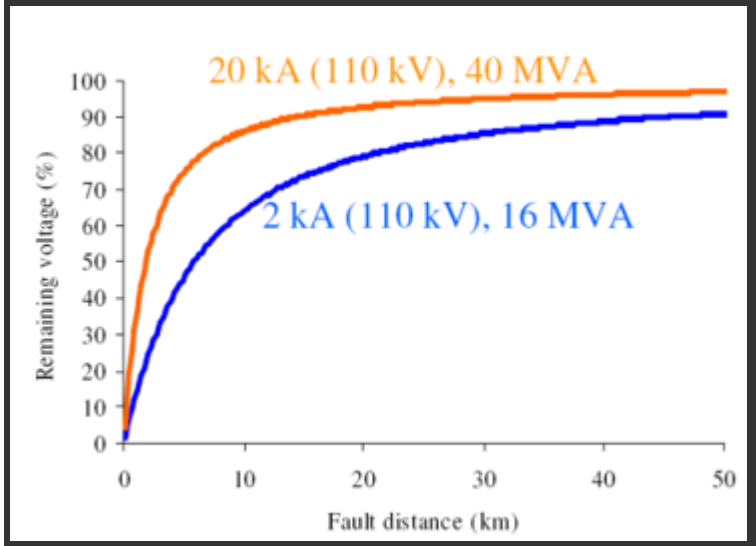
Voltage sag



SHORT DURATION VOLTAGE VARIATIONS

Voltage sag





$$U_{pcc} = Usag = E\frac{Z_F}{Z_s + ZF}$$

The dip magnitude during a fault is dependent on two impedances, the source impedance, *Z*s, and the impedance to the fault, Z_F.

SHORT DURATION VOLTAGE VARIATIONS

Voltage sag

Consequences of voltage dips:

- The torque of an induction machine is proportional to the square of the voltage. The whole production line risks to stop.
- A dip lasting seconds causes data loss, communication equipments.
- Lamps shine more weakly during the dip.

SHORT DURATION VOLTAGE VARIATIONS

- Voltage rises (swells)*: temporary increase in RMS value of AC voltage with the magnitude between 110% and 180% of the rated voltage.*
- As with sags, swells are usually associated with system fault conditions, but they are not as common as voltage sags.

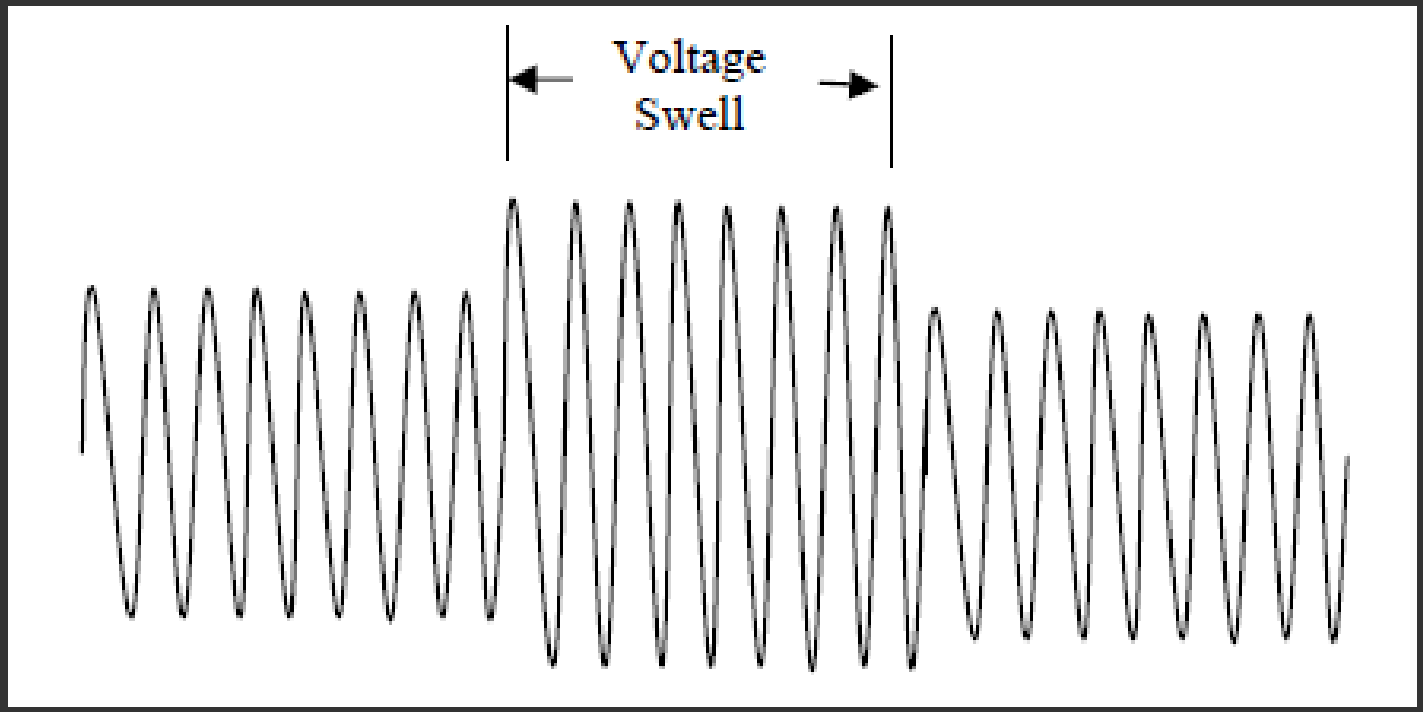
SHORT DURATION VOLTAGE VARIATIONS

Causes for voltage swells*:*

- De-energization of large load
- Energization of a capacitor bank
- Abrupt interruption of current
- Change in ground reference on ungrounded phases

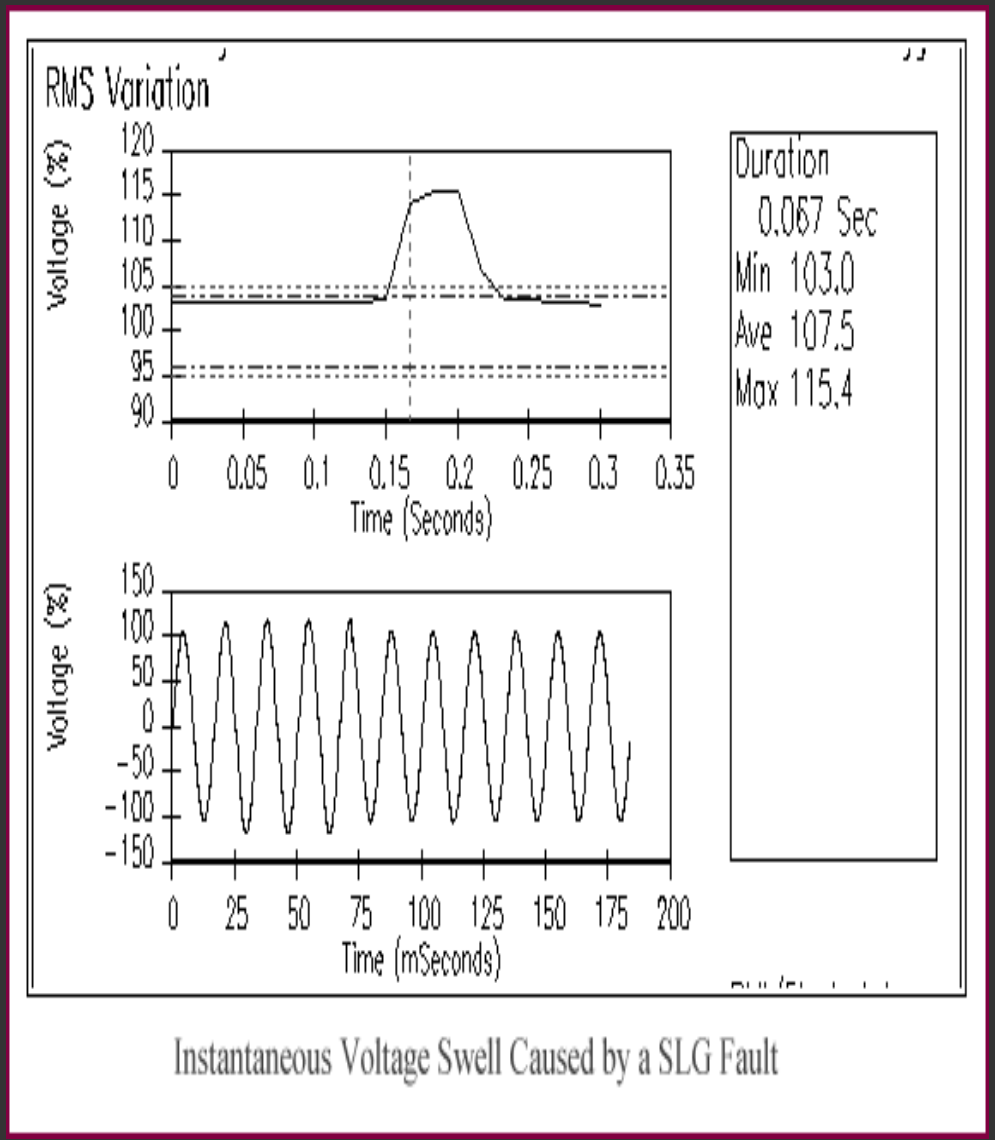
SHORT DURATION VOLTAGE VARIATIONS

- Voltage Swell

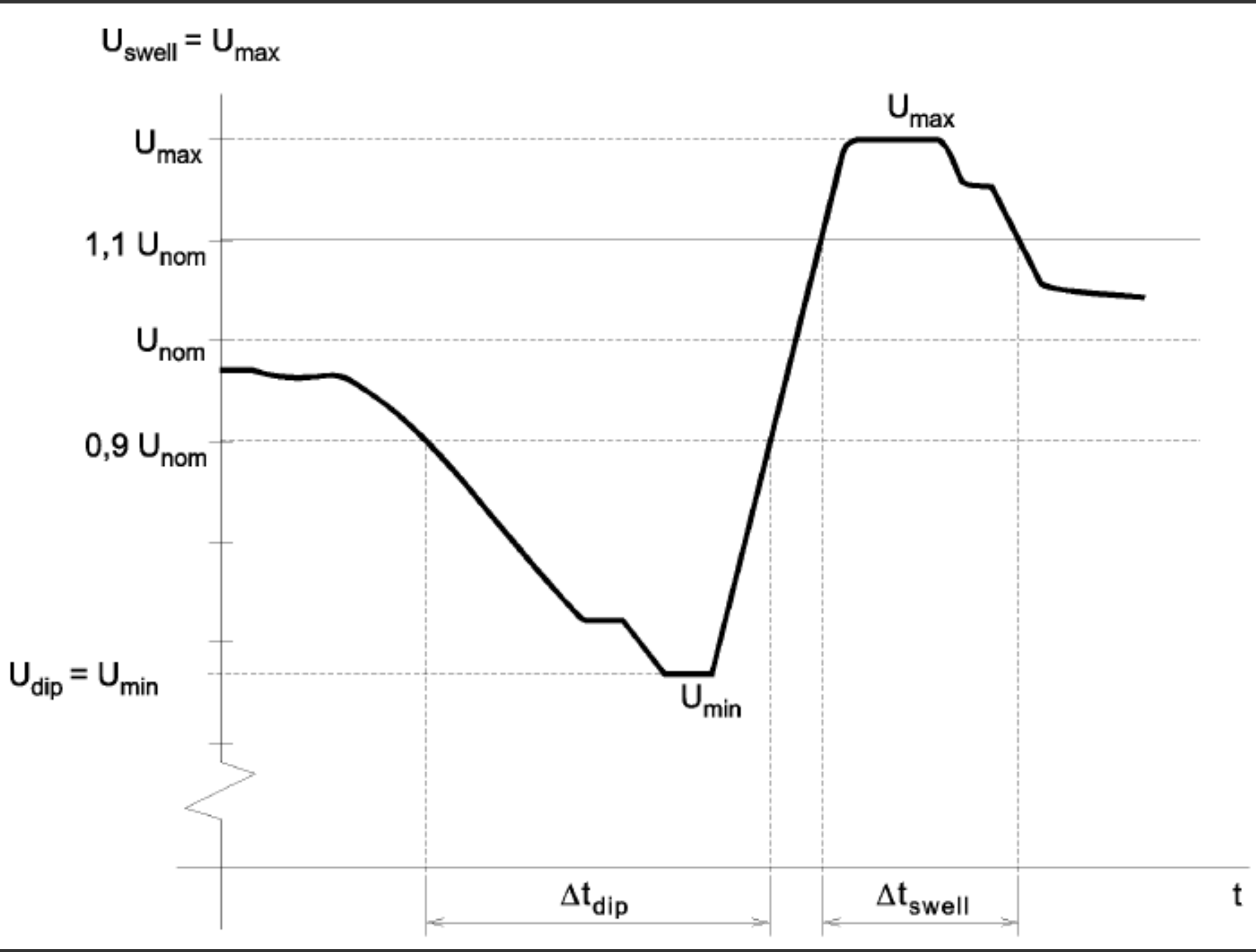


SHORT DURATION VOLTAGE VARIATIONS

- A *swell* is defined as an increase to between 1.1 pu and 1.8 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to one minute.



Instantaneous Voltage Swell Caused by a SLG Fault

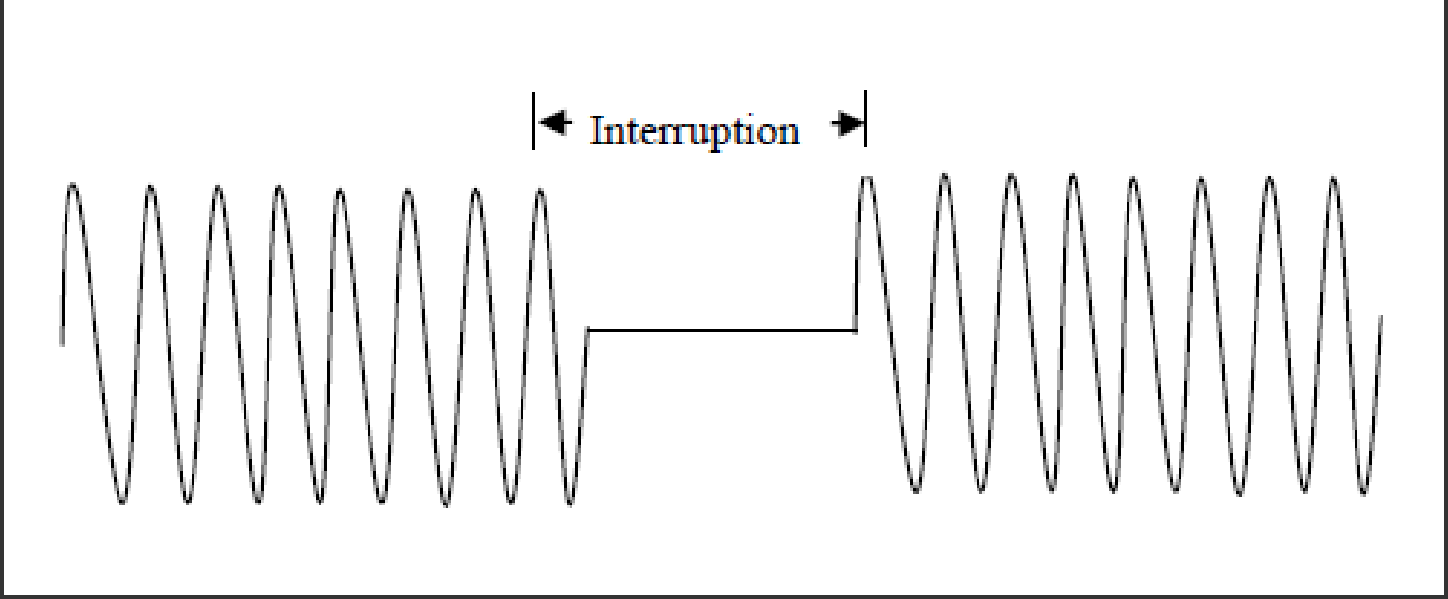

$U_{swell} = U_{max}$
U_{max}
$1{,}1\ U_{nom}$
U_{nom}
$0{,}9\ U_{nom}$
$U_{dip} = U_{min}$
U_{max}
U_{min}
Δt_{dip}
Δt_{swell}
t

SHORT DURATION VOLTAGE VARIATIONS

- Interruptions (< 1min): Disappearance of the supply voltage in all phases by some definitions also defined as in “..one or more phases”. Usually qualified by an additional term indicating the voltage drop or values depend on standard.
- Short interruptions:
  - IEEE = Un < 90% duration from 20 ms to 1 minute.

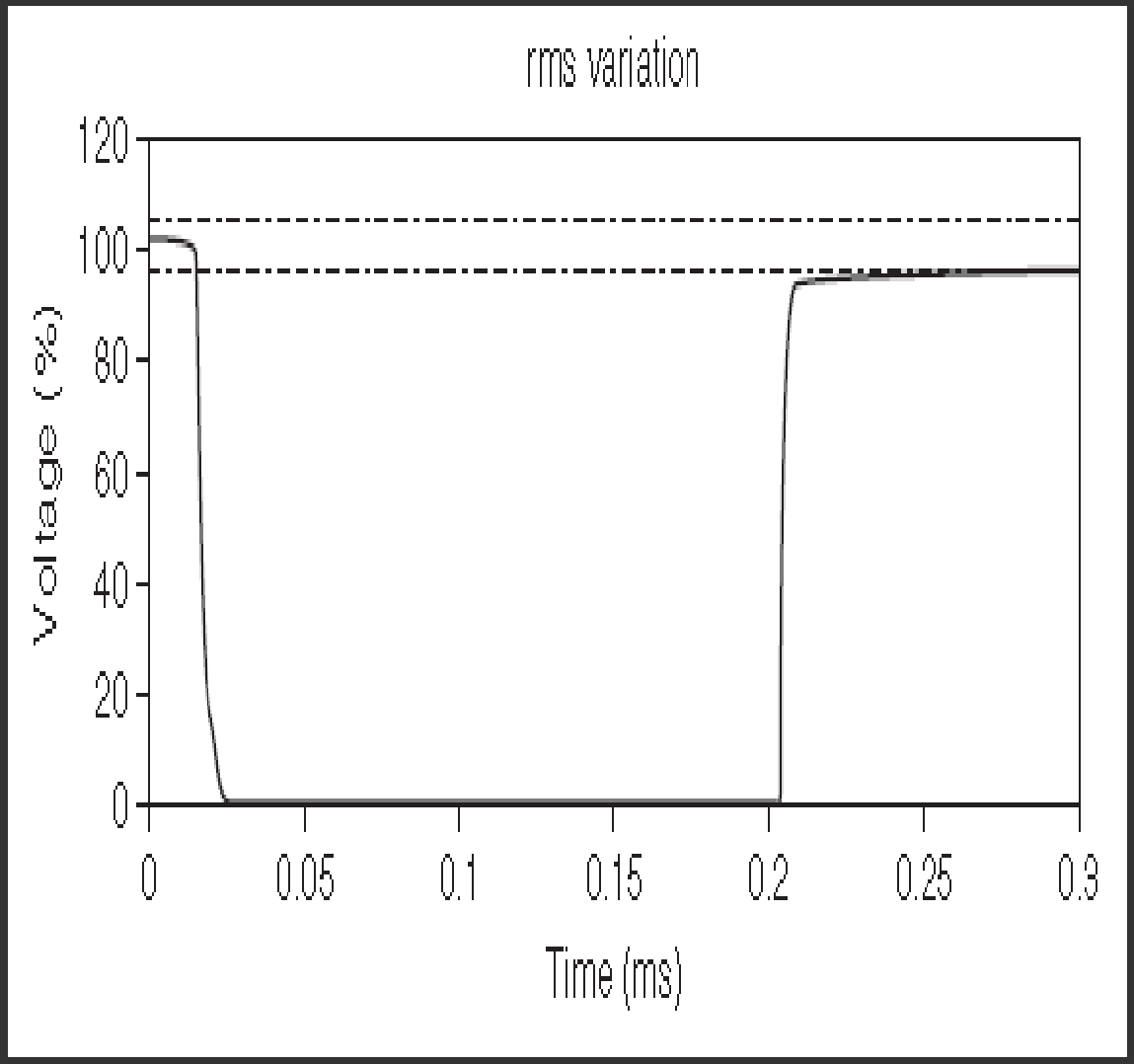
SHORT DURATION VOLTAGE VARIATIONS

Interruptions



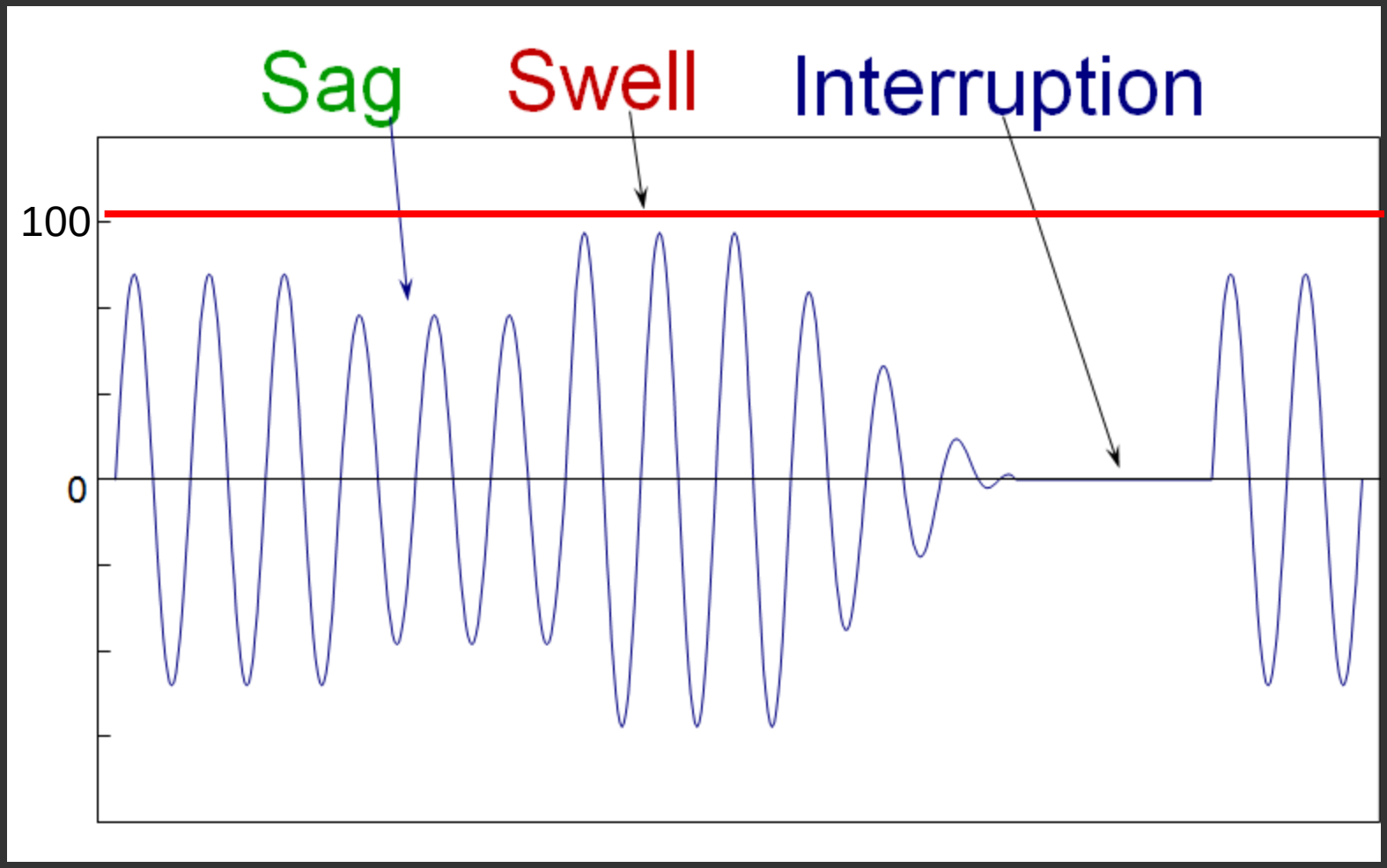
SHORT DURATION VOLTAGE VARIATIONS

- An interruption is defined as a reduction in line-voltage or current to less than 10 percent of nominal, not exceeding 60 seconds in length.



SHORT DURATION VOLTAGE VARIATIONS

RMS Voltage Variations



LONG DURATION VOLTAGE VARIATIONS

Long Duration Variations encompass rms deviations at power frequencies for longer than one minute. Long duration variations can be:

- Undervoltages
- Overvoltages
- Sustained interruptions

Overvoltages and undervoltages generally are caused by load variations on the system and system switching operations. Such variations are typically displayed as plots of rms voltage versus time.

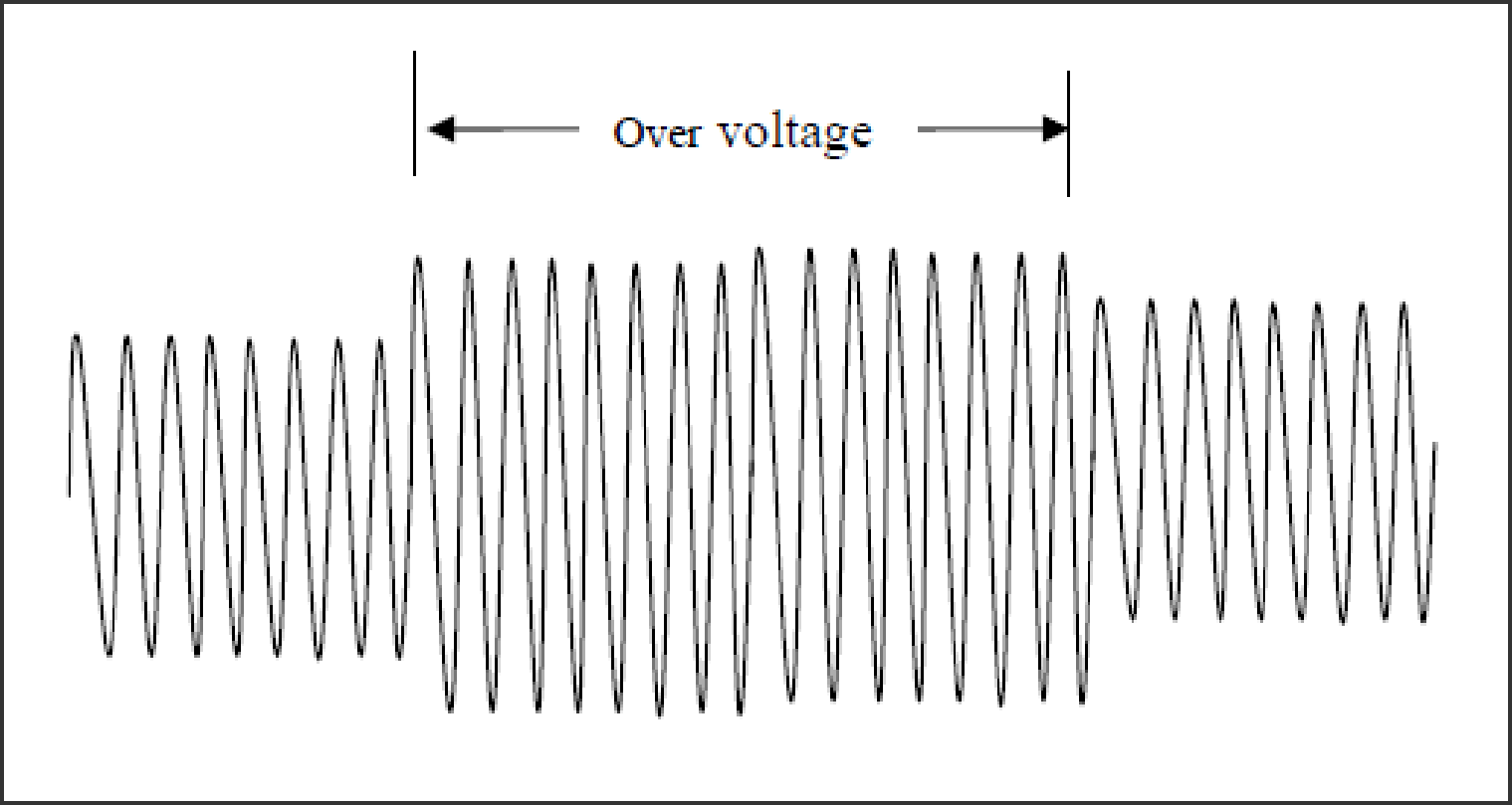
LONG DURATION VOLTAGE VARIATIONS

Overvoltage

- An *overvoltage* is an increase in the rms ac voltage greater than 110% at the power frequency for a duration longer than 1 minute.
- Overvoltages are usually the result of load switching (e.g., switching off a large load), or energizing a capacitor bank.
- An overvoltages might result due to inadequate voltage controls.
- Incorrect tap settings on transformers can also result in system overvoltages.

LONG DURATION VOLTAGE VARIATIONS

- Overvoltage



LONG DURATION VOLTAGE VARIATIONS

Undervoltage: is a decrease in the rms ac voltage to less than 90% at the power frequency for a duration longer than 1 minute.

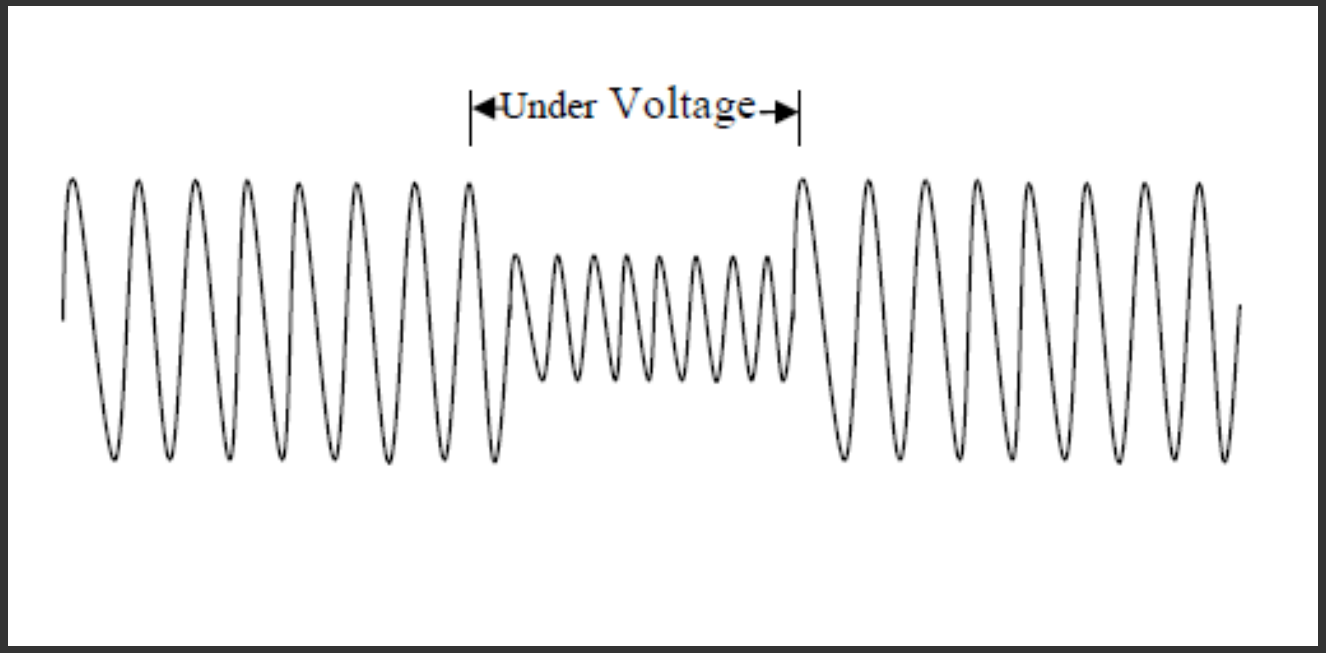
A load switching on or a capacitor bank switching off can cause an undervoltage until voltage regulation equipment on the system can bring the voltage back to within tolerances.

Overloaded circuits can result in undervoltages also.

The term *brownout* is often used to describe sustained periods of undervoltage.

LONG DURATION VOLTAGE VARIATIONS

Undervoltage: A larger load indeed produces a larger current. This current successively causes a larger voltage drop in the grid (law of Ohm), resulting in a lower voltage on the consumer side.



LONG DURATION VOLTAGE VARIATIONS

Sustained Interruptions: disappearance of the supply voltage in all phases by some definitions also defined as in"...one or more phases" for a period of time in excess of 1 minute, the long duration voltage variation is considered a *sustained interruption*.

Voltage interruptions longer than one minute are often permanent and require human intervention to repair the system for restoration.

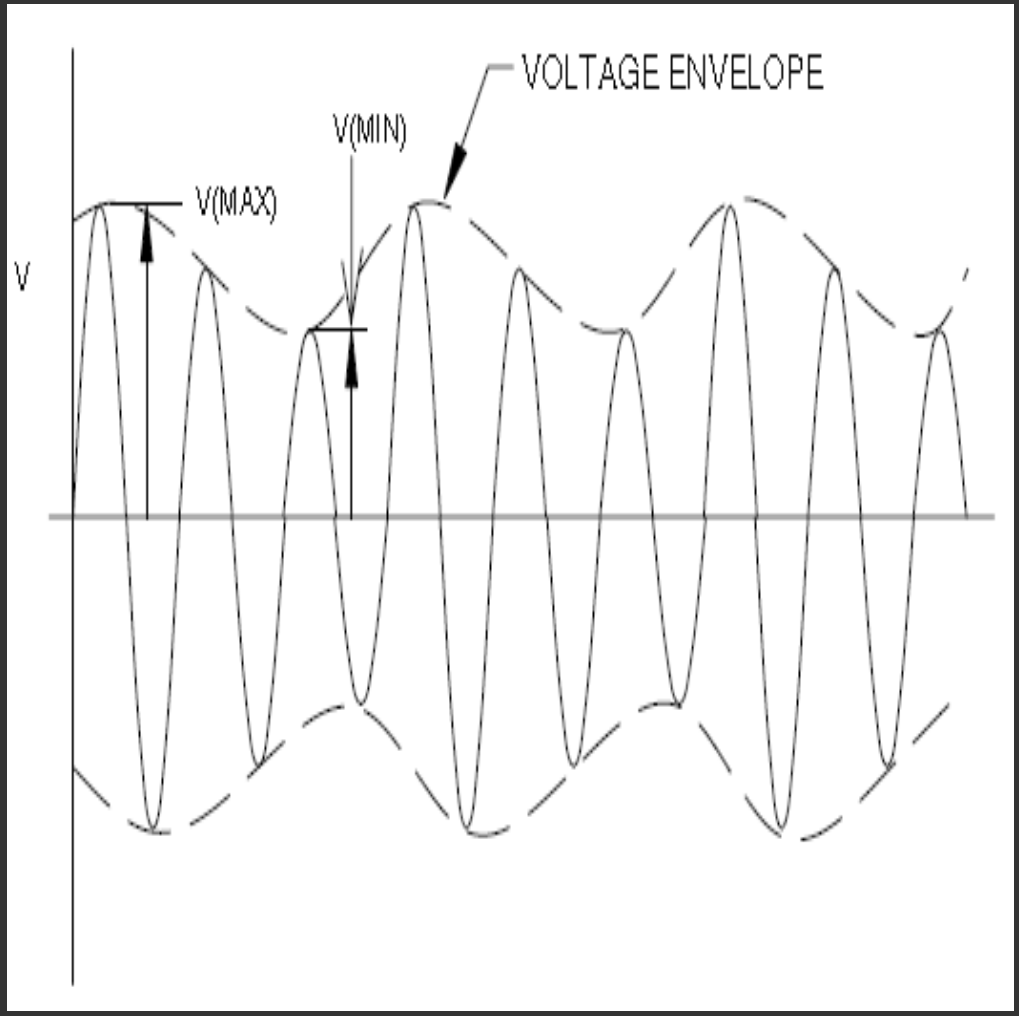
Long interruptions:

- IEEE = - Un < 90% for duration > 1 minute.

Voltage Fluctuations and Flicker

- **VOLTAGE FLUCTUATIONS** are systematic variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not normally exceed the voltage ranges specified by ANSI of 0.9 pu to 1.1 pu.
- Voltage fluctuations are relatively small (less than 5 percent) variations in the rms line-voltage that can cause voltage variations.
- Loads which can exhibit continuous, rapid variations in the load current magnitude can cause voltage variations that are often referred to as flicker.
- The term flicker is derived from the impact of the voltage fluctuation on lamps such that they are perceived to flicker by the human eye.

Voltage Fluctuations and Flicker



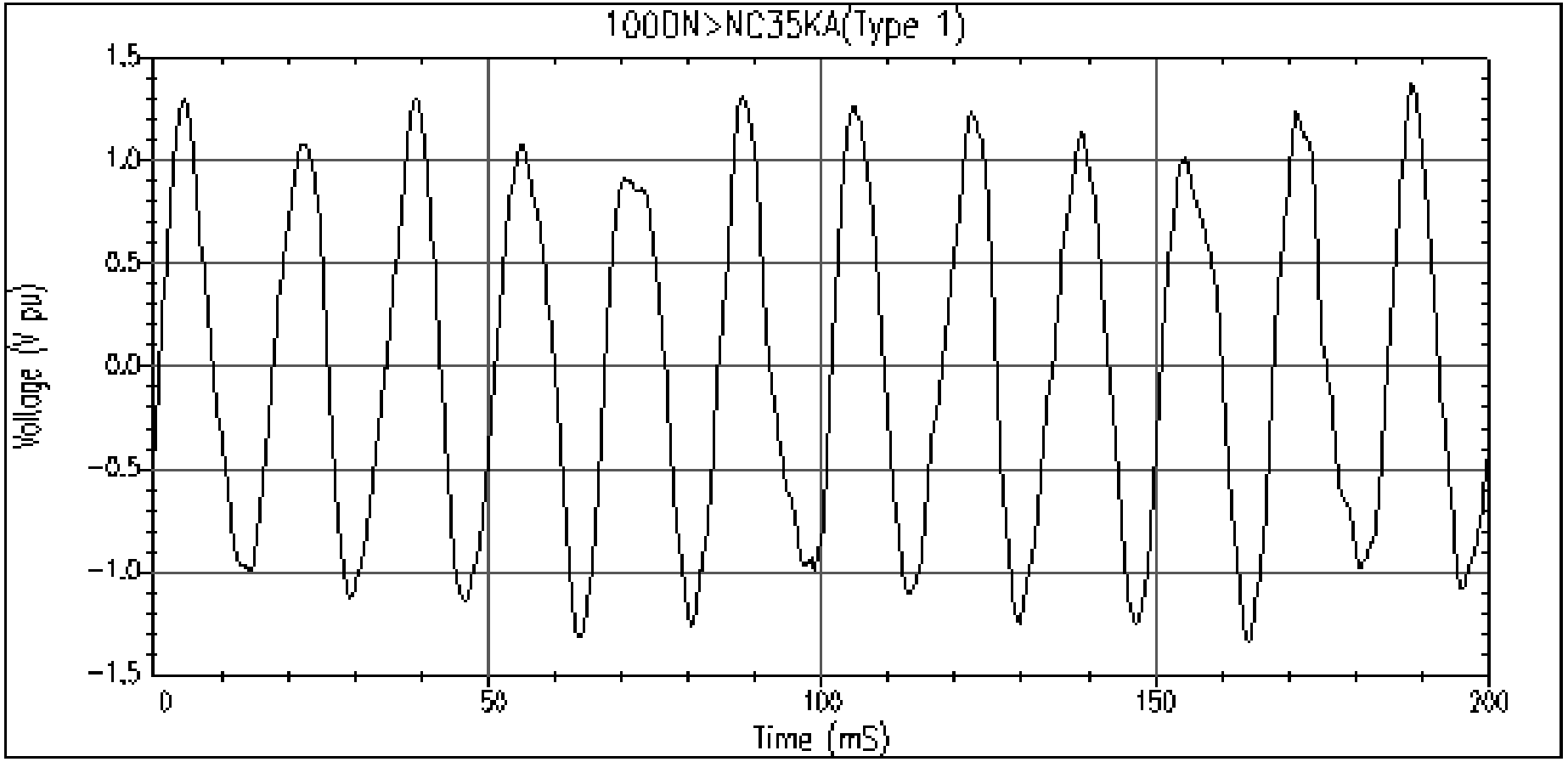
The envelope of the change in voltage represents the flicker content of the voltage. The rate at which the voltage changes is the flicker frequency.

$$\Delta V = V_{max} - V_{min}$$

$$V_{nom} = \text{average voltage} = (V_{max} + V_{min})/2$$

$$f = 2 \times (V_{max} - V_{min}) \times 100/(V_{max} + V_{min})$$

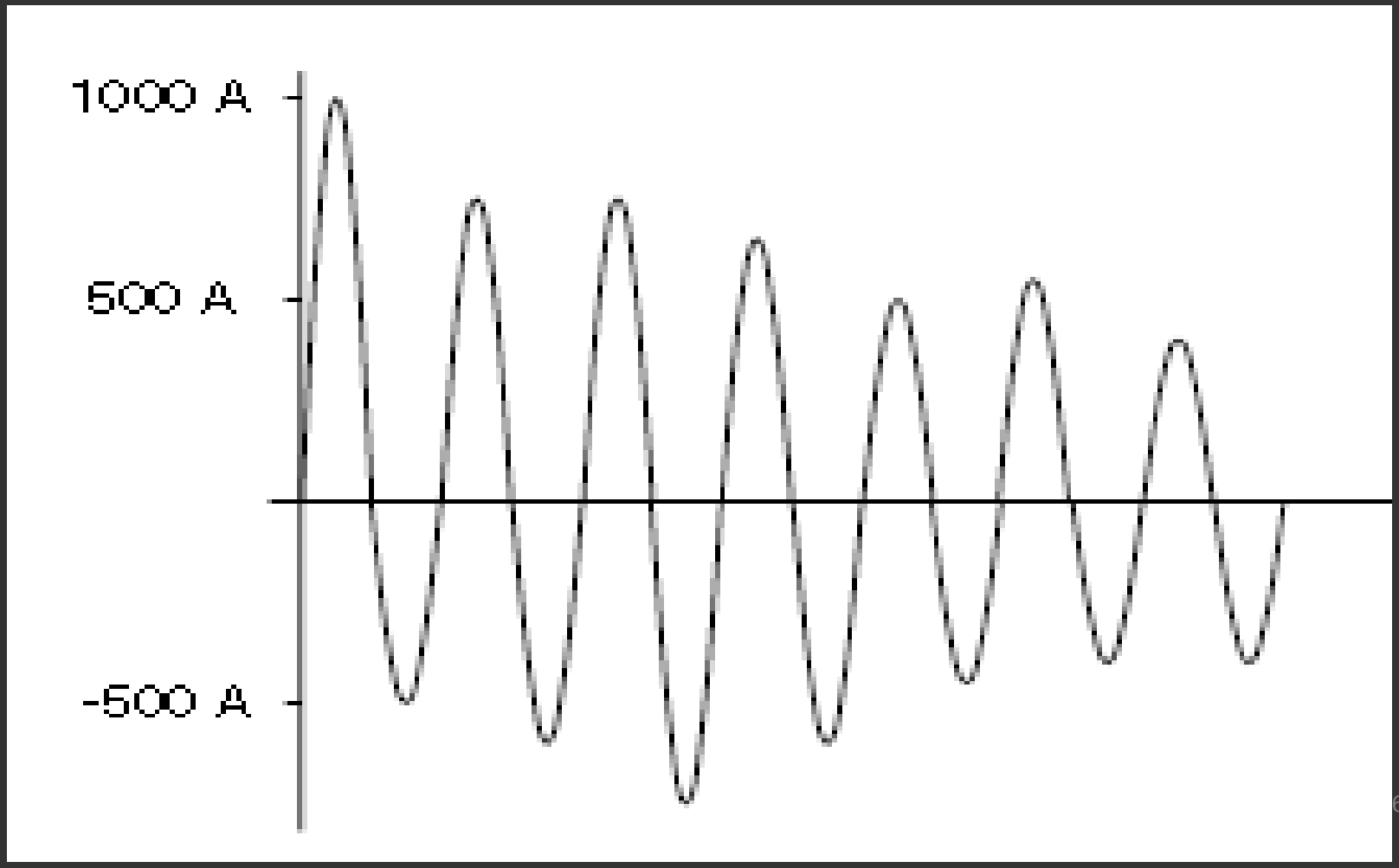
Voltage Fluctuations and Flicker



Voltage Flicker Caused by Arc Furnace Operation

Voltage Fluctuations and Flicker

Typical current draw by arc furnace



Voltage Fluctuations and Flicker

Flicker

- Flicker is the perturbation affected to lighting equipment by voltage fluctuations.
- Very small variations are sufficient to provoke variations of illumination that are unbearable (irritating) to the human eye. This sensitivity varies according to the frequency of occurrence of this phenomenon.
- The strongest human response to light flicker occurs between 7 Hz-10 Hz.

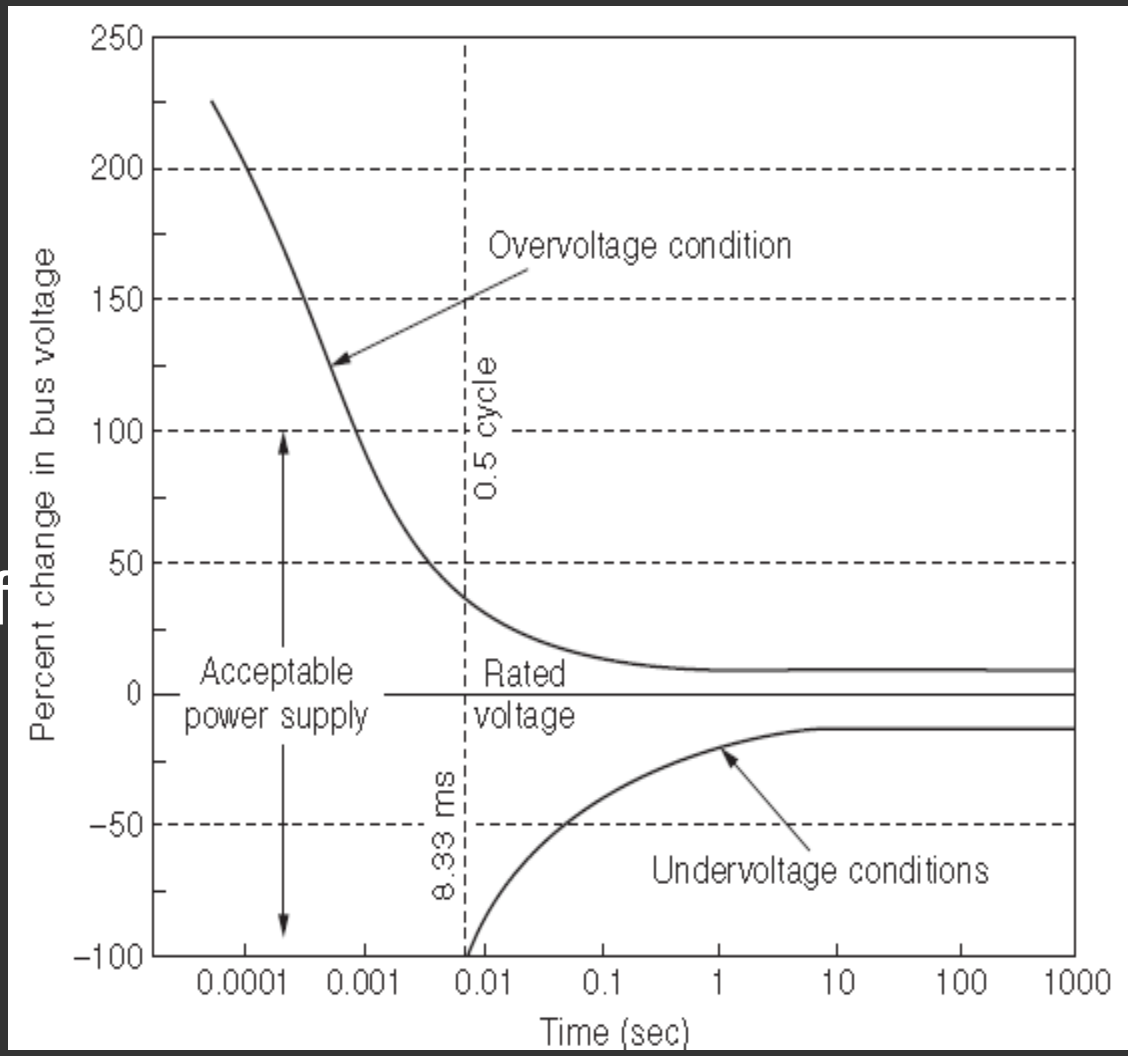
Voltage Fluctuations and Flicker

The main sources of rapid voltage fluctuations are industrial loads like

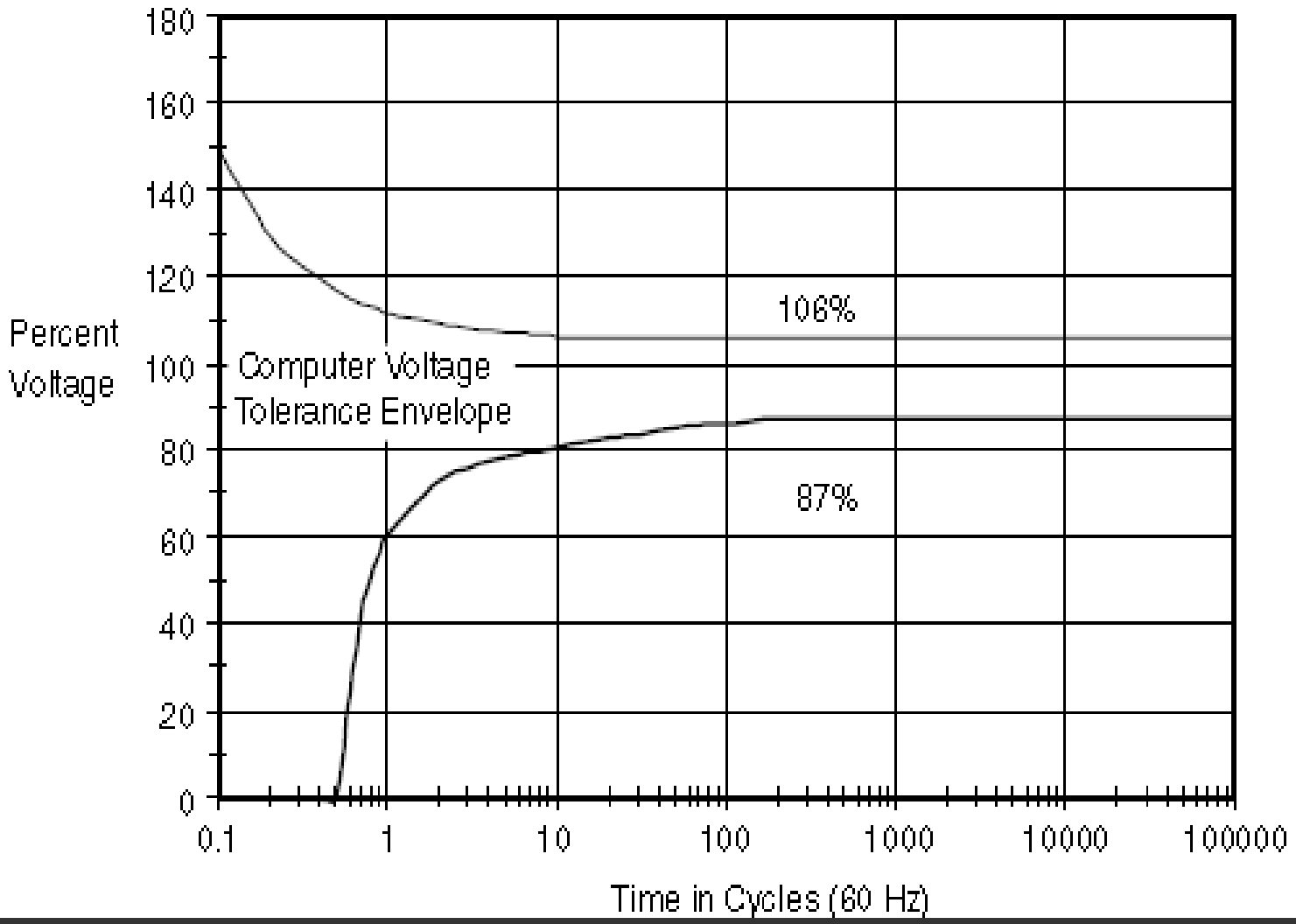
- *Large industrial motors with variable loads*
- *Arc furnace*
- *Arc welders*
- *Saw mills*
- *Switching on of capacitors*
- *X-ray machines*
- *Copying machines in offices*

CBEMA or ITI Curves

- The CBEMA curve shows the range of acceptable power supply voltages for equipment.
- The horizontal axis shows the duration of the sag or swell,
- The vertical axis shows the percent change in line voltage.



CBEMA or ITI Curves

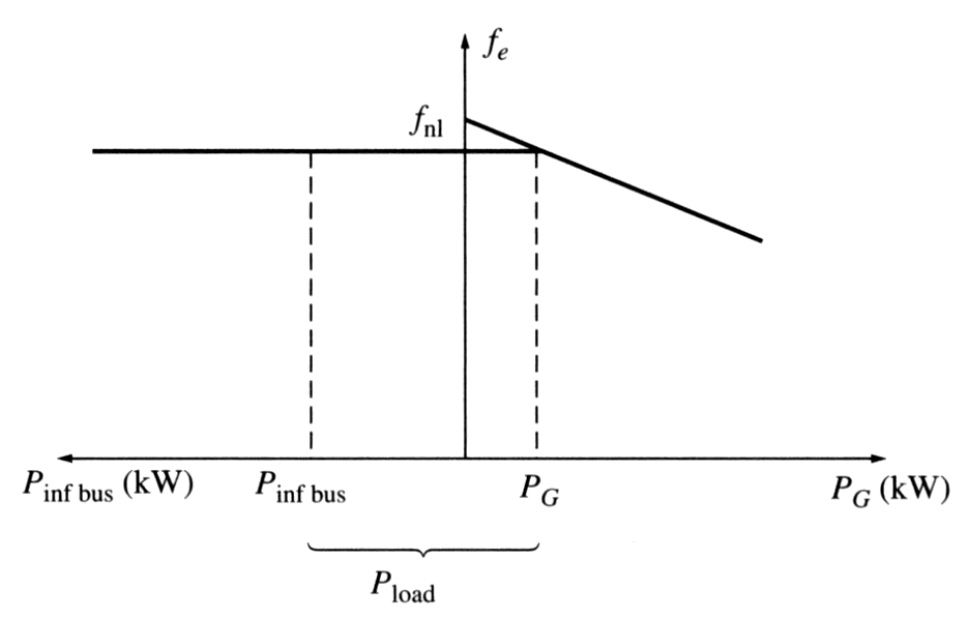


POWER FREQUENCY VARIATIONS

- *Power Frequency Variations are defined as the deviation of the power system fundamental frequency from its specified nominal value (e.g. 50 Hz or 60 Hz).*
- *The power system frequency is directly related to the rotational speed of the generators supplying the system.*
- *There are slight variations in frequency as the dynamic balance between load and generation changes.*

POWER FREQUENCY VARIATIONS

- *Frequency Variations with Power Demand*



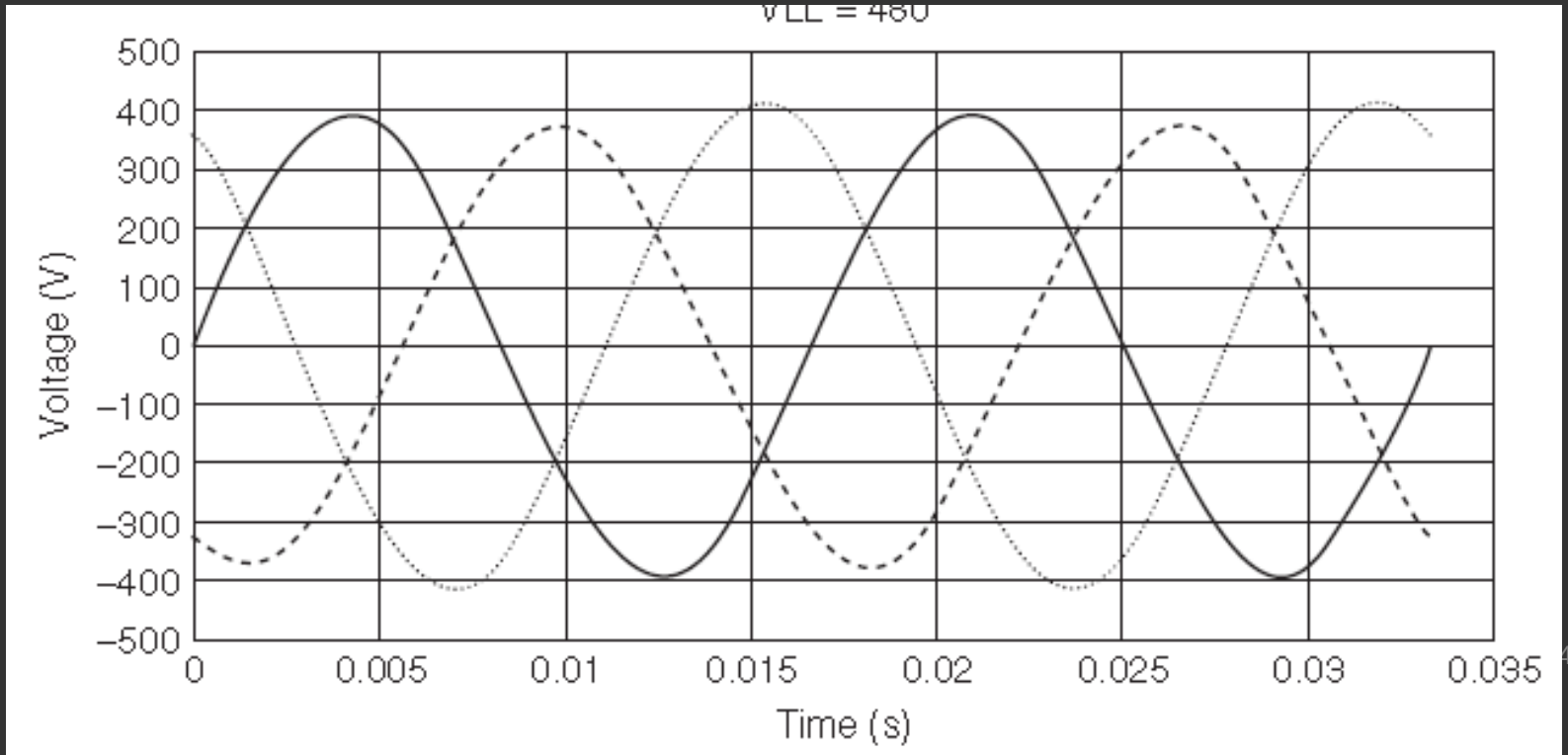
POWER FREQUENCY VARIATIONS

- *Frequency Impacts*

  - *Induction motor* $T\alpha \frac{1}{f^2}$
  - *Capacitor bank, Reactive power generated* $Q=2*\pi f*C*V^2$
  - *Transformers* $\phi=\frac{\sqrt{2}V}{2*\pi*f*N}$ *N-No of turns*
  - ✓ *A decrease of f, increases the flux and leading to more core losses.*

Voltage Imbalance

- A voltage “imbalance” is a variation in the amplitudes of three-phase voltages, relative to one another. This imbalance can be caused by different loads on the phases, resulting in different voltage drops through the phase-line impedances.



Voltage Imbalance

- Causes
  - Unequal loading
  - Unequal source impedance
  - Unequal source voltage
  - Unbalanced fault

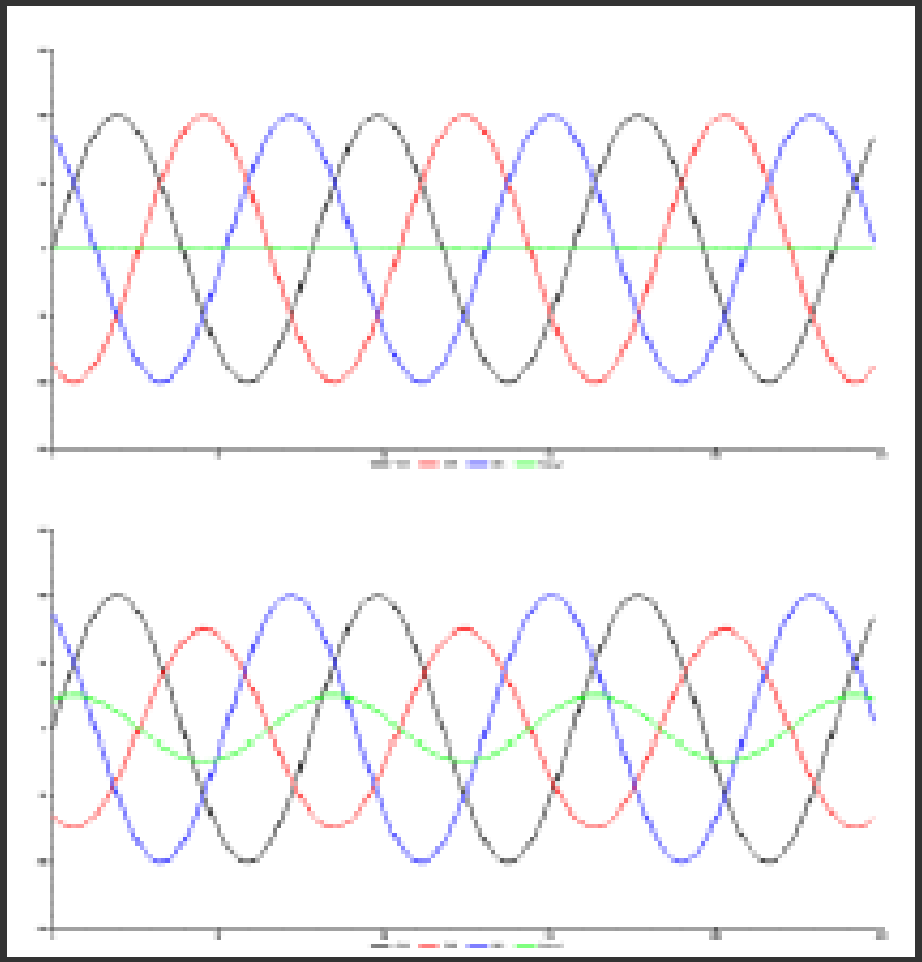
VOLTAGE IMBALANCE

- **VOLTAGE IMBALANCE** is sometimes defined as the maximum deviation from the average of the three phase voltages or currents, divided by the average of the three phase voltages, expressed in percent.
- Imbalance can also be defined using symmetrical components. The ratio of either the negative- or zero sequence component to the positive sequence component can be used to specify the percent unbalance.

Voltage Imbalance

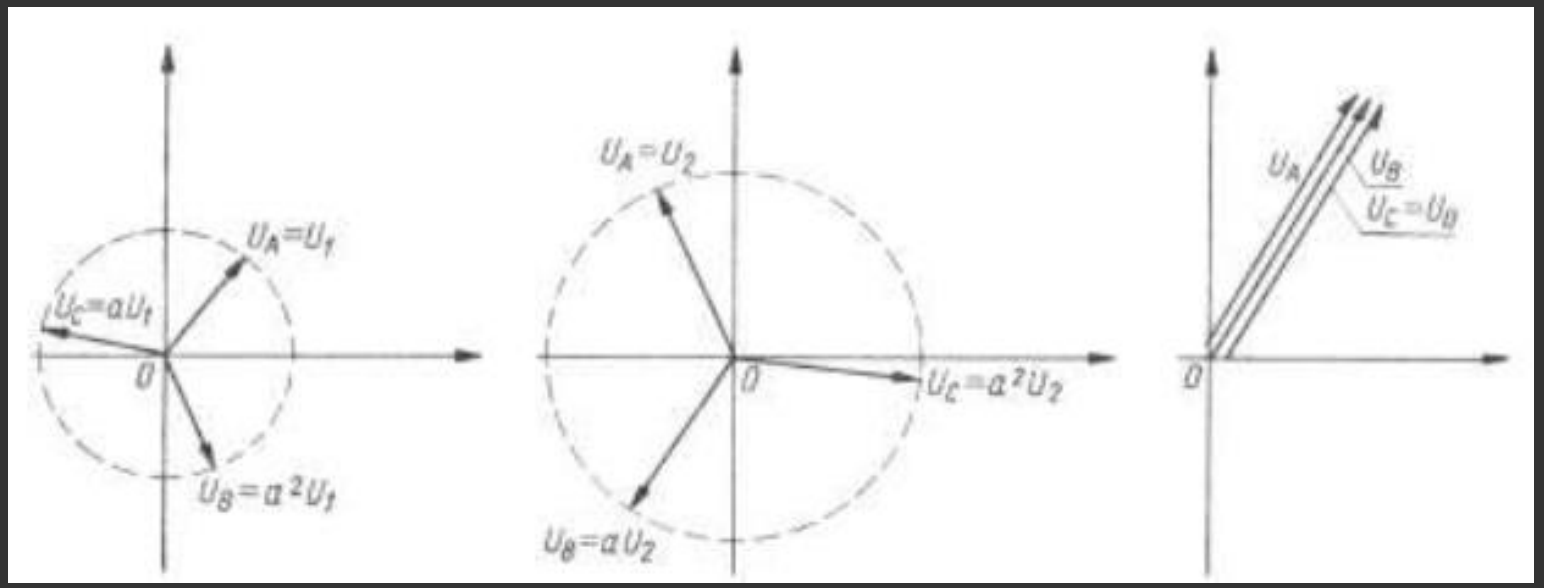
- No Unbalance
  - Phase currents offset

- Phase Unbalance
  - Imbalance = neutral



Voltage Imbalance

- Symmetrical components: Every arbitrary three-phase circuit can be resolved in three balanced three-phase systems, called symmetrical systems.



Positive sequence, negative sequence and zero sequence voltage systems

Voltage Imbalance

- To express quantities algebraically, the complex operator a is used

$$a = e^{j120^\circ} = \cos 120^\circ + j \sin 120^\circ = -0.5 + j\frac{\sqrt{3}}{2}$$

$$\begin{cases} a^2 = -0.5 - j\dfrac{\sqrt{2}}{3} \\ a^3 = 1 \end{cases}$$

$$1 + a + a^2 = 0$$

Voltage Imbalance

- The phase voltages are expressed in terms of symmetrical components

$$\overline{V}_a = \overline{V}_{a_0} + \overline{V}_{a_1} + \overline{V}_{a_2}$$

$$\overline{V}_b = \overline{V}_{b_0} + \overline{V}_{b_1} + \overline{V}_{b_2}$$

$$\overline{V}_c = \overline{V}_{c_0} + \overline{V}_{c_1} + \overline{V}_{c_2}$$

$$\overline{V}_{a_0} = \overline{V}_{b_0} = \overline{V}_{c_0} \equiv \overline{V}_0 = V_0 \angle \theta_0$$

zero sequence components

$$\overline{V}_{a_1} = \overline{V}_1 = V_1 \angle \theta_1$$

$$\overline{V}_{b_1} = V_1 \angle (\theta_1 - 120^\circ) = \overline{V}_1 \bullet 1 \angle -120^\circ$$

$$\overline{V}_{c_1} = V_1 \angle (\theta_1 + 120^\circ) = \overline{V}_1 \bullet 1 \angle +120^\circ$$

positive sequence components

Voltage Imbalance

- The phase voltages are expressed in terms of symmetrical components

$$\overline{V}_{a_2} = \overline{V}_2 = V_2 \angle \theta_2$$

$$\overline{V}_{b_2} = V_2 \angle (\theta_2 + 120^\circ) = \overline{V}_2 \bullet 1 \angle +120^\circ$$

$$\overline{V}_{c_2} = V_2 \angle (\theta_2 - 120^\circ) = \overline{V}_2 \bullet 1 \angle -120^\circ$$

Negative sequence components

Voltage Imbalance

- The phase voltages are expressed in terms of matrix form

$$\begin{bmatrix} \overline{V}_a \\ \overline{V}_b \\ \overline{V}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \overline{a}^2 & \overline{a} \\ 1 & \overline{a} & \overline{a}^2 \end{bmatrix} \begin{bmatrix} \overline{V}_0 \\ \overline{V}_1 \\ \overline{V}_2 \end{bmatrix}$$

$$\tilde{V}_{abc} = [\overline{T}]\,\tilde{V}_{012}$$

$$\begin{bmatrix} \overline{V}_0 \\ \overline{V}_1 \\ \overline{V}_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \overline{a} & \overline{a}^2 \\ 1 & \overline{a}^2 & \overline{a} \end{bmatrix} \begin{bmatrix} \overline{V}_a \\ \overline{V}_b \\ \overline{V}_c \end{bmatrix}$$

$$\tilde{V}_{012} = [\overline{T}]^{-1}\tilde{V}_{abc}$$

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

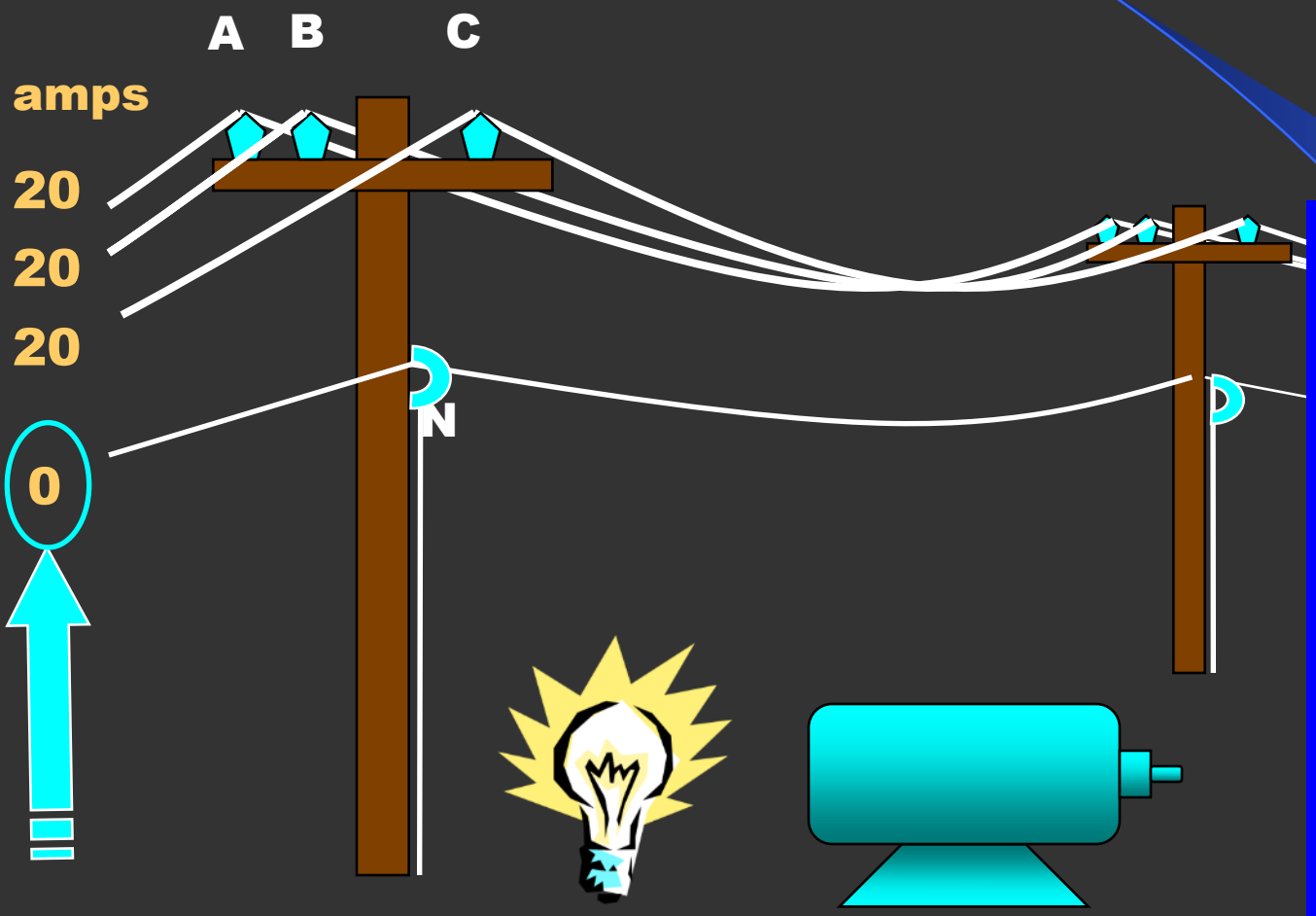
Voltage Imbalance

The unbalance ratio is expressed for the voltage

- $UN_{v2} = \frac{V_2}{V_1}$ (In terms of positive seq.)
- $UN_{v0} = \frac{V_0}{V_1}$ (In terms of zero seq.)
- This can be similarly defined for current unbalances.

Voltage Imbalance

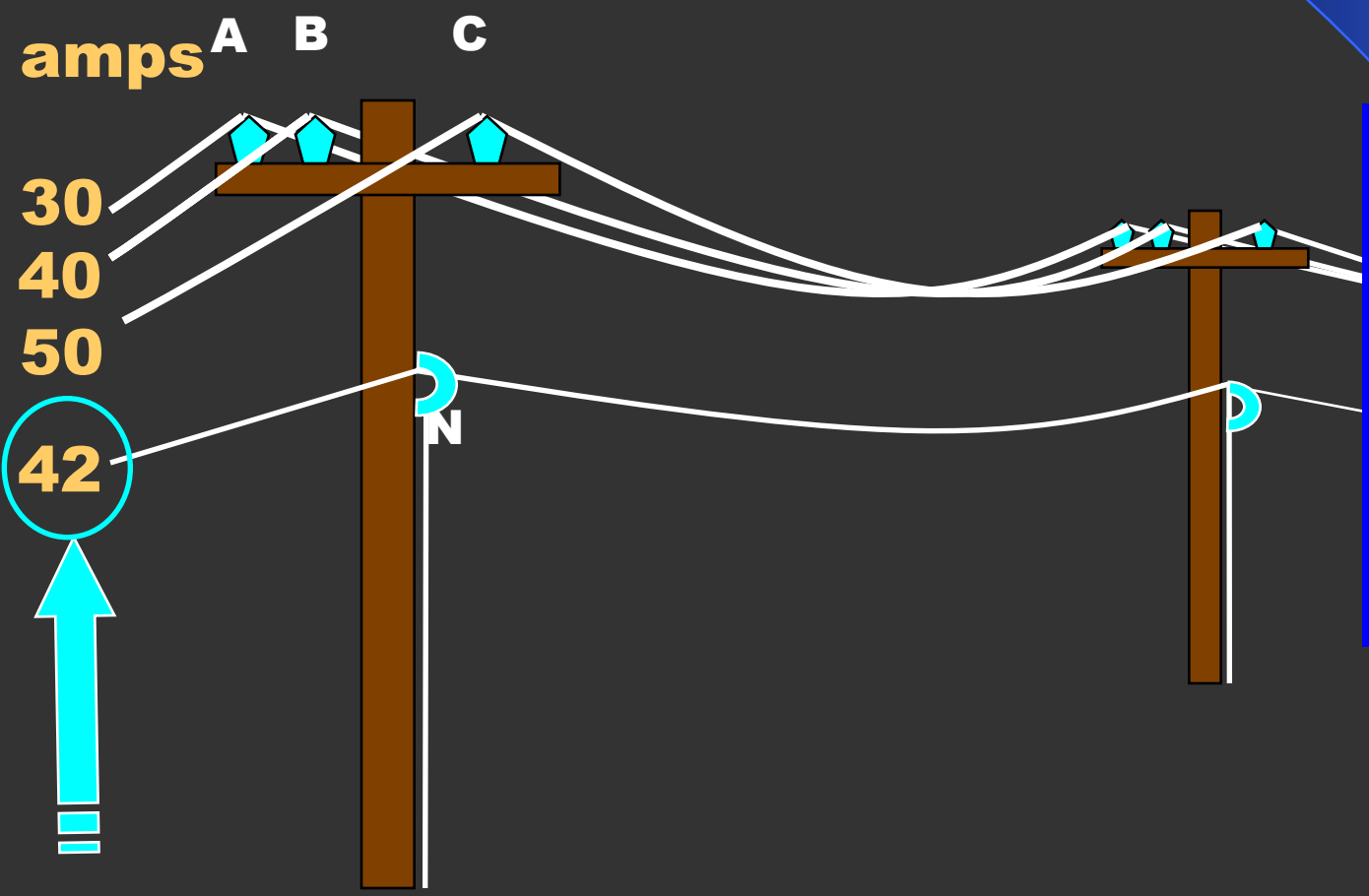
Wye System – Balanced Load



In the grounded wye distribution system, the unbalanced current should return to the substation via the neutral conductor.

Voltage Imbalance

System - Unbalanced



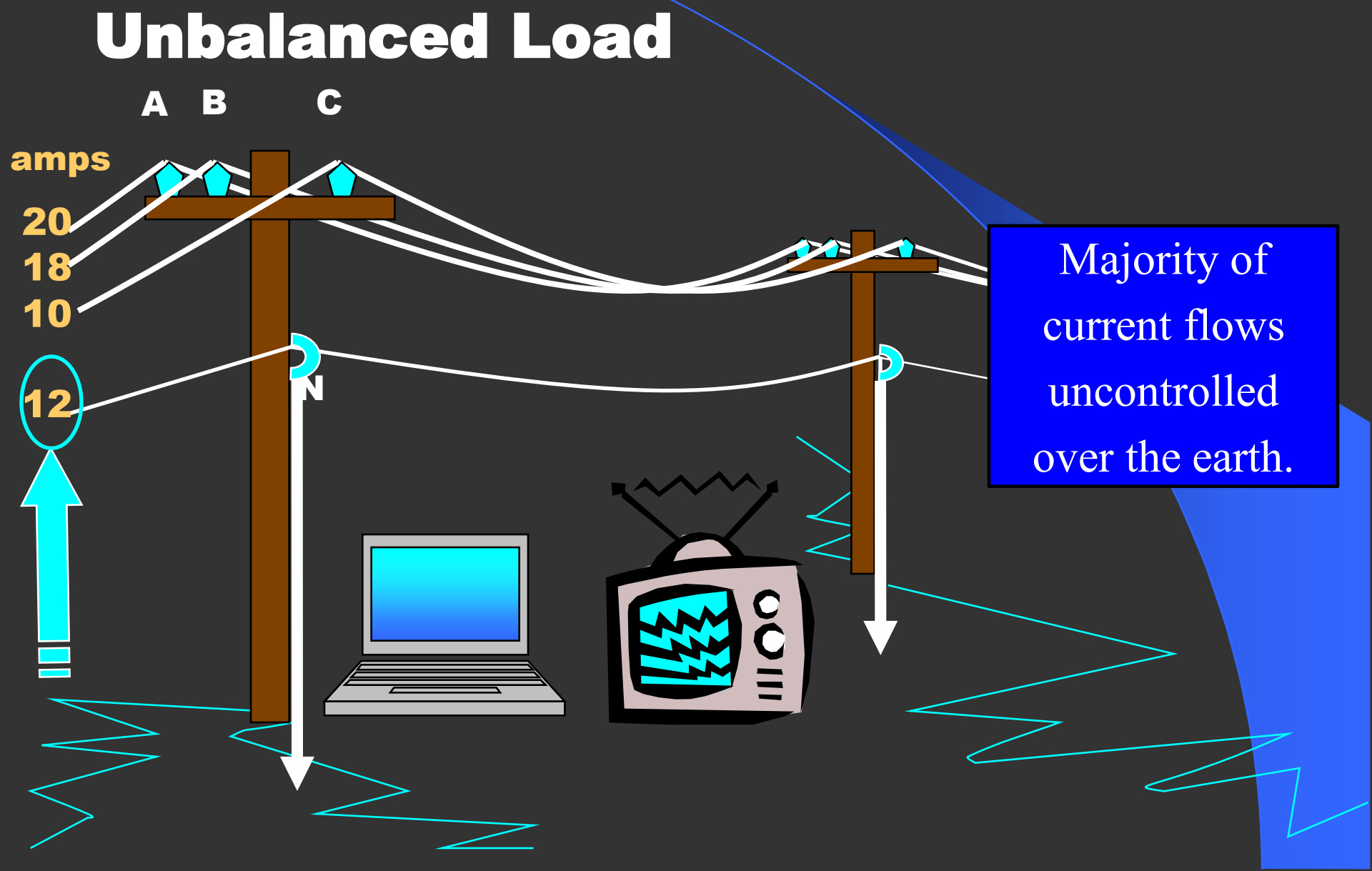
With unbalanced load, the neutral current can be **very high**.

Voltage Imbalance

Effects of Electrical Pollution

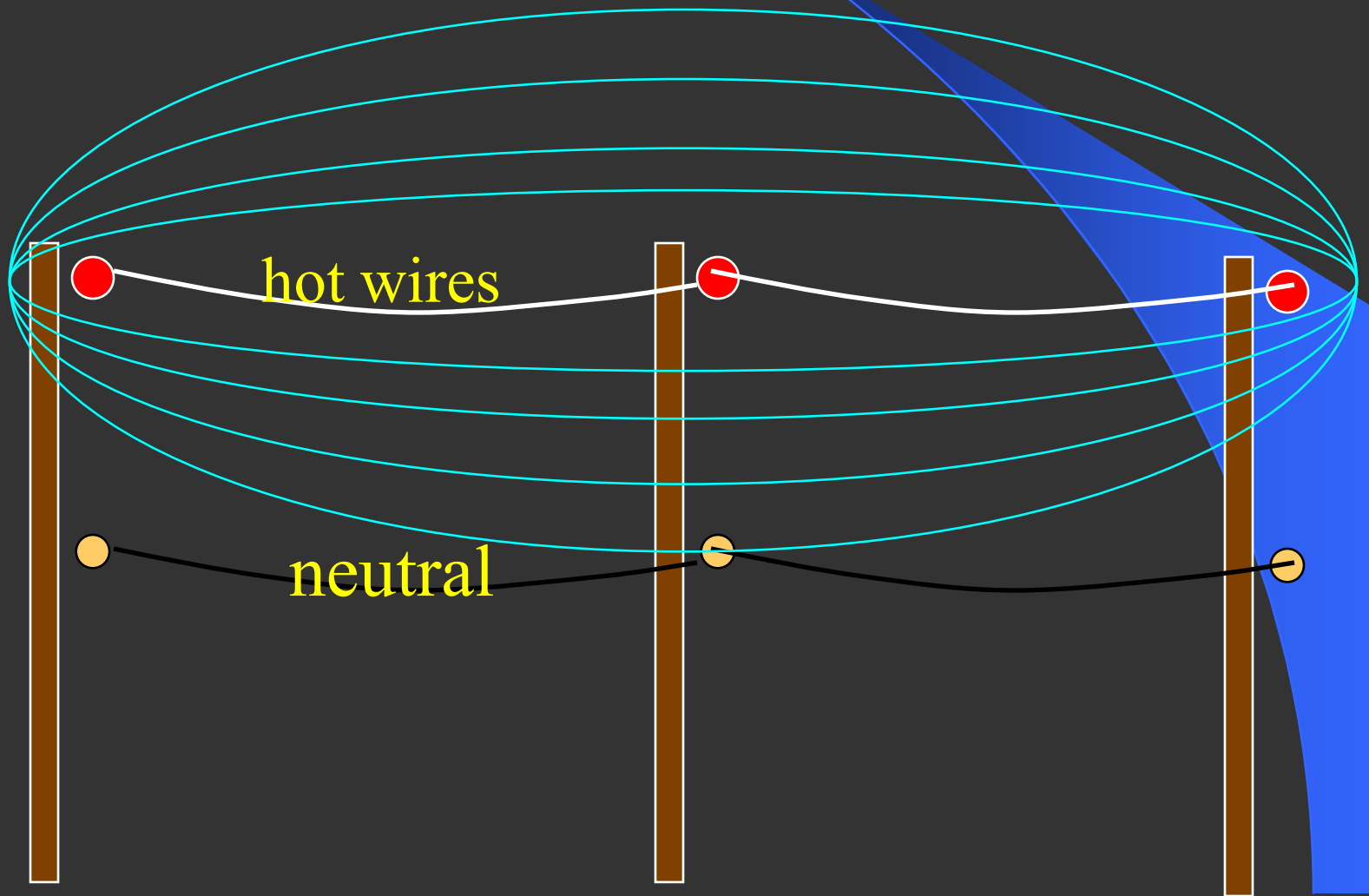
- Utility grounded neutral system is now overloaded.
- The earth has become the main path of neutral current return to utility substations.
- The lives and welfare of the people and animals are endangered.

Voltage Imbalance



Voltage Imbalance

RF Radiates from Wires



WAVEFORM DISTORTION

Waveform distortion *is defined as a steady state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation.*

There are five primary types of waveform distortion:

- **Harmonics**
- **DC offset**
- **Interharmonics**
- **Notching**
- **Noise**

WAVEFORM DISTORTION

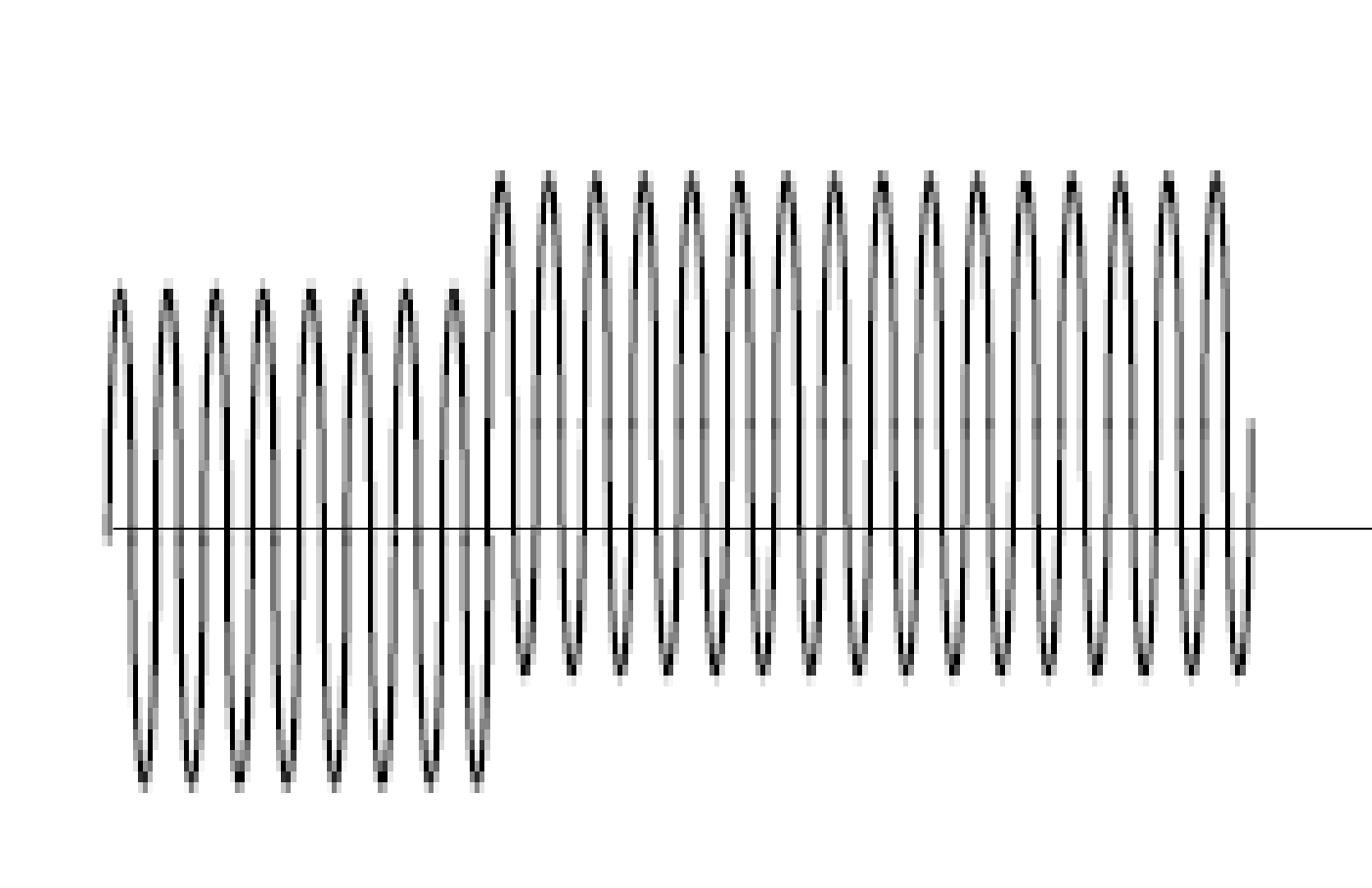
DC Offset:

- The presence of a dc voltage or current in an ac power system is termed dc offset.
- This can occur as the result of a geomagnetic disturbance or due to the effect of half-wave rectification.
- Direct current in alternating current networks can have a detrimental effect by biasing transformer cores so they saturate in normal operation. This causes additional heating and loss of transformer life.

WAVEFORM DISTORTION

DC Offset:

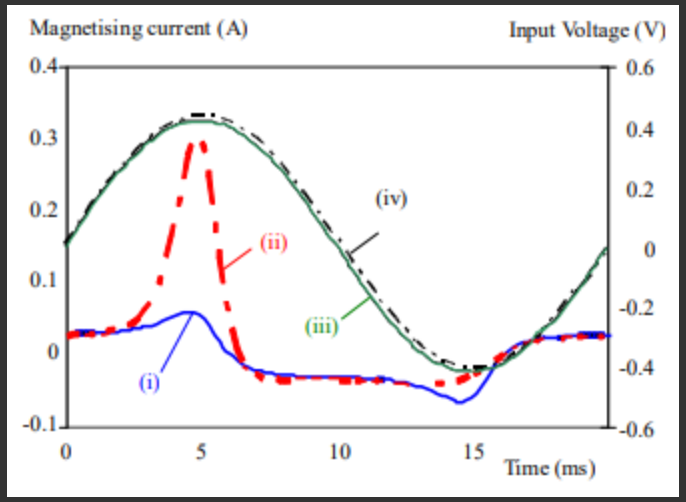
$$C_{Offset} = \frac{1}{T}\int_0^T F(t)\,dt$$



WAVEFORM DISTORTION

DC Offset:

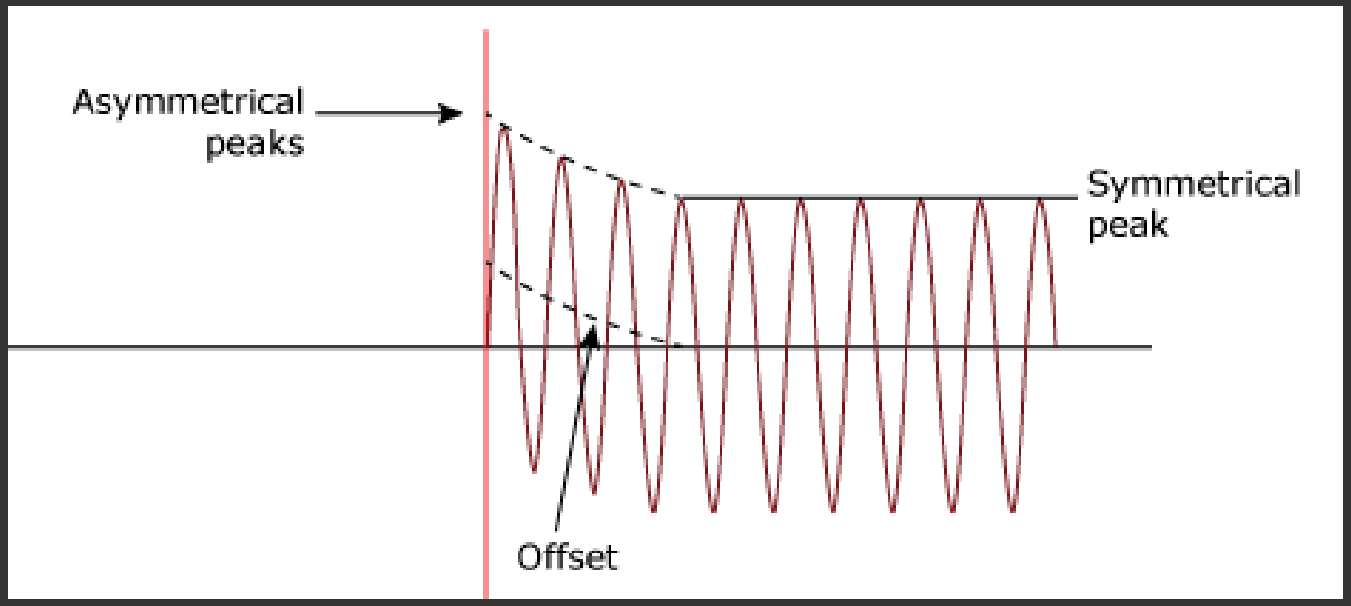
- Direct current in alternating current networks can have a detrimental effect by biasing transformer cores so they saturate in normal operation. This causes additional heating and loss of transformer life.



WAVEFORM DISTORTION

DC Offset:

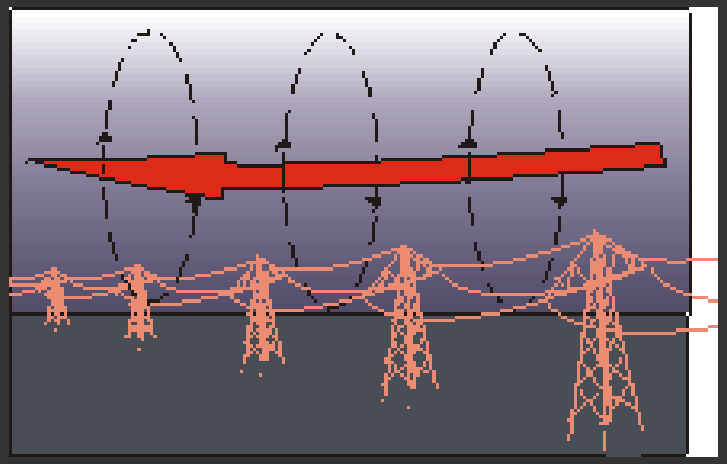
A fault is suddenly applied to the system and the sine wave suddenly becomes asymmetrical. The asymmetrical response to the fault is called DC Offset.



WAVEFORM DISTORTION

DC Offset:

Geomagnetic disturbances can have a serious effect on power systems. Currents induced in power lines flow to ground through substation transformers. Here they cause saturation of the transformer core and cause harmonics in the system.



WAVEFORM DISTORTION

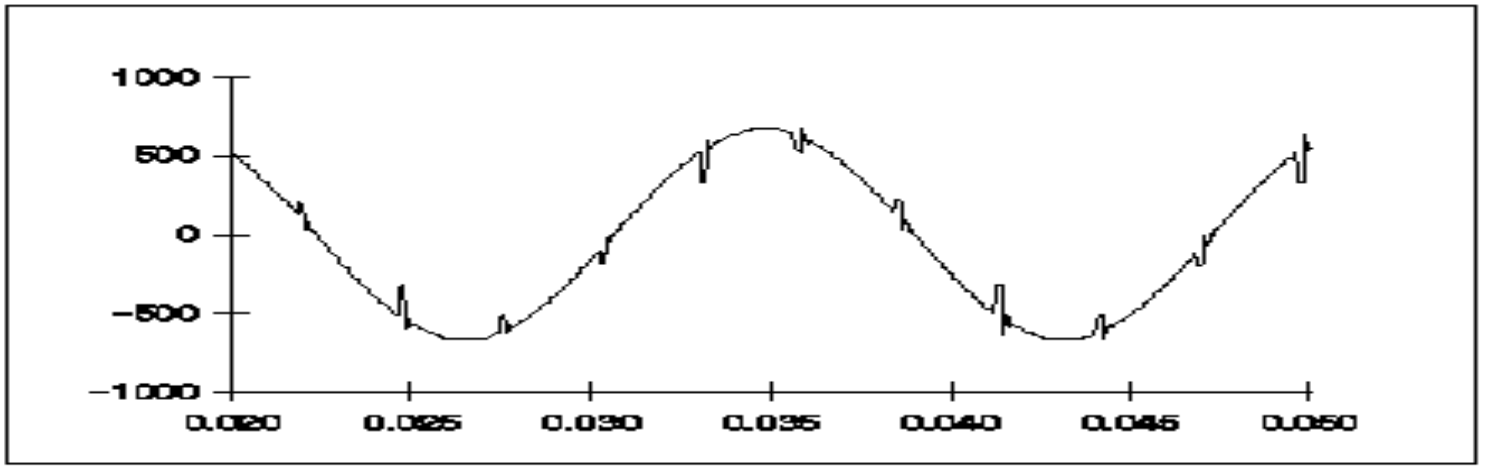
Interharmonics

- Voltages or currents having frequency components that are not integer multiples of the frequency at which the supply system is designed to operate (e.g., 50 Hz or 60 Hz) are called interharmonics.
- Inter-harmonics are a type of waveform distortion that are usually the result of a signal imposed on the supply voltage by electrical equipment such as static frequency converters, induction motors and arcing devices.

WAVEFORM DISTORTION

Notching

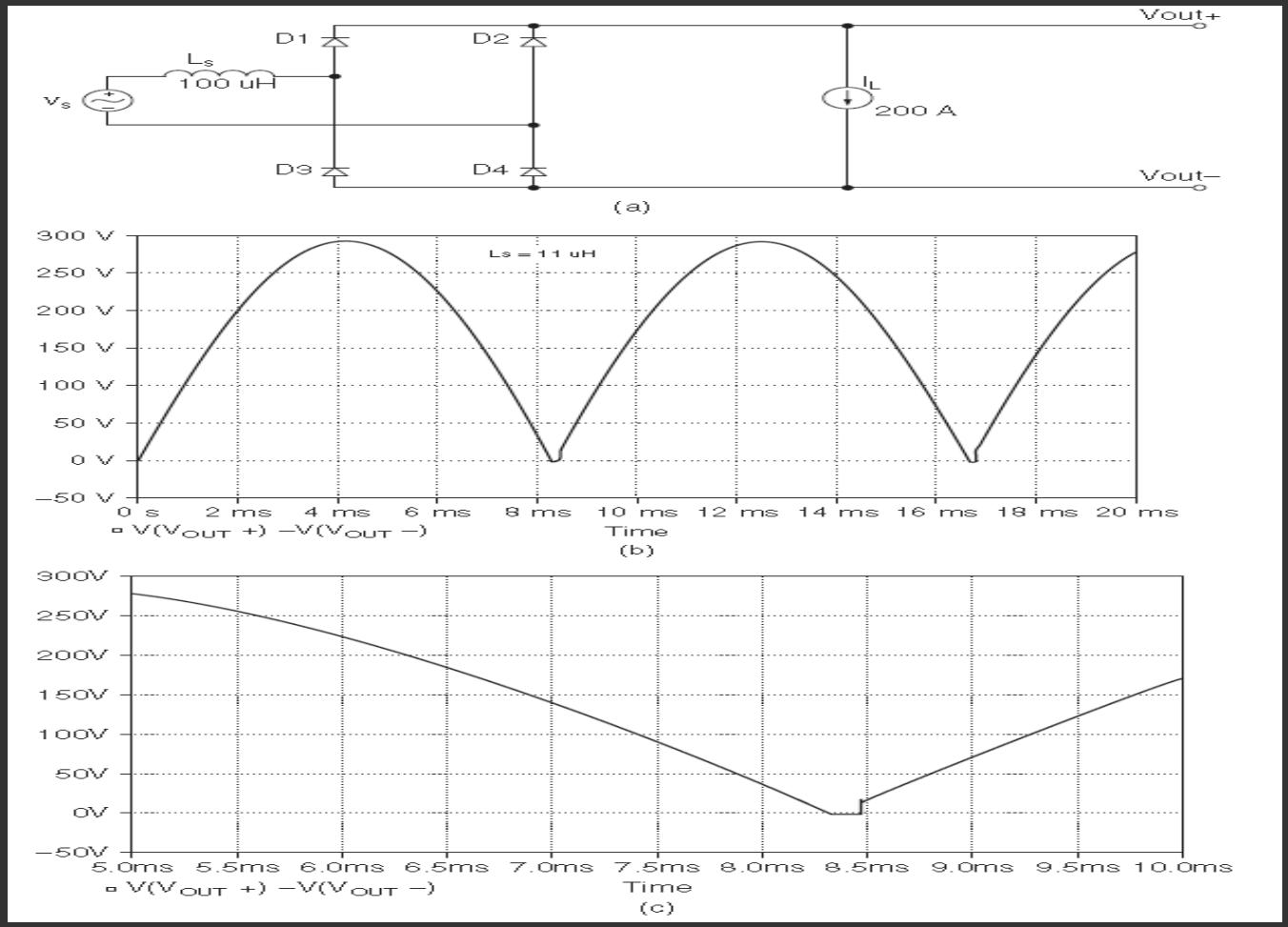
Notching is a periodic voltage disturbance caused by the normal operation of power electronics devices when current is commutated from one phase to another. During this period, there is a momentary short circuit between two phases pulling the voltage as close to zero as permitted by system impedances.



Voltage Notching Caused by a Three-Phase Converter

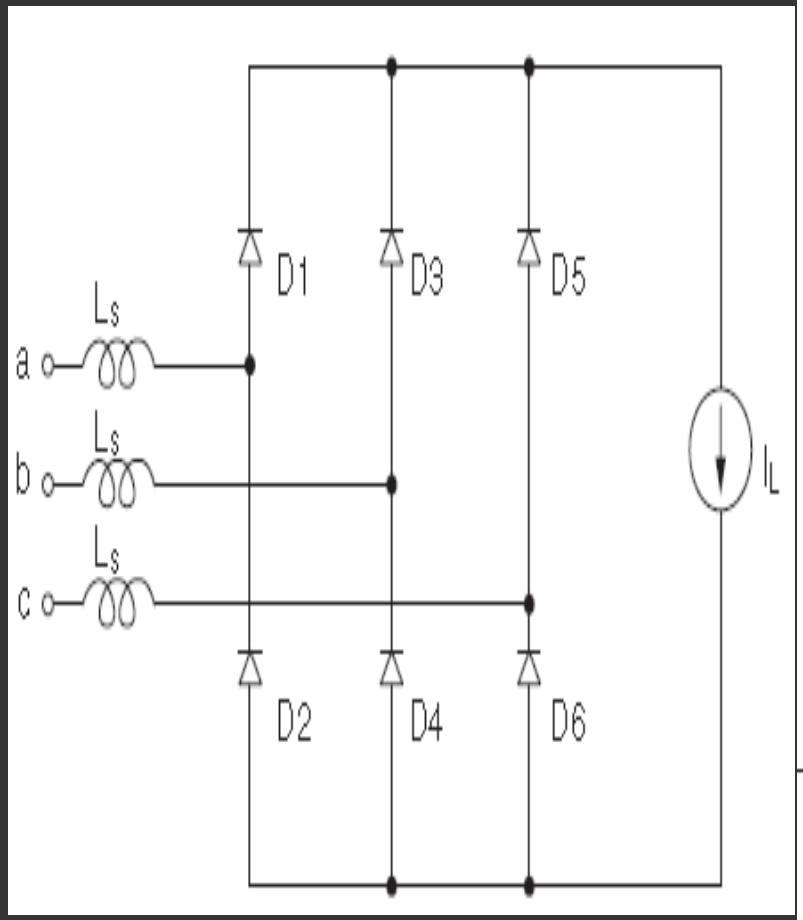
WAVEFORM DISTORTION

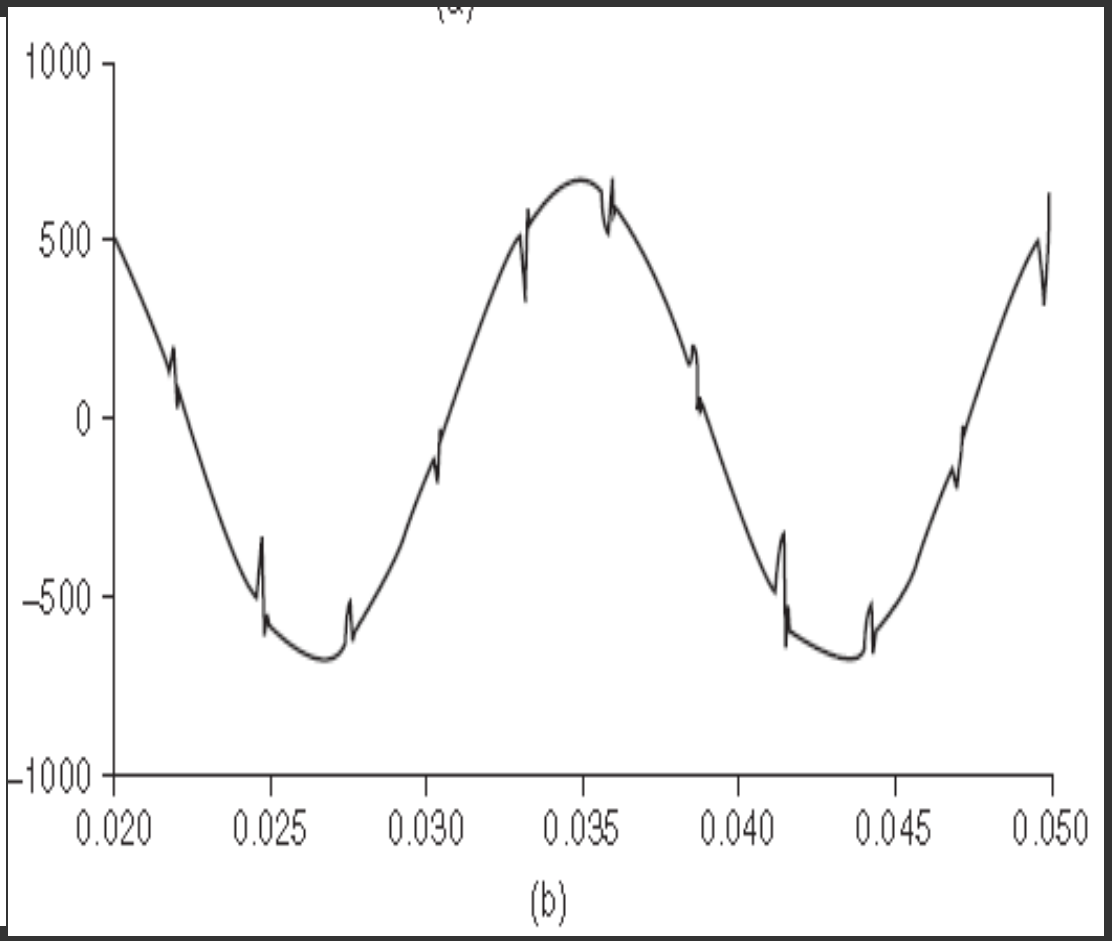
Notching



WAVEFORM DISTORTION

Notching





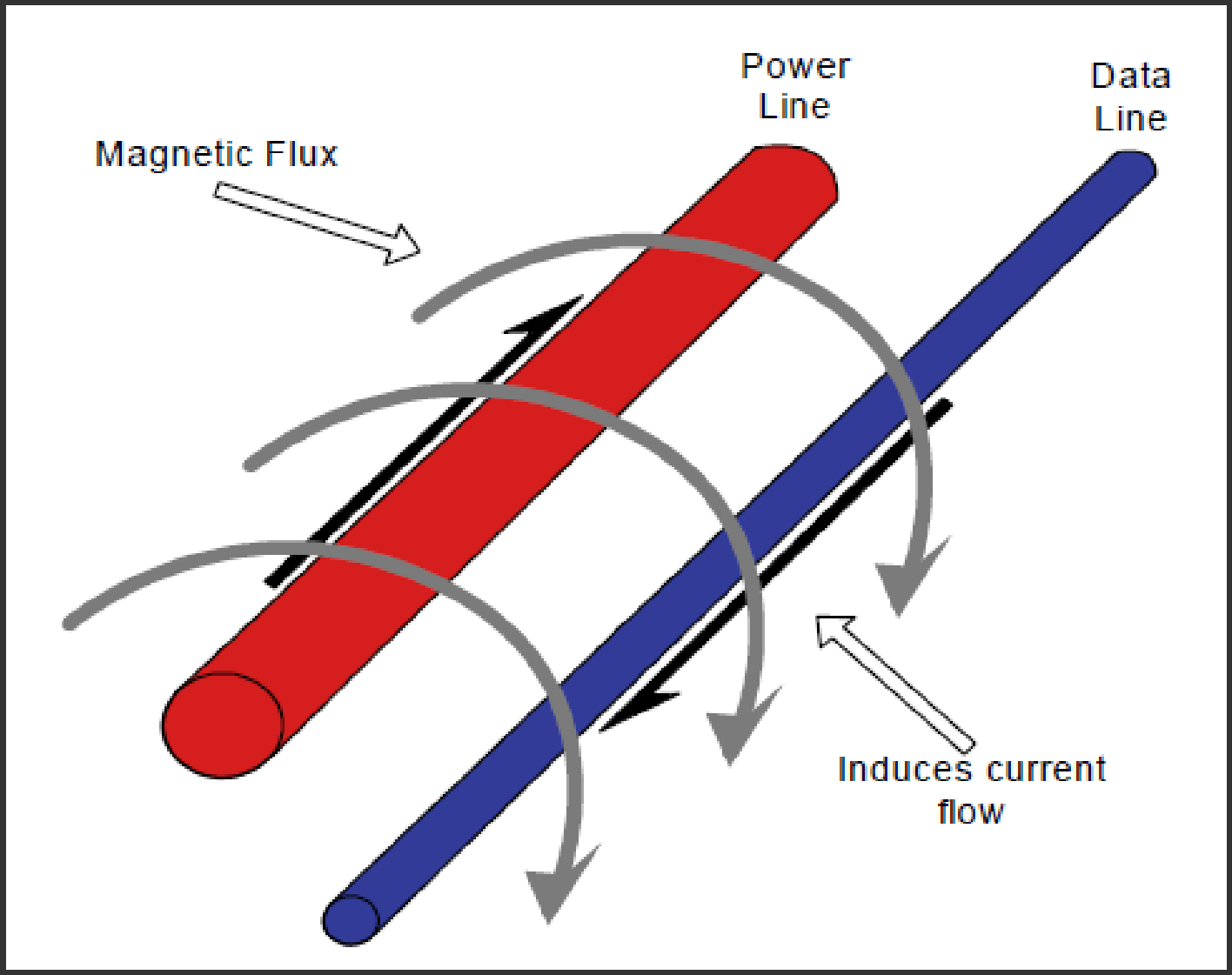
WAVEFORM DISTORTION

Noise *is defined as unwanted electrical signals with broadband spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase conductors, or found on neutral conductors or signal lines.*

- *Noise in power systems can be caused by power electronic devices, control circuits, arcing equipment, loads with solid-state rectifiers, and switching power supplies.*
- *Noise problems are often exacerbated by improper grounding that fails to conduct noise away from the power system.*

WAVEFORM DISTORTION

Noise:

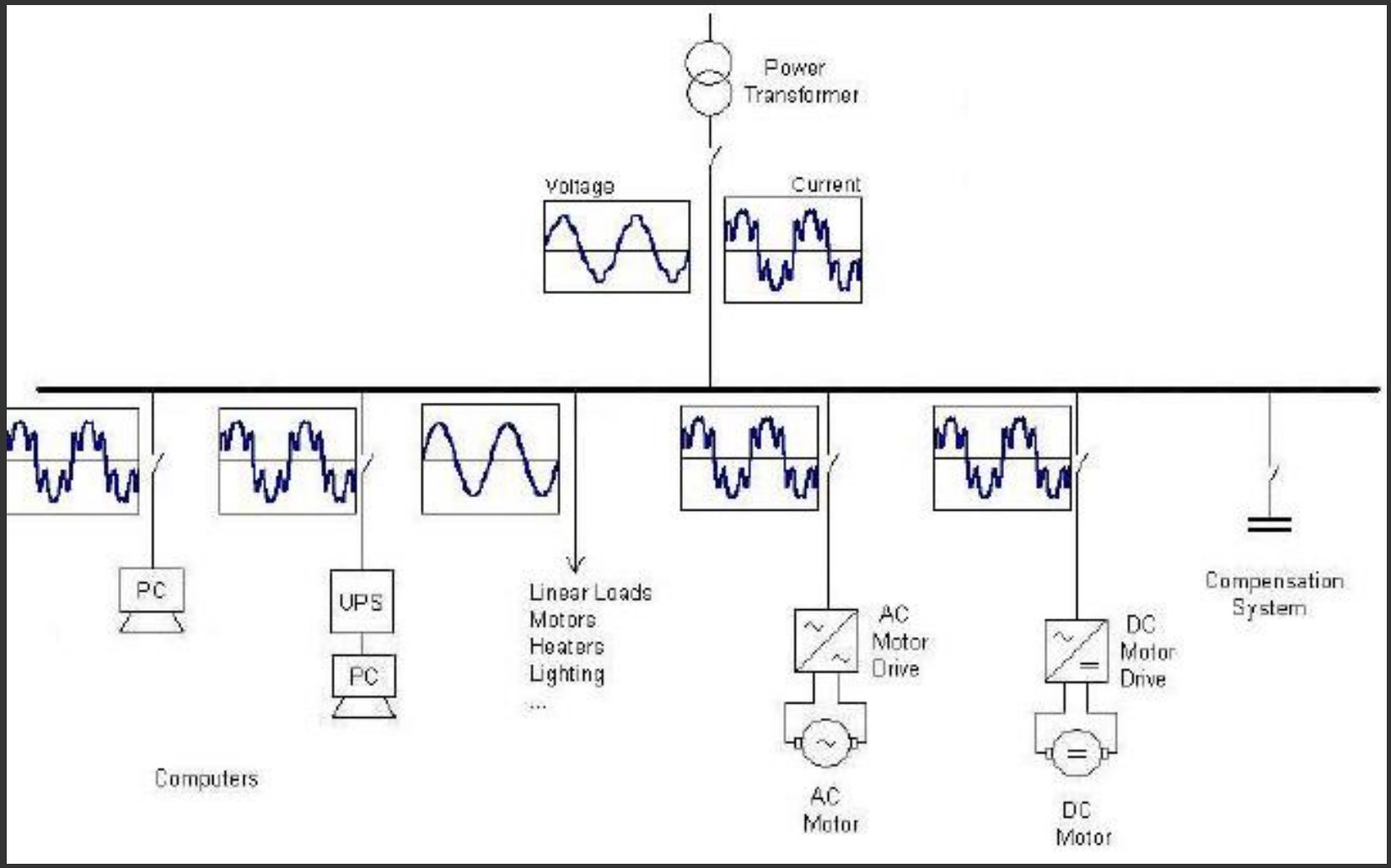


WAVEFORM DISTORTION

Harmonics

- Harmonics are periodic voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate (termed the fundamental frequency; usually 50 Hz or 60 Hz).
- Distorted waveforms can be decomposed into a sum of the fundamental frequency and the harmonics. Harmonic distortion originates in the nonlinear characteristics of devices and loads on the power system.

What Causes Harmonics?



WAVEFORM DISTORTION

What Causes Harmonics?

Non-Linear Loads

Current is not proportional to the applied voltage

Harmonics

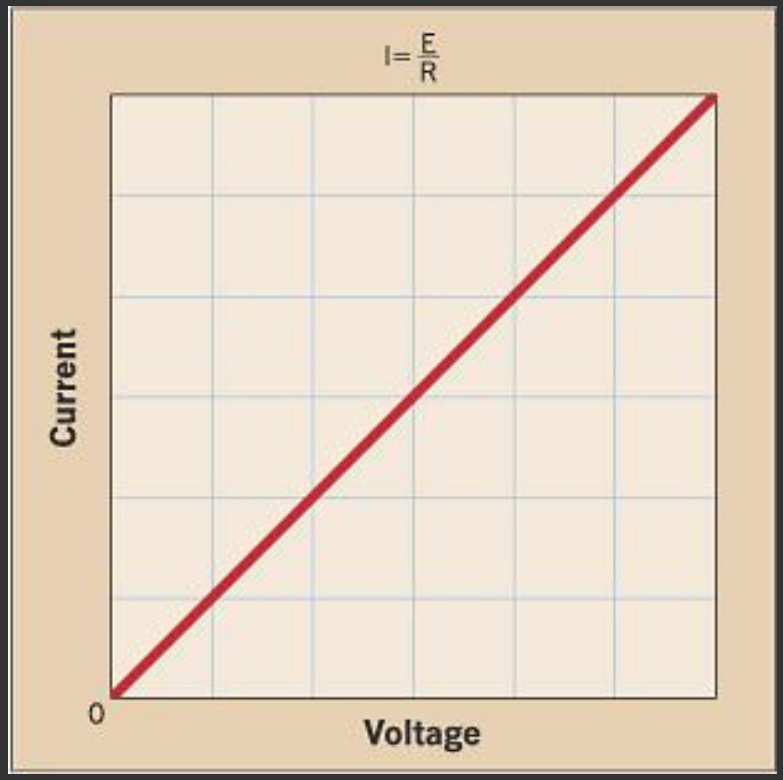
Linear loads and current waveforms.

Pure resistance, inductance, and capacitance are all linear.

What that means:

If a sine wave voltage of a certain magnitude is placed across a circuit containing pure resistance, the current in the circuit follows Ohm's Law: I = E ÷ R.

The relationship of volts and amperes is a straight line. The current will always be a sine wave of the same frequency.



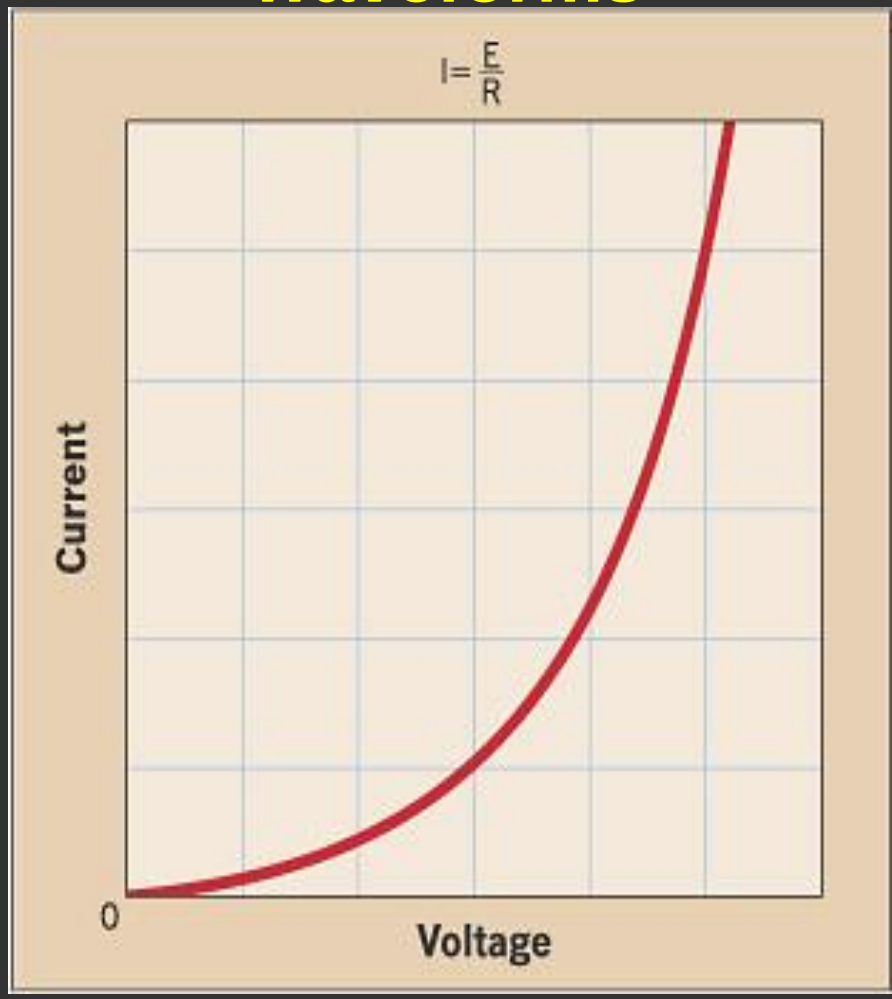
Harmonics

Solid state electronics is based on the use of semiconductors. These materials are totally different in that their response to voltage is not a straight line.

<u>What this means:</u>

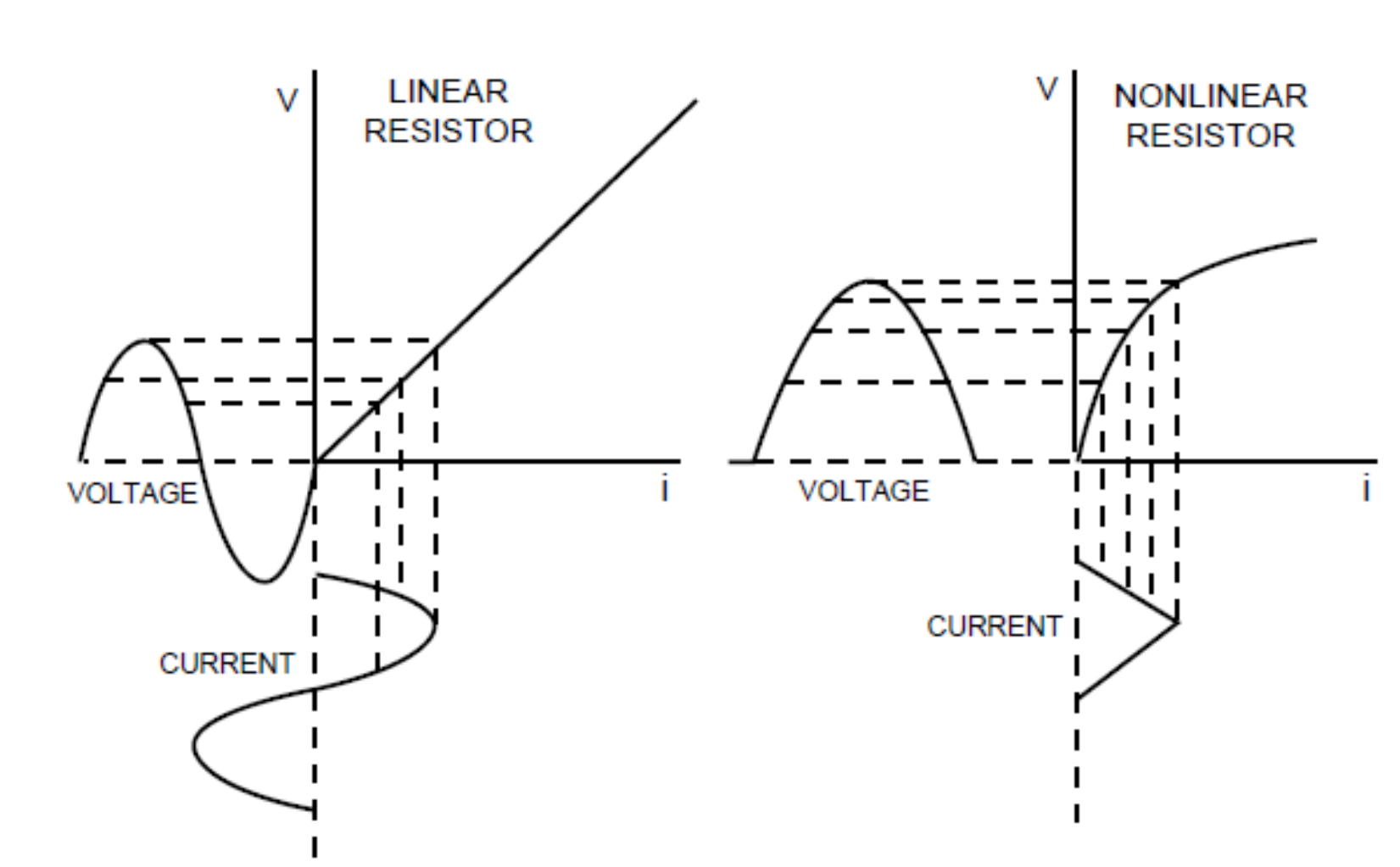
With a nonlinear load, you cannot easily predict the relationship between voltage and current — unless you have an exact curve for each device. With equipment containing many solid-state devices, such an approach is impossible.

Linear vs. Non-linear loads and current waveforms



Harmonics

Linear vs. Non-linear loads and current waveforms

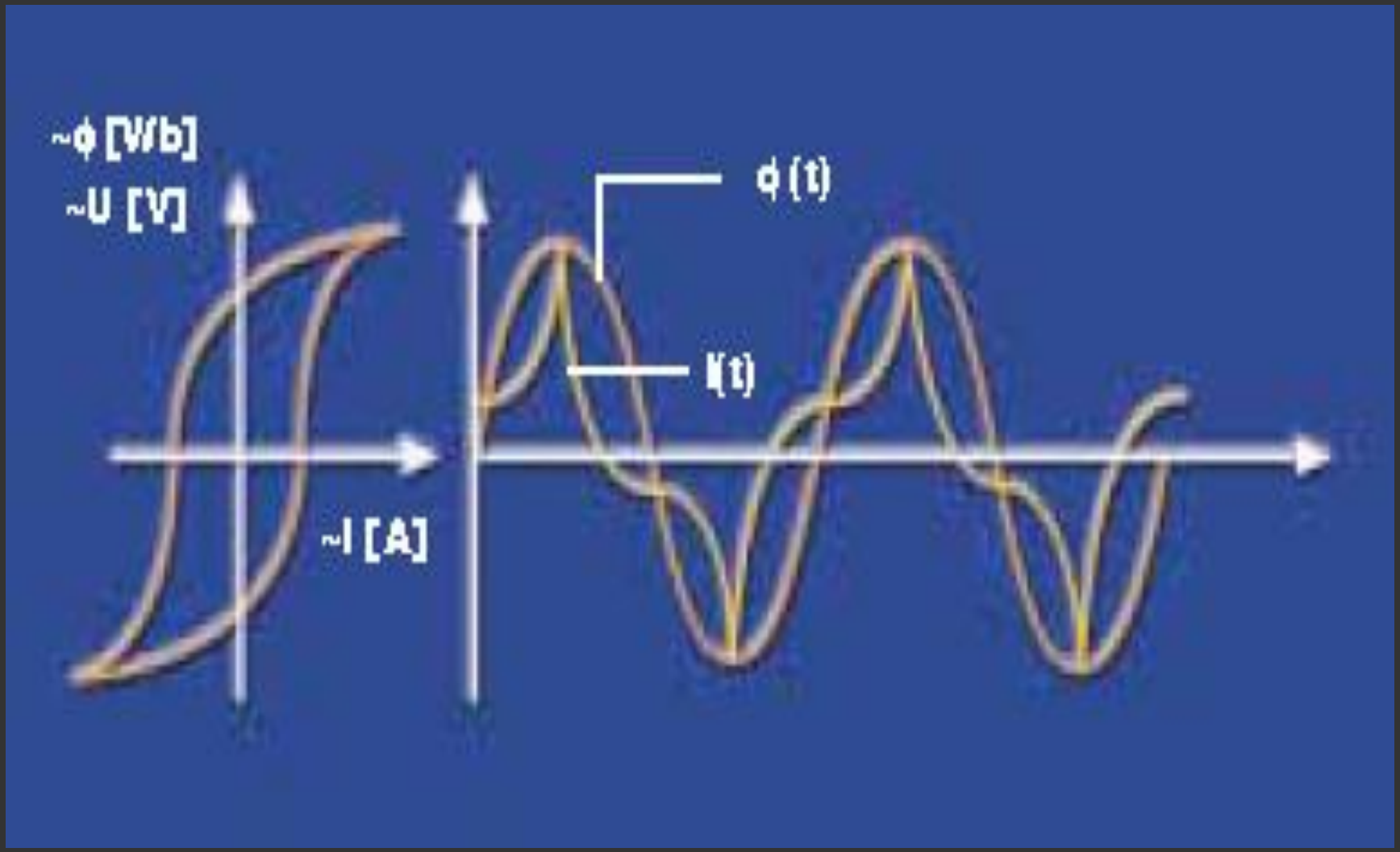


Harmonics

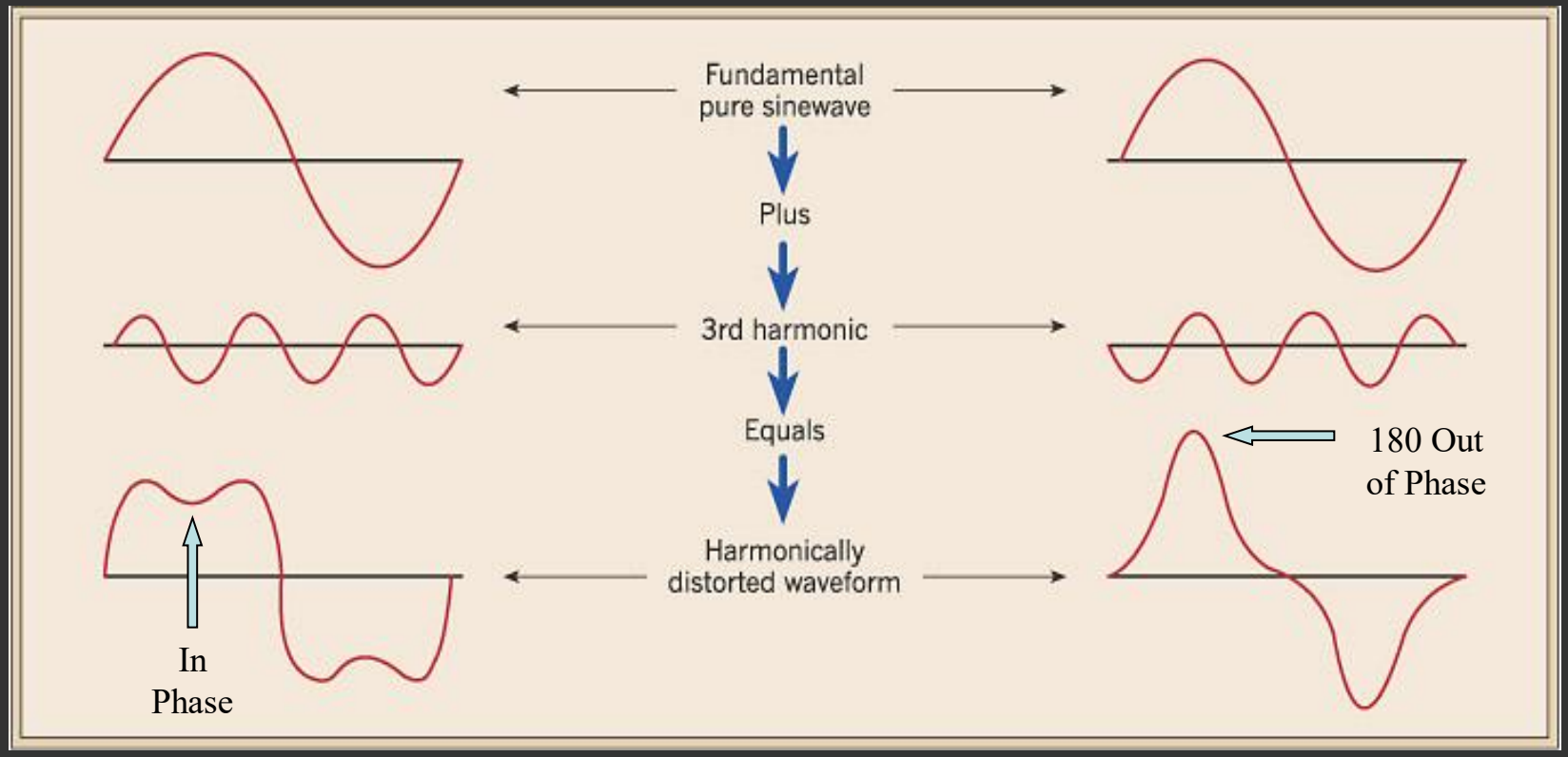
- Solid State Electronic Devices which contain a poor power supply
  - Computers (PCs/CPUs)
  - Laser Printers
  - Copy Machines
  - Video display terminals
  - File Servers
  - Battery Chargers
- Solid State UPS Units
- Solid State Devices (Fluorescent lighting ballasts)
- Rectifiers (AC-DC Converters → VFDs)
- Welding Units
- Arc Furnaces

Harmonics

Magnetization characteristic of a transformer



Harmonics



When a waveform is identical from one waveform to the next, it can be represented as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave.

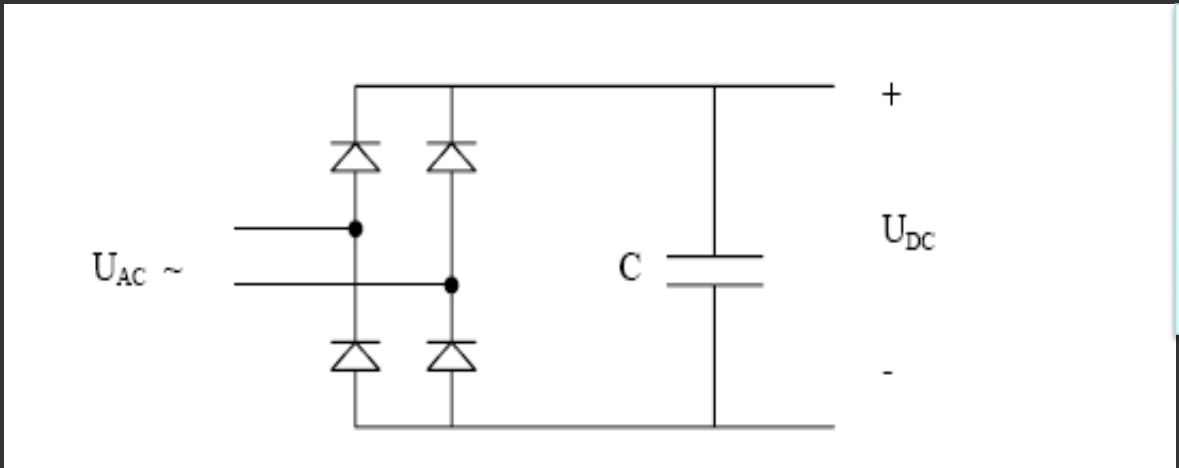
The sum of the sinusoids created by harmonics can be analyzed using the Fourier series concept

Harmonics

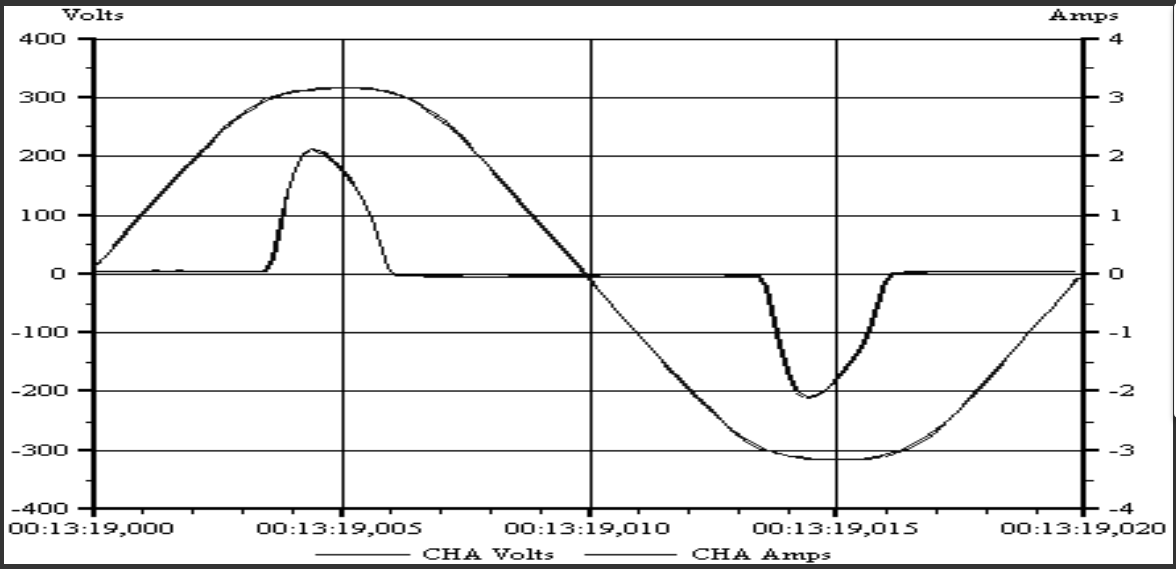
- Harmonics: Frequency components that are integer multiples of the fundamental line frequency

- fundamental frequency is 50 Hertz
  - 3rd Harmonic is 3 x 50Hz or *150Hz*
  - 5th Harmonic is 5 x 50Hz or *250Hz*, etc.

Harmonics

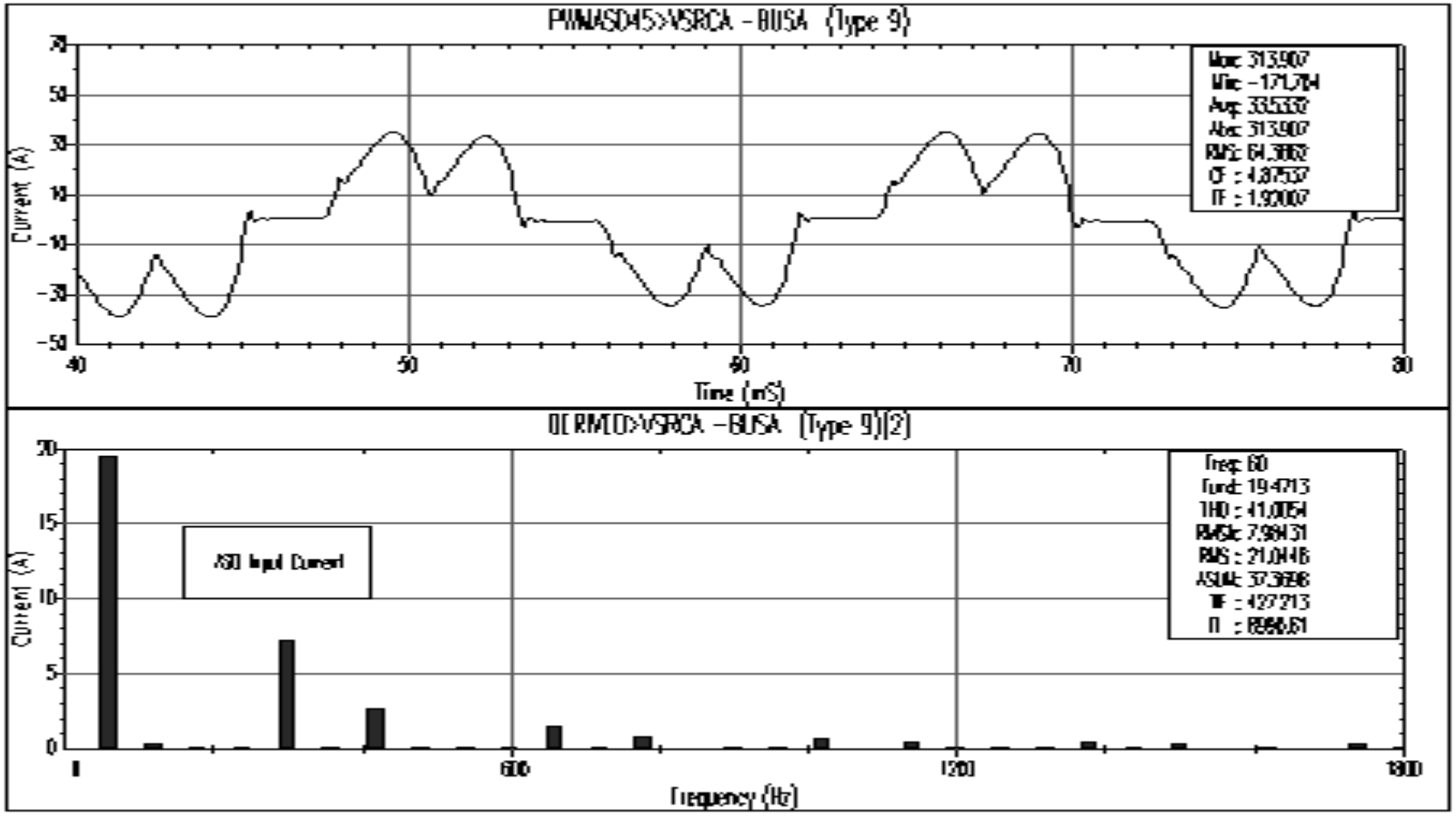


Single phase, two-pulse diode rectifier with capacitive DC-link



Phase voltage (continuous) and phase current (pulsed) to a television receiver

Harmonics



Current Waveform and Harmonic Spectrum for an ASD Input Current

Harmonics

- The Fourier theorem states that any periodic function f(t) can be described by an infinite series of sine and cosine terms of frequency that is the integer multiple of the fundamental frequency of f(t):

$$f(t) = a_0 + \sum_{h=1}^{\infty} a_h \cos(h\omega t) + b_h \sin(h\omega t)$$

$$a_0 = \frac{1}{T}\int_0^T f(t)dt$$

is the zero frequency or average value of f(t).

Harmonics

The Fourier theorem

- Special cases:
  - $a_o = 0$ half-wave symmetric waveforms
  - half-wave symmetric waveforms have no even-ordered harmonics
  - $b_h = 0$ for even functions {f(t)= f(-t)}, **no sine terms**
  - $a_h = 0$ for odd functions {f(t)= -f(-t)}; **no cosine terms**

Harmonics

- Coefficients

$$a_h = \frac{1}{T/2}\int_0^T f(t)\cos(h\omega t)\,d\,\omega t$$

$$b_h = \frac{1}{T/2}\int_0^T f(t)\sin(h\omega t)\,d\,\omega t$$

$$h = 1, 2, 3, \cdots$$

Harmonics

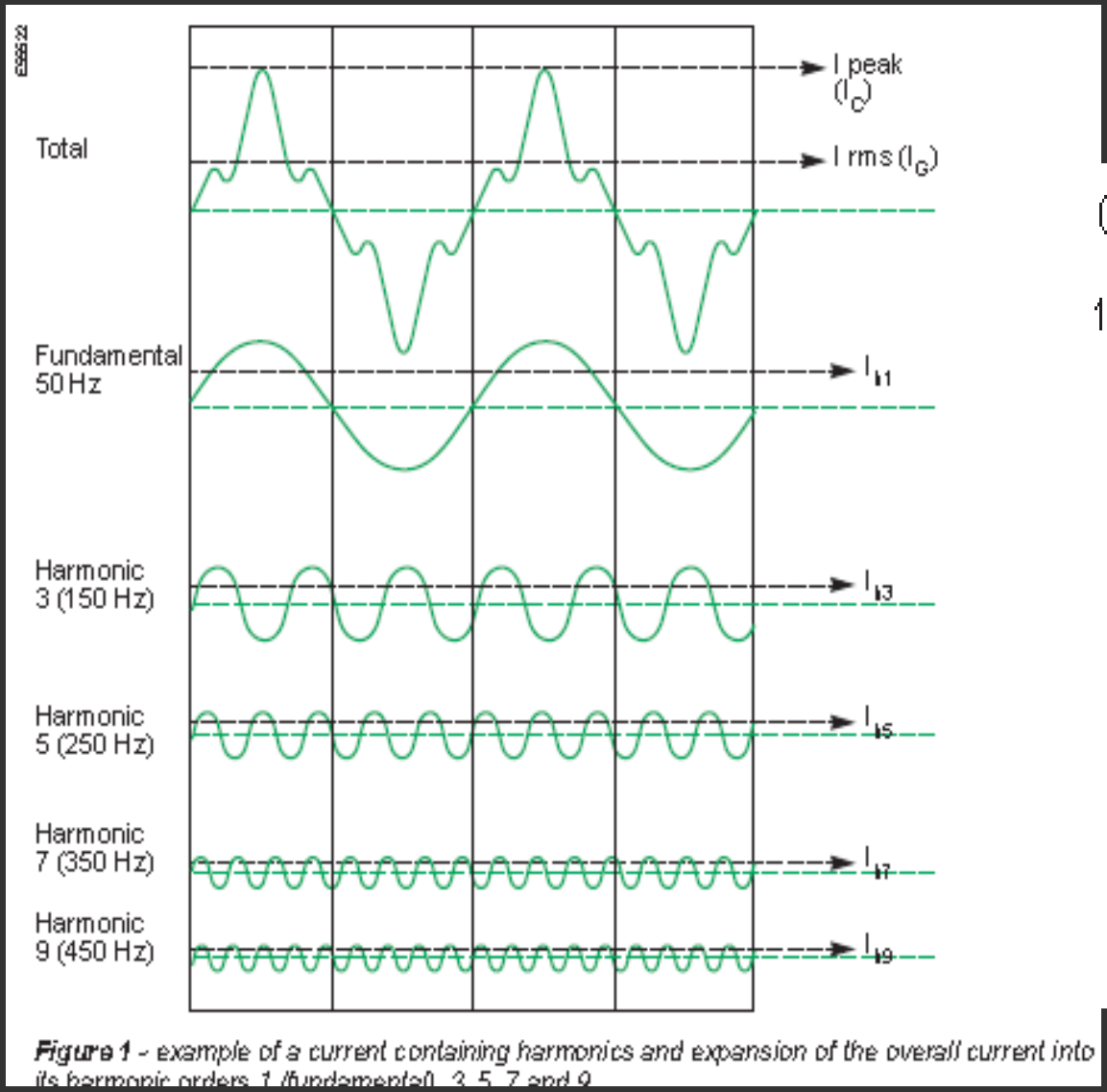
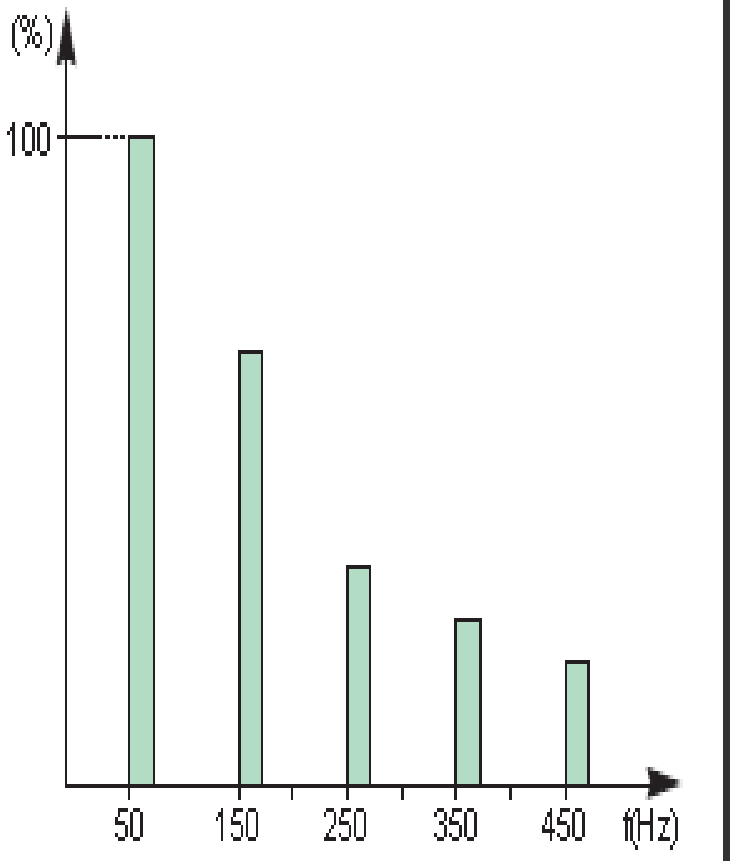


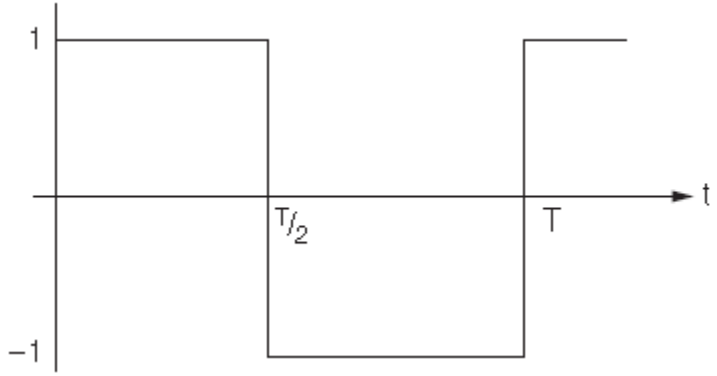
Figure 1 - example of a current containing harmonics and expansion of the overall current into its harmonic orders 1 (fundamental), 3, 5, 7 and 9

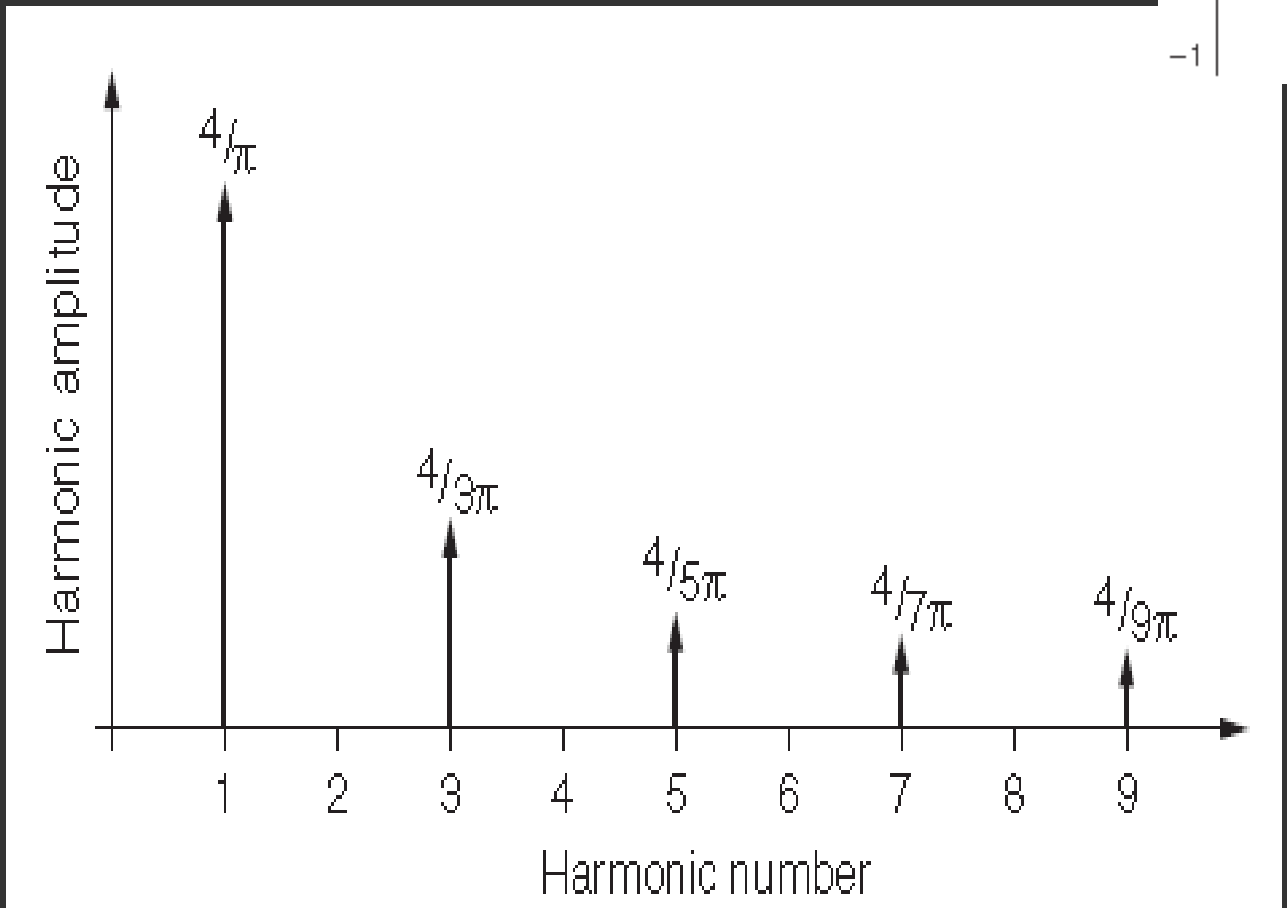
Frequency spectrum



WAVEFORM DISTORTION: Square Wave

$$v(t) = \left(\frac{4}{\pi}\right)\sin(\omega t) + \left(\frac{4}{3\pi}\right)\sin(3\omega t) + \left(\frac{4}{5\pi}\right)\sin(5\omega t) + \cdots$$





Harmonics

- **Root-mean square:** Root-mean square is a measure of the heating value of a periodic waveform when this periodic waveform drives a resistive load. Mathematically, the root-mean square or rms of a periodic voltage waveform is expressed as:

$$V_{\text{rms}} = \sqrt{\frac{1}{T}\int_0^T [v(t)]^2 dt}$$

Harmonics

- For a sine wave of peak value V_{pk}, the rms value is

$$V_{\text{rms}} = \frac{V_{\text{pk}}}{\sqrt{2}}$$

- A DC current has an rms value equal to the steady-state current, or:

$$I_{\text{rms}} = I$$

- The rms value of the total waveform made up of the sum of individual currents is the sum of the squares of the rms values of the individual components, or:

$$I_{\text{rms}} = \sqrt{I_{1,\text{rms}}^2 + I_{2,\text{rms}}^2 + I_{3,\text{rms}}^2 + \cdots}$$

Harmonics

THD

It is also common to use a single quantity, the Total Harmonic Distortion (THD), as a measure of the effective value of harmonic distortion.

$$THD = \sqrt{\sum_{h=2}^{h=h_{max}} \left(\frac{V_h}{V_1}\right)^2} \; x100 < 5\%$$

$$THD = \sqrt{\frac{V_{rms}^2 - V_{1,rms}^2}{V_{1,rms}^2}}$$

Where V_1-Fundamental frequency voltage component

V_h=h th harmonic voltage component

The *Total Demand Distortion (TDD) is the* same term as the Total Harmonic Distortion except that the distortion is expressed as a percent of some rated load current rather than as a percent of the fundamental current magnitude.

Harmonics

THD

$$THD(V) = \frac{100\ \sqrt{(V_2^2 + V_3^2 + \ldots + V_n^2)}}{V_1}(\%)$$

$$THD(I) = \frac{100\ \sqrt{(I_2^2 + I_3^2 + \ldots + I_n^2)}}{I_1}(\%)$$

Harmonics

Power and Reactivate Power in Harmonics

$$P = \sum_{h=1}^{\infty} V_h I_h \cos\varphi_h \quad , \quad Q = \sum_{h=1}^{\infty} V_h I_h \sin\varphi_h$$

$$\text{Distortion Power} \quad D = \sqrt{S^2 - P^2 - Q^2}$$

$$PF = \frac{1}{\sqrt{1 + THD^2}} \text{Cos}\ \varphi$$

Harmonics

K-Factor:

- *Both No load & Load losses are affected by the presence of harmonics. But the variation in load losses contributes more to excessive heat generation in distribution transformer.*
- *The tolerance level of the transformer to withstand the disturbance is described by the K-factor.*

$$K-\text{factor}=\sum_{h=1}^{n} I_{h\,p.u}{}^{2}h^{2}$$

$$I_{h\,p.u}=\frac{I_h}{I_{RMS}}$$

- *h-harmonic term*

Harmonics

Derating Factor:

- *If the transformer is not designed with the consideration of harmonics, its rating will be proportionally decreased when carrying harmonic currents.*

$$K-derate=\frac{1}{\sqrt{1+0.1*(I_{h\,p.u}{}^{2}h^{1.6})}}$$

$$I_{h\,p.u}=\frac{I_h}{I_1}$$

Harmonics

Harmonic relationship with respect to the fundamental component.

- Positive sequence harmonics (4th, 7th, 10th , .. (6n+1) th) have the same phase rotation as the fundamental component. These harmonics circulate between the phases.
- Negative sequence harmonics (2^{nd}, 5^{th}, 8^{th}.. (6n-1) th) have the opposite phase rotation with respect to the fundamental component. These harmonics circulate between the phases.
- Zero sequence harmonics (3rd, 6th, 9th, ….. (6n-3) th) do not produce a rotating field. These harmonics circulate between the phase and neutral or ground. These third order or zero sequence harmonics, unlike positive and negative sequence harmonic currents, do not cancel but add up arithmetically at the neutral bus.

Harmonics

- What do harmonics do?
- Harmonics are carried through the system from the source and can nearly **double** the amount of current on the neutral conductor in three phase four wire distribution systems.
- Distorted currents from harmonic-producing loads also distort the voltage as they pass through the system impedence. Therefore, a distorted voltage can be presented to other end users on the system.
- Overall electrical system and power quality is affected by the introduction of harmonics.

Harmonics

Effect of harmonics

- Overheated Transformers and Motors
  - Increases Hysteresis (magnetization) losses in steel and iron cores of transformers, motor and magnetic trip units of circuit breakers (Equipment inefficiencies and overheating)
- Heating of Neutral Conductors
- Low Voltage at End Loads

Harmonics

- Effect of Harmonics

  Fuses and Thermal Relays

  - Fuses & bimetal strips respond to True RMS
  - Harmonic currents increase eddy current losses in the core steel of the metallic strip.
  - This causes an overprotection situation… Increased losses generate additional heat, this effect the thermal trip of the unit.

Harmonics

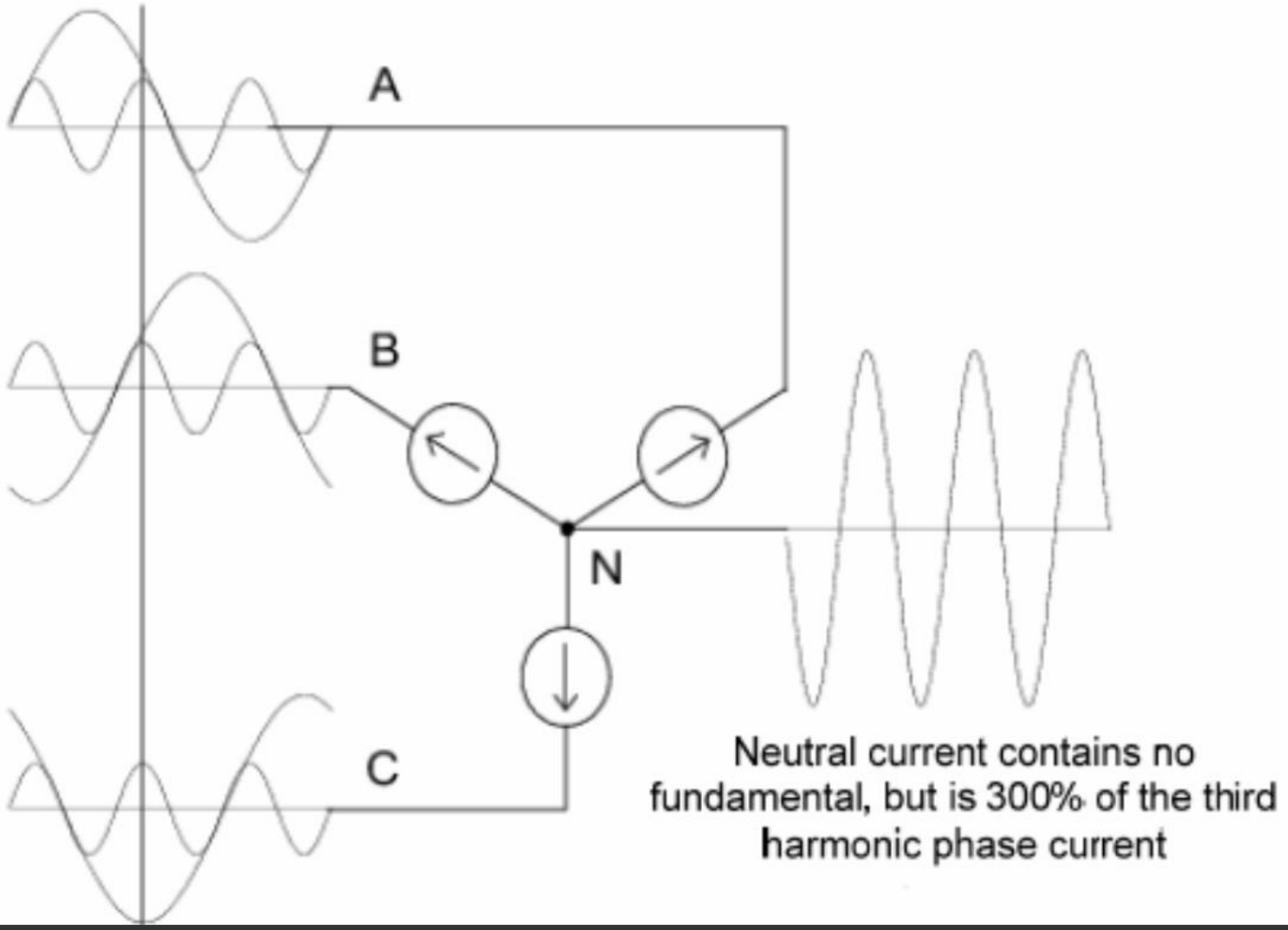
- Operation Problems of Relays and Circuit Breakers
  - Electronic Trip Circuit Breakers
    - Magnitude and phase angle(s) of harmonic current(s) in relationship to the fundamental current can cause:
      - Overprotection: Peak current sensing > True RMS
      - Underprotection: Peak current sensing < True RMS
    - Changing power system loads will vary the magnitude and phase angle, resulting in inaccurate and unpredictable sensing units and overload protection

Harmonics

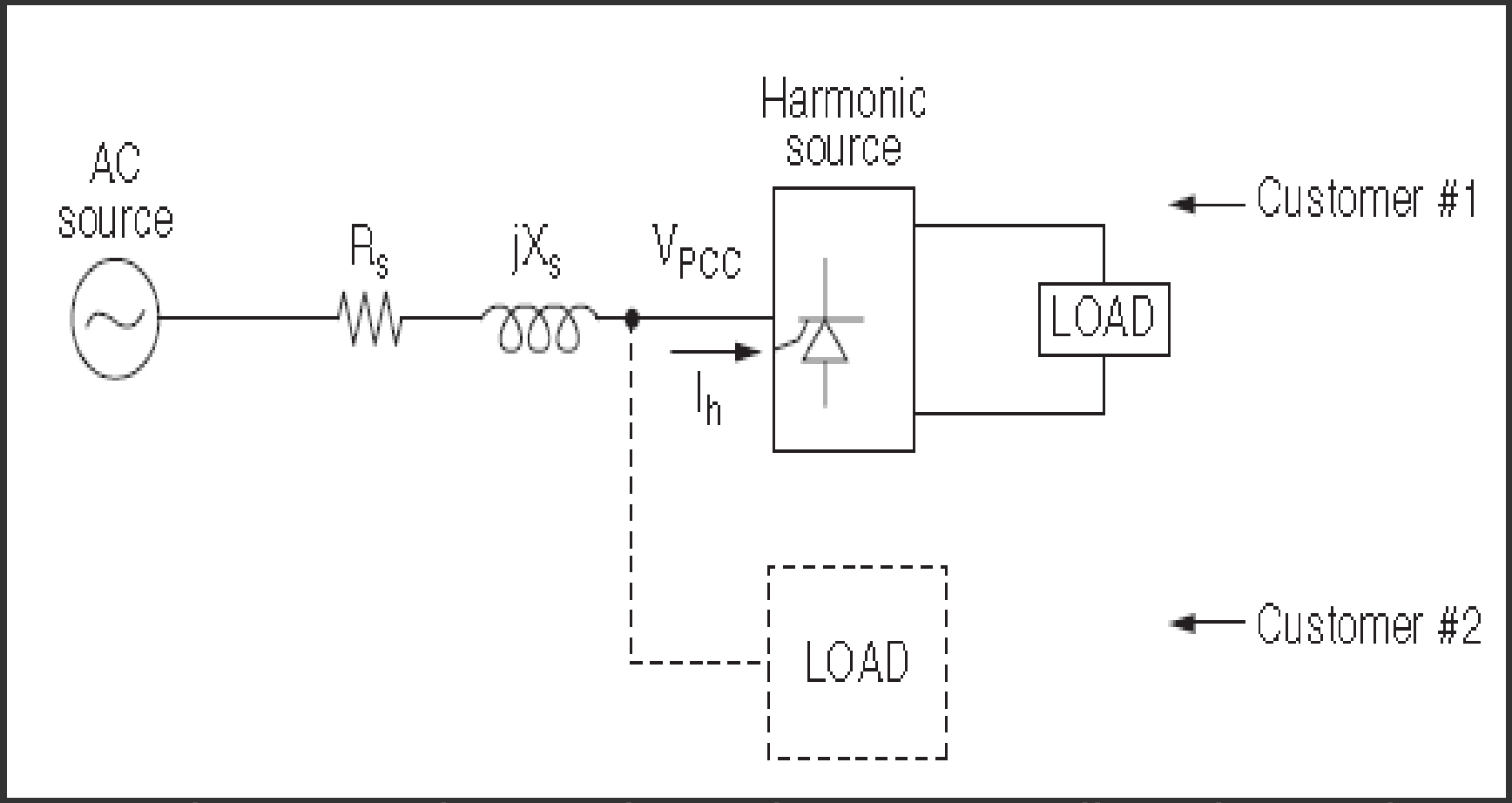
- Communication Problems
  - If sharing common parallel path, potential for harmonics to have inductive coupling effect on unshielded cabling
- Current Measurement Problems (distorted waveform)
- Unreliable Operation of Electronic Equipment
  - Mis-operation of electronic equipment that measures frequency or uses the zero crossing point of a sine wave.
  - Control of Speed and Voltage Problems on Emergency Generators (supplying power)
  - Computer (PC/CPU) data errors / data loss
  - Affects power supplies and sensitive electronics

Harmonics

Zero sequence current

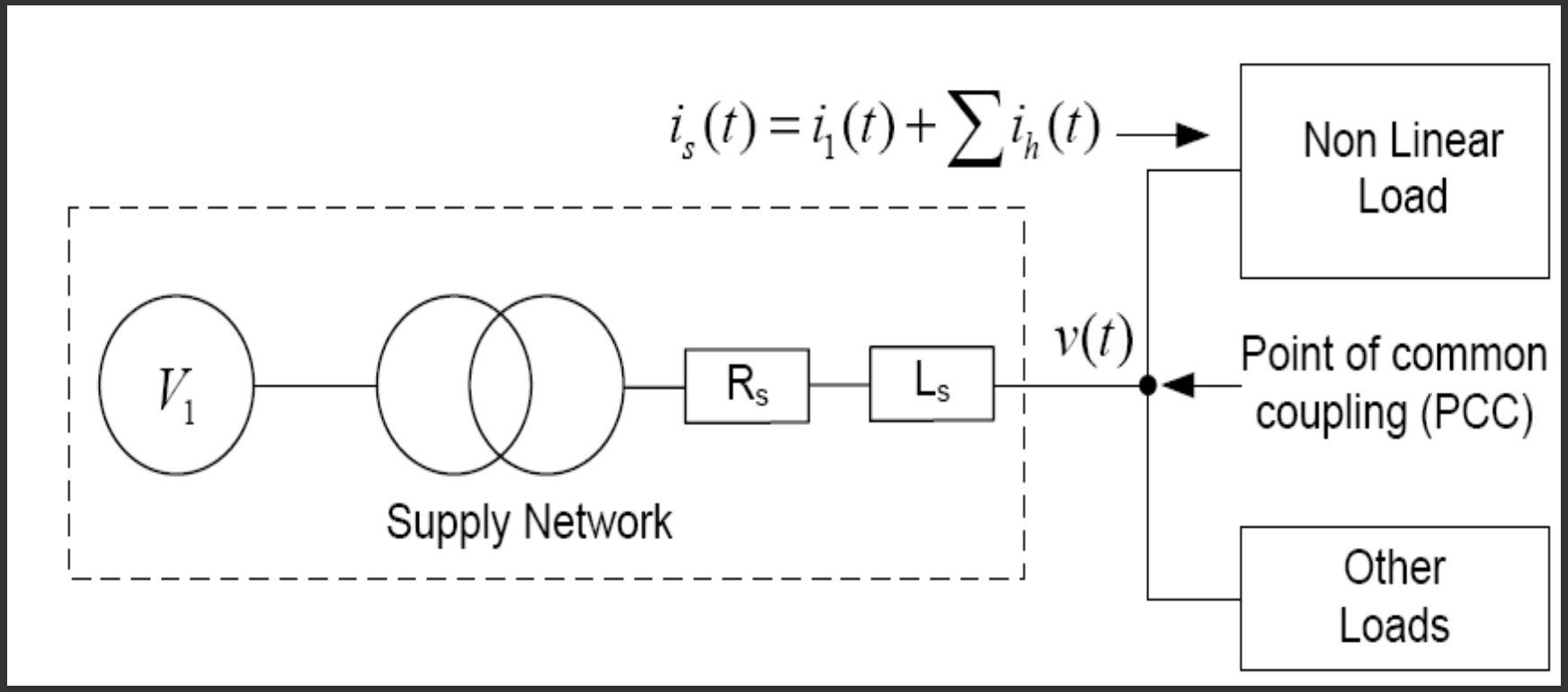


Harmonics



Harmonic-generating load causing voltage distortion at the point of common coupling (PCC). The AC source is modeled as an ideal voltage source in series with a resistance *Rs and a reactance* jX_s.

Harmonics


$i_s(t) = i_1(t) + \sum i_h(t)$
Non Linear Load
V_1
R_s
L_s
$v(t)$
Point of common coupling (PCC)
Supply Network
Other Loads

Power-Quality Standards

- IEEE Standards 519- defines acceptable power quality
- IEEE Standards 1159- defines the measurement of power-quality “events”

Power-Quality Standards- IEEE 519

Table 11.1
Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Power-Quality Standards

Current Distortion Limits for General Distribution Systems (120 V Through 69 000 V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

- *I_{SC} maximum short-circuit current at PCC.*
- *I_L maximum demand load-current (fundamental frequency component) at PCC.*

How Can Harmonics be Reduced?

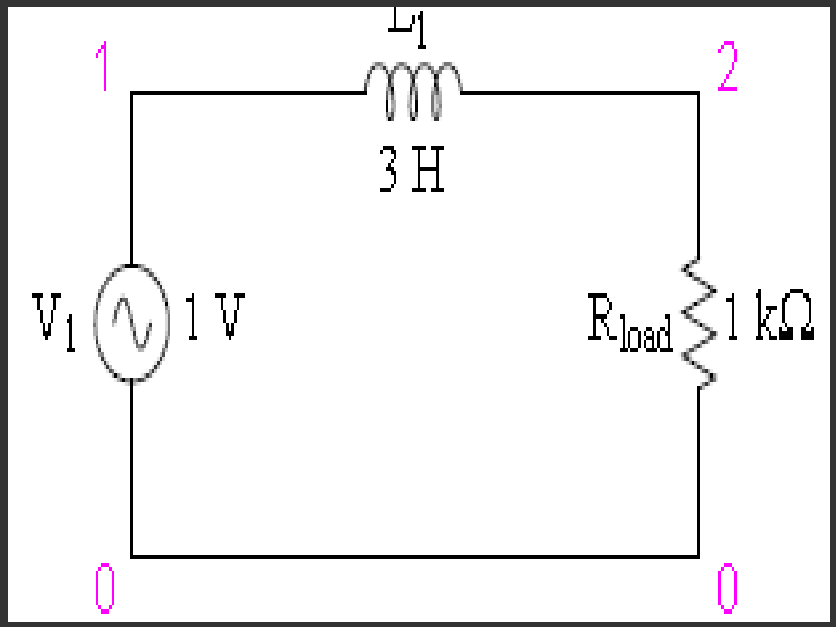
- Isolate harmonic loads on separate circuits
- Filter capacitor banks: a circuit capable of selectively filtering one frequency or range of frequencies out of a mix of different frequencies is called a filter circuit, or simply a filter.
- Utilize ample transformer and conductor sizes.

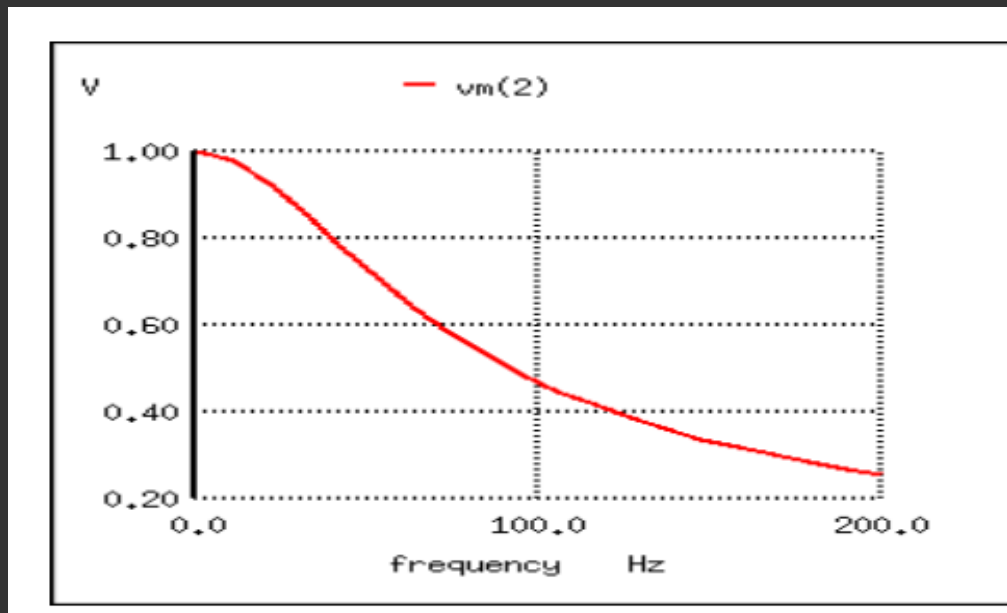
How Can Harmonics be Reduced?

- Utilize ample transformer and conductor sizes.
- Switch power-factor correction capacitors in small steps.
- Utilize soft motor starters.
- Use of appropriate transformers types. Y-Δ zigzag connection. The 30-degree phase shift between the two secondary voltages serves to cancel the fifth and seventh of the primary current.

Filters

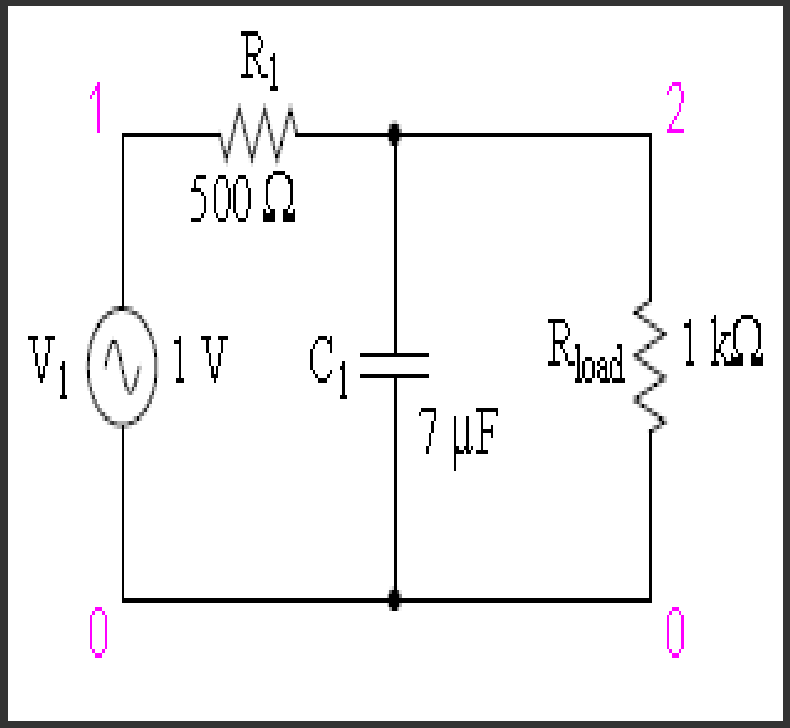
- A low-pass filter is a circuit offering easy passage to low-frequency signals and difficult passage to high-frequency signals. The inductor's impedance increases with increasing frequency. This high impedance in series tends to block high-frequency signals from getting to the load.

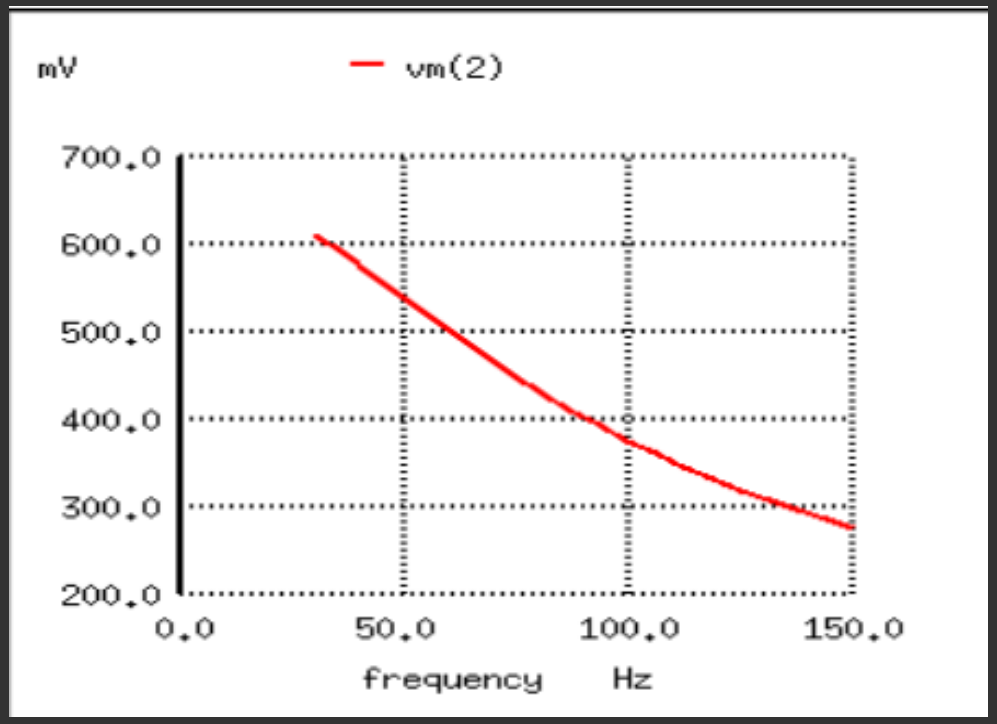




Filters

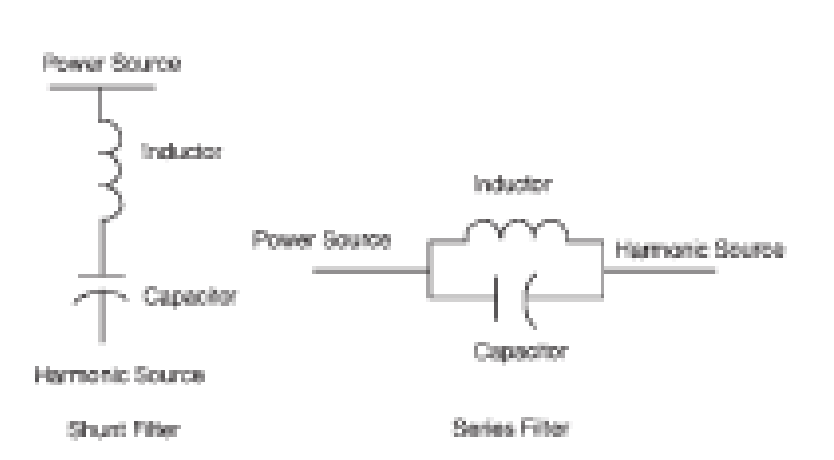
- A high-pass filter: The capacitor's impedance decreases with increasing frequency. This low impedance in parallel with the load resistance tends to short out high-frequency signals, dropping most of the voltage across series resistor.





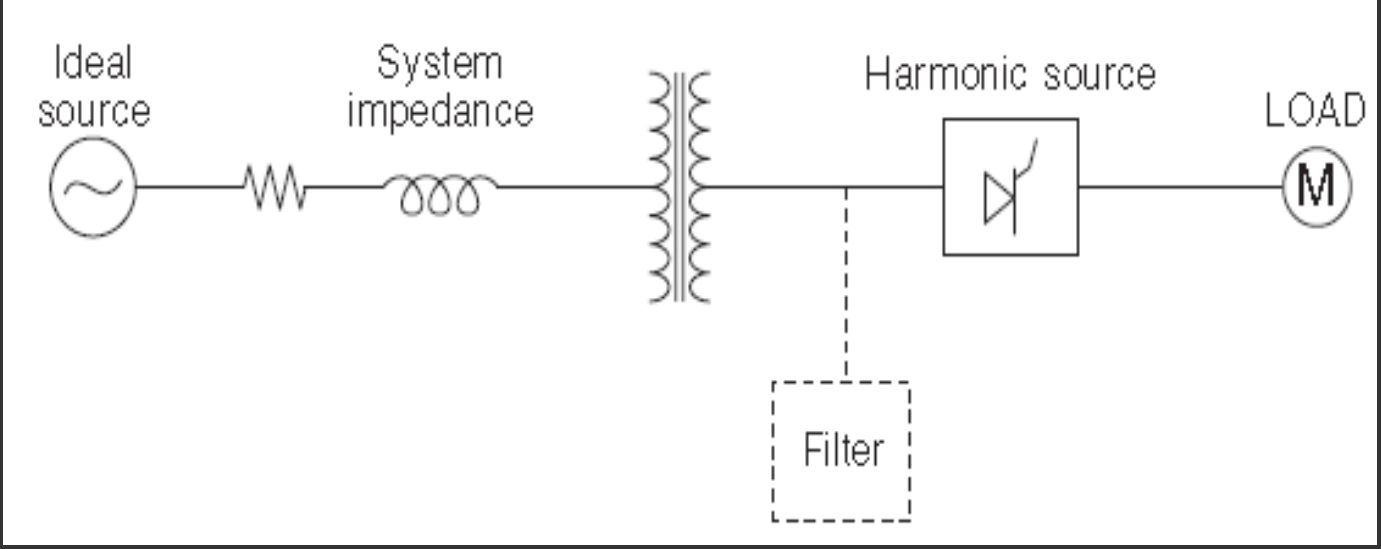
Filters

Passive filters: Shunt and Series Filters



Filters

- **Shunt passive filters.** The most common type of passive filter is the single-tuned “notch” filter. The notch filter is series-tuned to present a low impedance to a particular harmonic current and is connected in shunt with the power system. Thus, harmonic currents are diverted from their normal flow path on the line through the filter.



Filters

- **Shunt passive filters.** The filter is usually placed as shown in Figure to divert a selected portion of the harmonic currents produced by the nonlinear load. The filter is usually made up of one or more sections, as shown in Figure. The single-tuned RLC filter for each harmonic frequency is the most common. The impedance *Z of the single-tuned section shown in Figure* is given by:

$$Z = R + j(X_L - X_C)$$

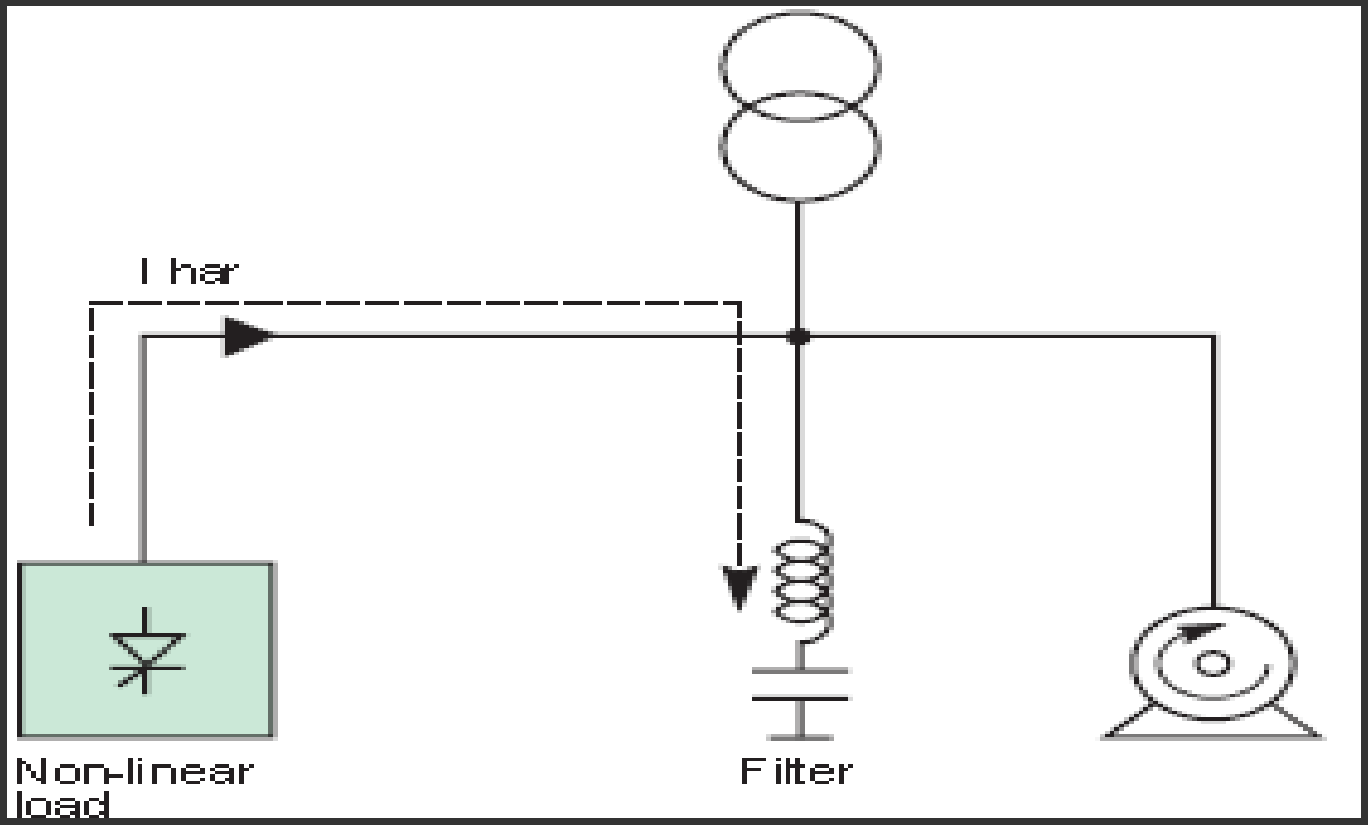
- The resistance *R is due to the winding loss and the core loss of the* inductor. The quality factor, or *Q of an inductor, is given by:*

$$Q = \frac{\omega L}{R} = \frac{X_L}{R}$$

- Typical values of *Q for filter inductors are 25 to 45 at 50 Hz.*

Filters

Passive filter



Passive filter is tuned to a harmonic order near the one to be eliminated. A number of parallel-connected filters may be used when a significant reduction in distortion over a range of orders is required.

Filters

Passive filter

- This impedance is given by

$$Z_o = j\left(\omega L - \frac{1}{\omega C}\right)$$

And the corresponding series resonance frequency at which the filter is tuned is given by

$$fo = \frac{1}{2\pi\sqrt{LC}}$$

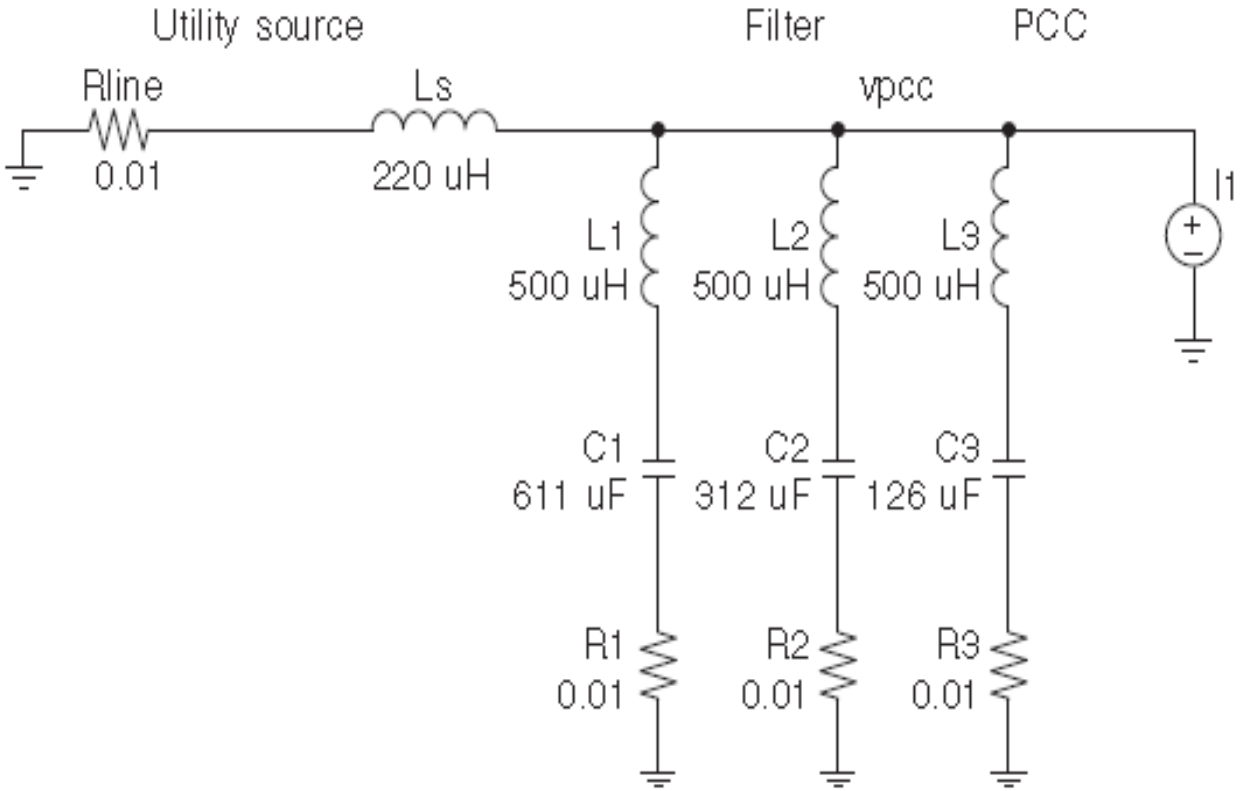
Filters

Passive Filters:

- **Series passive filters.** Unlike a notch filter which is connected in shunt with the power system, a series passive filter is connected in series with the load.
- The inductance and capacitance are connected in parallel and are tuned to provide a high impedance at a selected harmonic frequency.

Filters

- Multi-section filters: The filter is designed to attenuate higher-order harmonics such as the 5th, 7th, and 11th that are generated by the nonlinear load.



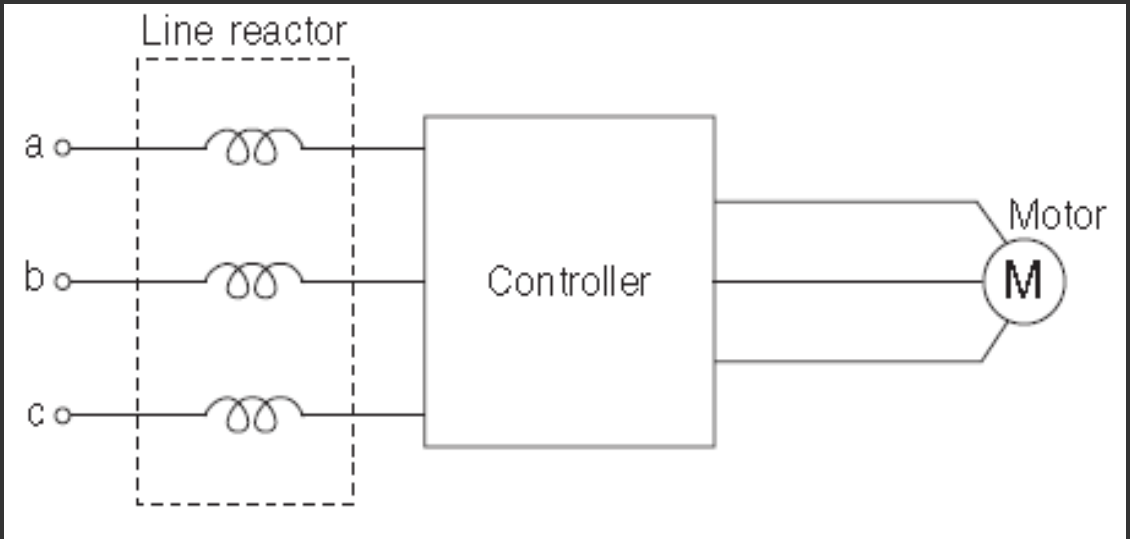
$$f_1 = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

$$f_2 = \frac{1}{2\pi\sqrt{L_2 C_2}}$$

$$f_3 = \frac{1}{2\pi\sqrt{L_3 C_3}}$$

Filters

- **Line reactor:** One of the simplest harmonic filters is the line reactor shown as the three-legged inductor in Figure. This magnetic component is often used in the line in series with motor controllers and other converters that draw significant harmonic current. The reactor presents high impedance to high frequency currents while passing the fundamental.



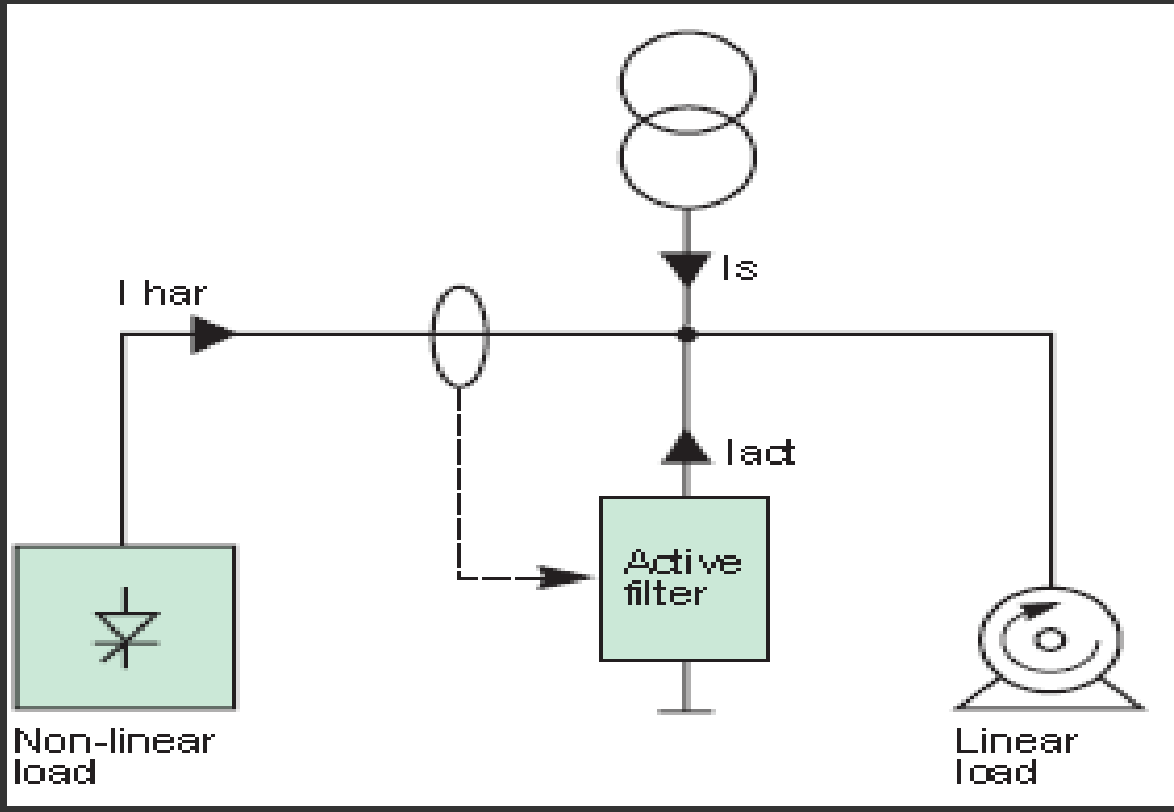
Filters

Active filters

- Active filters are relatively new types of devices for eliminating harmonics. They are based on sophisticated power electronics and are much more expensive than passive filters.
- They can also address more than one harmonic at a time and combat other power quality problems such as flicker.
- The basic idea is to replace the portion of the sine wave that is missing in the current in a nonlinear load.

Filters

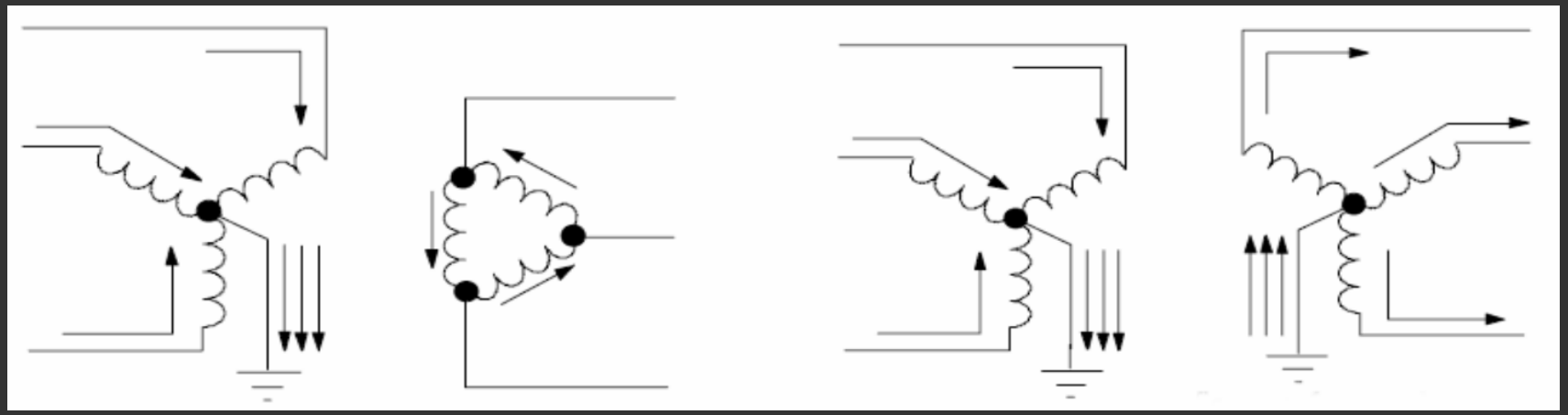
The active filter injects, in opposite phase, the harmonics drawn by the load, such that the line current I_s remains sinusoidal.



An electronic control monitors the line voltage and/or current, and force it to be sinusoidal.

Harmonics Mitigation

Transformer connection



Balanced triplen harmonic currents are blocked by delta transformer windings