AC POWER SYSTEMS HANDBOOK

Third Edition

Jerry C. Whitaker

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For Jenny and Andy,
very special people

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Preface

Disturbances on the ac power line are what headaches are made of. Outages, surges, sags, transients: they combine to create an environment that can damage or destroy sensitive load equipment. They can take your system down and leave you with a complicated and expensive repair job.

Ensuring that the equipment at your facility receives clean ac power has always been important. But now, with computers integrated into a wide variety of electronic products, the question of ac power quality is more critical than ever. The computer-based systems prevalent today can garble or lose data because of power-supply disturbances or interruptions. And if the operational problems are not enough, there is the usually difficult task of equipment troubleshooting and repair that follows a utility system fault.

This book examines the key elements of ac power use for commercial and industrial customers. The roots of ac power-system problems are identified, and effective solutions are detailed. The book follows a logical progression from generating ac energy to the protection of life and property. General topics include:

- **Power-System Operation.** Every electronic installation requires a steady supply of clean power to function properly. The ac power line into a facility is, in fact, the lifeblood of any operation. It is also, however, a frequent source of equipment malfunctions and component failures. This book details the process of generating ac energy and distributing it to end-users. The causes of power-system disturbances are detailed, and the characteristics of common fault conditions are outlined.
- **Protecting Equipment Loads.** Power quality is a moving target. Utility companies work hard to maintain acceptable levels of performance. However, the wide variety of loads and unpredictable situations make this job difficult. Users cannot expect power suppliers to solve all their problems. Responsibility for protecting sensitive loads clearly rests with the end-user. Several chapters are devoted to this important topic. Power-system protection options are outlined, and their relative benefits discussed. Evaluating the many tradeoffs involved in protection system design requires a thorough knowledge of the operating principles.
- **How Much Protection**? The degree of protection afforded a facility is generally a compromise between the line abnormalities that will account for most of the expected problems and the amount of money available to spend on that protection. Each installation is unique and requires an assessment of the importance of keeping the system up and running at all times, as well as the threat of disturbances posed by the ac feed to the plant. The author firmly believes that the degree of protection provided a power-distribution system should match the threat of system failure. In this publication, all alternatives are examined with an eye toward deciding how much protection really is needed, and how much money can be justified for ac protection hardware.
- **Grounding.** The attention given to the design and installation of a facility ground system is a key element in the day-to-day reliability of any plant. A well-planned ground network is invisible to the

engineering staff. A marginal ground system, however, will cause problems on a regular basis. Although most engineers view grounding primarily as a method to protect equipment from damage or malfunction, the most important element is operator safety. The 120 V or 208 V ac line current that powers most equipment can be dangerous — even deadly — if improperly handled. Grounding of equipment and structures provides protection against wiring errors or faults that could endanger human life. Grounding concepts and practices are examined in detail. Clear, step-by-step guidelines are given for designing and installing an effective ground system to achieve good equipment performance, and to provide for operator safety.

- **Standby Power**. Blackouts are, without a doubt, the most troublesome utility company problem that a facility will have to deal with. Statistics show that power failures are, generally speaking, a rare occurrence in most areas of the country. They also are usually short in duration. Typical failure rates are not normally cause for alarm to commercial users, except where computer-based operations, transportation control systems, medical facilities, and communications sites are concerned. When the continuity of operation is critical, redundancy must be carried throughout the system. All of the practical standby power systems are examined in this book. The advantages and disadvantages of each approach are given, and examples are provided of actual installations.
- **Safety**. Safety is critically important to engineering personnel who work around powered hardware, and who may work under time pressures. Safety is not something to be taken lightly. The voltages contained in the ac power system are high enough to kill through electrocution. The author takes safety seriously. A full chapter is devoted to the topic. Safety requires not only the right equipment, but operator training as well. Safety is, in the final analysis, a state of mind.

The utility company ac feed contains not only the 60 Hz power needed to run the facility, but also a variety of voltage disturbances, which can cause problems ranging from process control interruptions to life-threatening situations. Protection against ac line disturbances is a science that demands attention to detail. This work is not inexpensive. It is not something that can be accomplished overnight. Facilities will, however, wind up paying for protection one way or another, either before or after problems occur. Power protection is a *systems problem* that extends from the utility company ac input to the circuit boards in each piece of hardware. There is nothing magical about effective systems protection. Disturbances on the ac line can be suppressed if the protection method used has been designed carefully and installed properly. That is the goal of this book.

Jerry C. Whitaker

About the Author

Jerry C. Whitaker is vice president of standards development at the Advanced Television Systems Committee (ATSC). Mr. Whitaker supports the work of the various ATSC technology and planning committees and assists in the development of ATSC standards, recommended practices, and related documents. ATSC is an international, nonprofit organization developing voluntary standards for digital television.

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Mr. Whitaker has been involved in various aspects of the electronics industry for over 30 years. Current CRC book titles include:

- *The Electronics Handbook*, 2nd edition
- *Electronic System Maintenance Handbook*, 2nd edition
- *Power Vacuum Tubes Handbook*, 2nd edition
- *The RF Transmission Systems Handbook*
- *Microelectronics*, 2nd edition

Mr. Whitaker has lectured extensively on the topic of electronic systems design, installation, and maintenance. He is the former editorial director and associate publisher of *Broadcast Engineering* and *Video Systems* magazines, and a former radio station chief engineer and television news producer.

Mr. Whitaker has twice received a Jesse H. Neal Award Certificate of Merit from the Association of Business Publishers for editorial excellence. He has also been recognized as educator of the year by the Society of Broadcast Engineers.

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1 AC Power Systems

1.1 Introduction

Every electronic installation requires a steady supply of clean power to function properly. Recent advances in technology have made the question of alternating current (ac) power quality even more important, as microcomputers are integrated into a wide variety of electronic products.

When the subject of power quality is discussed, the mistaken assumption is often made that the topic only has to do with computers. At one time this may have been true, because data processing (DP) centers were among the first significant loads that did not always operate reliably on the raw power received from the serving electrical utility. With the widespread implementation of control by microprocessor-based single-board computers (or single-chip computers), however, there is a host of equipment that now operates at voltage levels and clock speeds similar to that of the desktop or mainframe computer. Equipment as diverse as electronic instrumentation, cash registers, scanners, motor drives, and television sets all depend upon onboard computers to give them instructions. Thus, the quality of the power this equipment receives is as important as that supplied to a data processing center. The broader category, which covers all such equipment, including computers, is perhaps best described as *sensitive electronic equipment*.

The heart of the problem that seems to have suddenly appeared is that although the upper limit of circuit speed of modern digital devices is continuously being raised, the logic voltages have simultaneously been reduced. Such a relationship is not accidental. As more transistors and other devices are packed together onto the same surface area, the spacing between them is necessarily reduced. This reduced distance between components tends to lower the time the circuit requires to perform its designed function. A reduction in the operating voltage level is a necessary — and from the standpoint of overall performance, particularly heat dissipation, desirable — by-product of the shrinking integrated circuit (IC) architectures.

The ac power line into a facility is, of course, the lifeblood of any operation. It is also, however, a frequent source of equipment malfunctions and component failures. The utility company ac feed contains not only the 60 Hz power needed to run the facility, but also a variety of voltage sags, surges, and transients. These abnormalities cause different problems for different types of equipment.

1.1.1 Defining Terms

To explain the ac power-distribution system, and how to protect sensitive loads from damage resulting from disturbances, it is necessary first to define key terms:

- *active filter*. A switching power processor connected between the line and a nonlinear load, with the purpose of reducing the harmonic currents generated by the load.
- *alternator*. An ac generator.
- *boost rectifier*. An unfiltered rectifier with a voltage-boosting direct current (dc)/dc converter between it and the load that shapes the line current to maintain low distortion.
- *circular mil*. The unit of measurement for current-carrying conductors. One mil is equal to 0.001 in. (0.025 mm). One circular mil is equal to a circle with a diameter of 0.001 in. The area of a circle with a 1-in. diameter is 1,000,000 circular mils.
- *common-mode noise*. Unwanted signals in the form of voltages appearing between the local ground reference and each of the power conductors, including neutral and the equipment ground.
- *cone of protection* (lightning). The space enclosed by a cone formed with its apex at the highest point of a lightning rod or protecting tower, the diameter of the base of the cone having a definite relationship to

the height of the rod or tower. When overhead ground wires are used, the space protected is referred to as a *protected zone*.

- *cosmic rays*. Charged particles (ions) emitted by all radiating bodies in space.
- *Coulomb*. A unit of electric charge. The coulomb is the quantity of electric charge that passes the cross section of a conductor when the current is maintained constant at 1 A.
- *counter-electromotive force*. The effective electromotive force within a system that opposes the passage of current in a specified direction.
- *counterpoise*. A conductor or system of conductors arranged (typically) below the surface of the earth and connected to the footings of a tower or pole to provide grounding for the structure.
- *demand meter*. A measuring device used to monitor the power demand of a system; it compares the peak power of the system with the average power.
- *dielectric* (ideal). An insulating material in which all of the energy required to establish an electric field in the dielectric is recoverable when the field or impressed voltage is removed. A perfect dielectric has zero conductivity, and all absorption phenomena are absent. A complete vacuum is the only known perfect dielectric.
- *eddy currents*. The currents that are induced in the body of a conducting mass by the time variations of magnetic flux.
- *efficiency* (electric equipment). Output power divided by input power, expressed as a percentage.
- *electromagnetic compatibility* (EMC). The ability of a device, piece of equipment, or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances.
- *generator*. A machine that converts mechanical power into electrical power. (In this book, the terms *alternator* and *generator* will be used interchangeably.)
- *grid stability*. The capacity of a power distribution grid to supply the loads at any node with stable voltages; its opposite is *grid instability*, manifested by irregular behavior of the grid voltages at some nodes.
- *ground loop*. Sections of conductors shared by two different electronic or electric circuits, usually referring to circuit return paths.
- *horsepower*. The basic unit of mechanical power. One horsepower (hp) equals 550 foot-pounds per second or 746 watts.
- *HVAC*. Abbreviation for heating, ventilation, and air-conditioning system.
- *hysteresis loss* (magnetic, power, and distribution transformer). The energy loss in magnetic material that results from an alternating magnetic field as the elementary magnets within the material seek to align themselves with the reversing field.
- *impedance*. A linear operator expressing the relationship between voltage and current. The inverse of impedance is *admittance*.
- *induced voltage*. A voltage produced around a closed path or circuit by a time rate of change in a magnetic flux linking that path when there is no relative motion between the path or circuit and the magnetic flux.
- *joule*. A unit of energy equal to 1 watt-second.
- *life safety system*. System designed to protect life and property, such as emergency lighting, fire alarms, smoke exhaust and ventilating fans, and site security.
- *lightning flash*. An electrostatic atmospheric discharge. The typical duration of a lightning flash is approximately 0.5 scc. A single flash is made up of various discharge components, usually including three or four high-current pulses called *strokes*.
- *metal-oxide varistor*. A solid-state voltage-clamping device used for transient-suppression applications.
- *normal-mode noise*. Unwanted signals in the form of voltages appearing in line-to-line and line-to-neutral signals.
- *permeability*. A general term used to express relationships between magnetic induction and magnetizing force. These relationships are either (1) *absolute permeability*, which is the quotient of a change in

magnetic induction divided by the corresponding change in magnetizing force, or (2) *specific* (relative) *permeability*, which is the ratio of absolute permeability to the magnetic constant.

- *point of common coupling* (PCC). The point at which the utility and the consumer's power systems are connected (usually where the energy meter is located).
- *power factor (PF)*. The ratio of total watts to the total root-mean-square (rms) volt-amperes in a given circuit. Power factor = W/VA.
- *power quality*. The degree to which the utility voltage approaches the ideal case of a stable, uninterrupted, zero-distortion, and disturbance-free source.
- *radio frequency interference*. Noise resulting from the interception of transmitted radio frequency energy.
- *reactance*. The imaginary part of impedance.
- *reactive power*. The quantity of unused power that is developed by reactive components (inductive or capacitive) in an ac circuit or system.
- *safe operating area*. A semiconductor device parameter, usually provided in chart form, that outlines the maximum permissible limits of operation.
- *saturation* (in a transformer). The maximum intrinsic value of induction possible in a material.
- *self-inductance*. The property of an electric circuit whereby a change of current induces an electromotive force in that circuit.
- *single-phasing*. A fault condition in which one of the three legs in a three-phase power system becomes disconnected, usually because of an open fuse or fault condition.
- *solar wind*. Charged particles from the sun that continuously bombard the surface of the earth.
- *switching power supply*. Any type of ac/ac, ac/dc, dc/ac, or dc/dc power converter using periodically operated switching elements. Energy-storage devices (capacitors and inductors) are usually included in such supplies.
- *transient disturbance*. A voltage pulse of high energy and short duration impressed upon the ac waveform. The overvoltage pulse may be 1 to 100 times the normal ac potential (or more in some cases) and may last up to 15 ms. Rise times typically measure in the nanosecond range.
- *uninterruptible power system* (UPS). An ac power-supply system that is used for computers and other sensitive loads to (1) protect the load from power interruptions, and (2) protect the load from transient disturbances.
- *VAR compensator*. A switching power processor, operating at the line frequency, with the purpose of reducing the reactive power being produced by a piece of load equipment.
- *voltage regulation*. The deviation from a nominal voltage, expressed as a percentage of the nominal voltage.

1.1.2 Power Electronics

Power electronics is a multidisciplinary technology that encompasses power semiconductor devices, converter circuits, electrical machines, signal electronics, control theory, microcomputers, very-large-scale integration (VLSI) circuits, and computer-aided design techniques. Power electronics in its present state has been possible as a consequence of a century of technological evolution. In the late 19th and early 20th centuries, the use of rotating machines for power control and conversion was well known [1]. Popular examples are the Ward Leonard speed control of dc motors and the Kramer and Scherbius drives of wound rotor induction motors.

The history of power electronics began with the introduction of the glass bulb mercury arc rectifier in 1900 [2]. Gradually, metal tank rectifiers, grid-controlled rectifiers, ignitions, phanotrons, and thyratrons were introduced. During World War II, magnetic amplifiers based on saturable core reactors and selenium rectifiers became especially attractive because of their ruggedness, reliability, and radiation-hardened characteristics.

Possibly the greatest revolution in the history of electrical engineering occurred with the invention of the transistor by Bardeen, Brattain, and Shockley at the Bell Telephone Laboratories in 1948. In 1956,

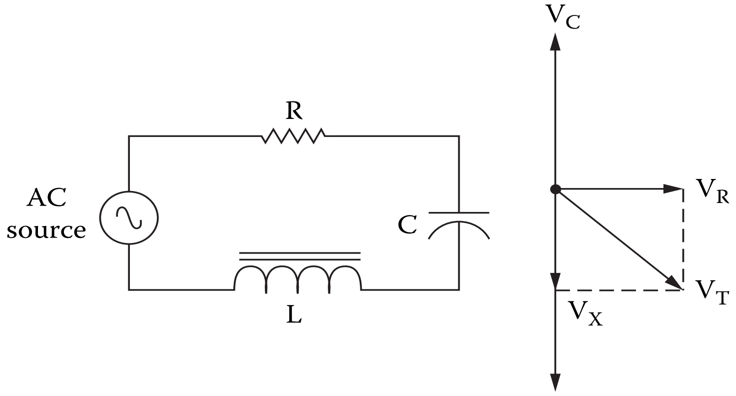


Figure 1.1 Voltage vectors in a series RLC circuit.

the same laboratory invented the PNPN triggering transistor, which later came to be known as the thyristor or silicon controlled rectifier (SCR). In 1958, the General Electric Company introduced the first commercial thyristor, marking the beginning of the modern era of power electronics. Many different types of power semiconductor devices have been introduced since that time, further pushing the limits of operating power and efficiency, and long-term reliability.

It is interesting to note that in modern power electronics systems, there are essentially two types of semiconductor elements: the power semiconductors, which can be regarded as the muscle of the equipment, and the microelectronic control chips, which make up the brain. Both are digital in nature, except that one manipulates power up to gigawatt levels and the other deals with milliwatts or microwatts. Today's power electronics systems integrate both of these end-of-the-spectrum devices, providing large size and cost advantages, and intelligent operation.

1.2 AC Circuit Analysis

Vectors are used commonly in ac circuit analysis to represent voltage or current values. Rather than using waveforms to show phase relationships, it is accepted practice to use vector representations (sometimes called *phasor diagrams*). To begin a vector diagram, a horizontal line is drawn, its left end being the *reference point*. Rotation in a counterclockwise direction from the reference point is considered to be positive. Vectors may be used to compare voltage drops across the components of a circuit containing resistance, inductance, or capacitance. Figure 1.1 shows the vector relationship in a series RLC circuit, and Figure 1.2 shows a parallel RLC circuit.

1.2.1 Power Relationship in AC Circuits

In a dc circuit, power is equal to the product of voltage and current. This formula also is true for purely resistive ac circuits. However, when a reactance — either inductive or capacitive — is present in an ac circuit, the dc power formula does not apply. The product of voltage and current is, instead, expressed in volt-amperes (VA) or kilovoltamperes (kVA). This product is known as the *apparent power*. When meters are used to measure power in an ac circuit, the apparent power is the voltage reading multiplied by the current reading. The actual power that is converted to another form of energy by the circuit is measured with a wattmeter, and is referred to as the *true power*. In ac power-system design and operation, it is desirable to know the ratio of true power converted in a given circuit to the apparent power of the circuit. This ratio is referred to as the power factor.

1.2.2 Complex Numbers

A complex number is represented by a *real part* and an *imaginary part*. For example, in $A = a + jb$, A is the complex number; a is real part, sometimes written as Re(A) and b is the imaginary part of A, often

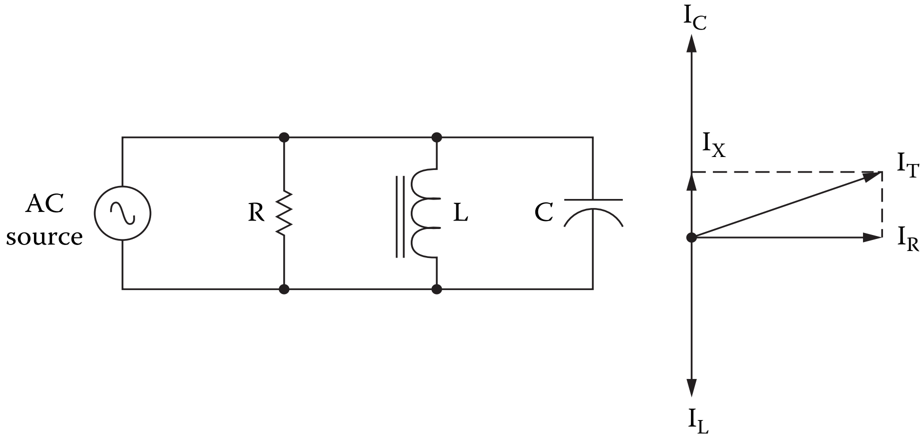


Figure 1.2 Current vectors in a parallel RLC circuit.

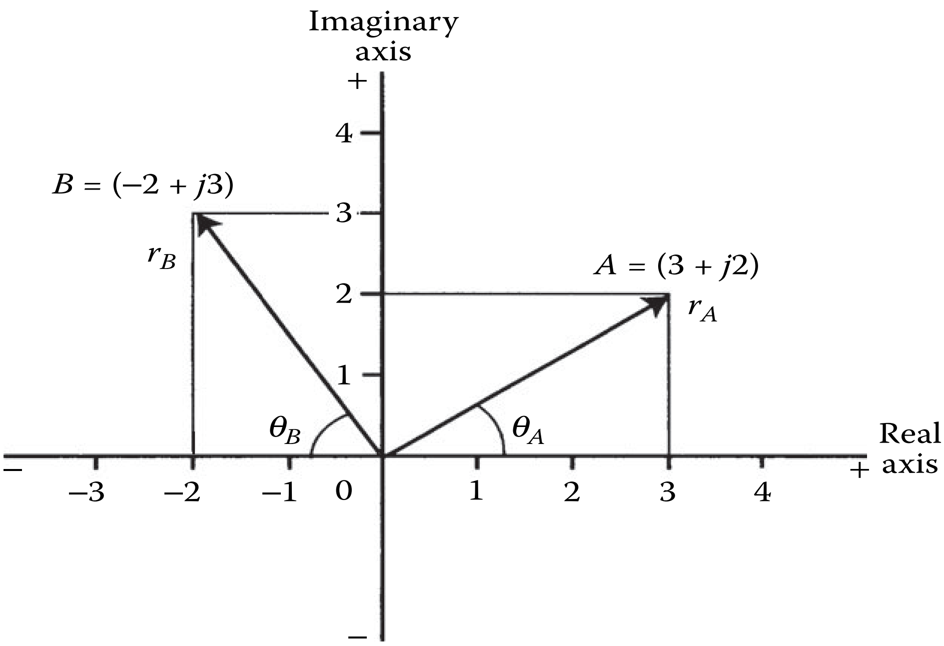


Figure 1.3 The *s* plane representing two complex numbers. (*From* Reference 3. *Used with permission.*)

written as Im(A). It is a convention to precede the imaginary component by the letter j (or i). This form of writing the real and imaginary components is called the *Cartesian form* and symbolizes the complex (or s) plane, wherein both the real and imaginary components can be indicated graphically [3]. To illustrate this, consider the same complex number A when represented graphically, as shown in Figure 1.3. A second complex number B is also shown to illustrate the fact that the real and imaginary components can take on both positive and negative values. Figure 1.3 also shows an alternate form of representing complex numbers. When a complex number is represented by its magnitude and angle, for example, $A = r_A \angle \theta_A$, it is called the *polar representation.*

To see the relationship between the Cartesian and the polar forms, the following equations can be used:

$$r_A = \sqrt{a^2 + b^2} \tag{1.1}$$

$$\theta_A = \tan^{-1} \frac{b}{a} \tag{1.2}$$

Conceptually, a better perspective can be obtained by investigating the triangle shown in Figure 1.4, and considering the trigonometric relationships. From this figure, it can be seen that

$$a = Re(A) = r_A \cos(\theta_A) \tag{1.3}$$

$$b = Im\,(A) = r_A \sin(\theta_A) \tag{1.4}$$

The well-known *Euler's identity* is a convenient conversion of the polar and Cartesian forms into an exponential form, given by

$$\exp\ (j\ \theta) = \cos\ \theta + j\ \sin\ \theta \tag{1.5}$$

1.2.3 Phasors

The ac voltages and currents appearing in distribution systems can be represented by phasors, a concept useful in obtaining analytical solutions to one-phase and three-phase system design. A phasor is generally defined as a transform of sinusoidal functions from the time domain into the complex-number domain and given by the expression

$$\boldsymbol{V} = \quad V\ \exp(j\theta) = P\{V\cos(\omega\, t + \theta)\} = V\angle\theta \tag{1.6}$$

where $\boldsymbol{V}$ is the phasor, V is the magnitude of the phasor, and θ is the angle of the phasor. The convention used here is to use boldface symbols to symbolize phasor quantities. Graphically, in the time domain, the phasor $\boldsymbol{V}$ would be a simple sinusoidal wave shape, as shown in Figure 1.5. The concept of a phasor leading or lagging another phasor becomes very apparent from the figure.

Phasor diagrams are also an effective medium for understanding the relationships between phasors. Figure 1.6 shows a phasor diagram for the phasors represented in Figure 1.5. In this diagram, the convention of positive angles being read counterclockwise is used. The other alternative is certainly possible, as well. It is quite apparent that a purely capacitive load could result in the phasors shown in Figure 1.5 and Figure 1.6.

1.2.4 Per Unit System

In the per unit system, basic quantities such as voltage and current are represented as certain percentages of base quantities. When so expressed, these per unit quantities do not need units, thereby making numerical analysis in power systems somewhat easier to handle. Four quantities encompass all variables required to solve a power system problem. These quantities are:

- Voltage
- Current
- Power
- Impedance

Out of these, only two base quantities, corresponding to voltage (V_b) and power (S_b), are required to be defined. The other base quantities can be derived from these two. Consider the following. Let

V_b = Voltage base, kV
S_b = Power base, MVA
I_b = Current base, A
Z_b = Impedance base, Q

Then,

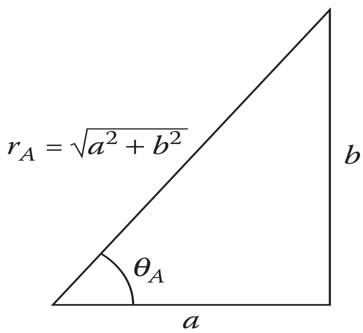


Figure 1.4 The relationship between Cartesian and polar forms. (*From* Reference 3. *Used with permission.*)

$$Z_b = \frac{V_b^2}{S_b}\,\Omega \tag{1.7}$$

$$I_b = \frac{V_b 10^3}{Z_b} A \tag{1.8}$$

1.3 Elements of the AC Power System

The process of generating, distributing, and controlling the large amounts of power required for a municipality or geographic area is highly complex. However, each system, regardless of its complexity, is composed of the same basic elements with the same basic goal: deliver ac power where it is needed by customers. The primary elements of an ac power system can be divided into the following general areas of technology:

- Power generators
- Power transformers
- Capacitors
- Transmission circuits
- Control and switching systems, including voltage regulators, protection devices, and fault isolation devices

The path that electrical power takes to end users begins at a power plant, where electricity is generated by one of several means and is then stepped-up to a high voltage (500 kV is common) for transmission on high-tension lines. Step-down transformers reduce the voltage to levels appropriate for local distribution and eventual use by customers. Figure 1.7 shows how these elements interconnect to provide ac power to consumers.

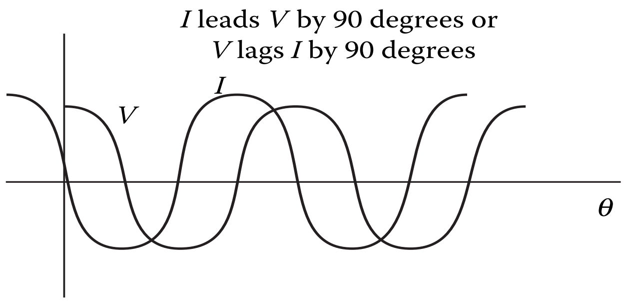


Figure 1.5 Waveforms representing leading and lagging phasors. (*From* Reference 3. *Used with permission.*)

1.3.1 Transmission Circuits

The heart of any utility power-distribution system is the cable used to tie distant parts of the network together. Conductors are rated by the American Wire Gauge (AWG) scale. The smallest is no. 36, and the largest is no. 0000. There are 40 sizes in between. Sizes larger than no. 0000 AWG are specified in *thousand circular mil* units, referred to as "MCM" units (M is the Roman numeral expression for 1000). The cross-sectional area of a conductor doubles with each increase of three AWG sizes. The diameter doubles with every six AWG sizes.

Most conductors used for power transmission are made of copper or aluminum. Copper is the most common. Stranded conductors are used where flexibility is required. Stranded cables usually are more durable than solid conductor cables of the same AWG size. For long distances, utilities typically use uninsulated aluminum conductors or aluminum conductor steel-reinforced cables. For shorter distances, insulated copper wire normally is used.

Ampacity is the measure of the ability of a conductor to carry electric current. Although all metals will conduct current to some extent, certain metals are more efficient than others. The three most common high-conductivity conductors are

- Silver, with a resistivity of 9.8 Ω/circular mil-ft
- Copper, with a resistivity of 10.4 Ω/circular mil-ft
- Aluminum, with a resistivity of 17.0 Ω/circular mil-ft

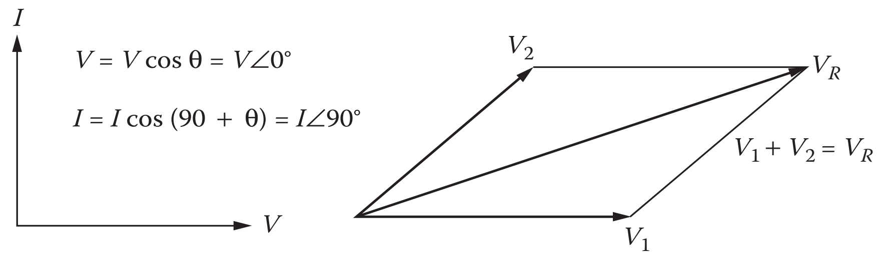


Figure 1.6 Phasor diagram showing phasor representation and phasor operation. (*From* Reference 3. *Used with permission.*)

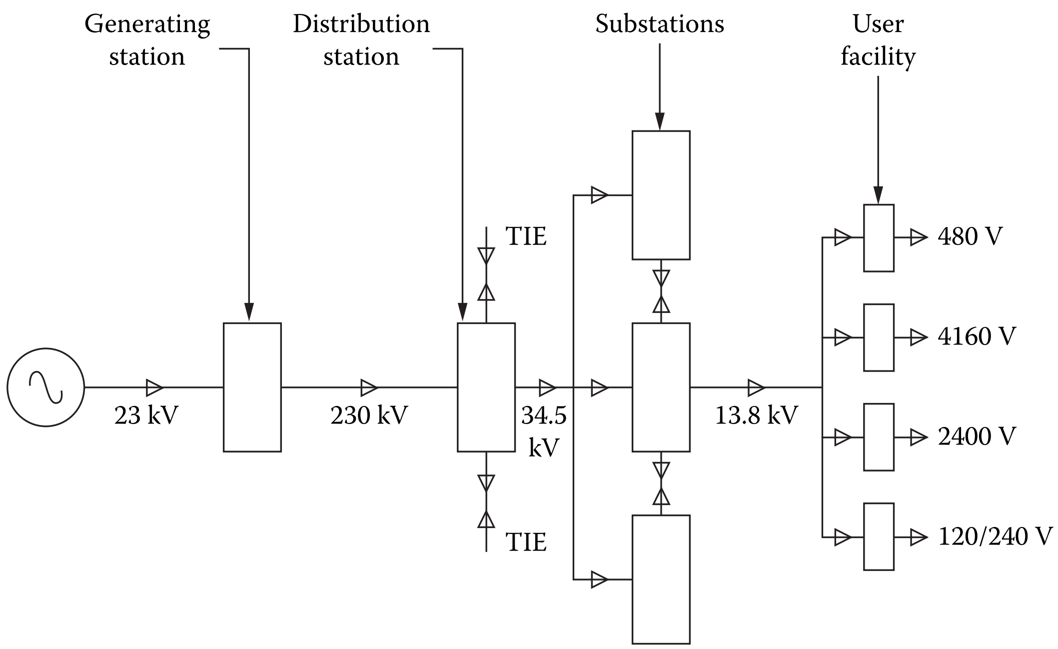


Figure 1.7 A typical electrical power-generation and distribution system. Although this schematic diagram is linear, in practice power lines branch at each voltage reduction to establish the distribution network. (*From* [4]. *Used with permission.*)

The ampacity of a conductor is determined by the type of material used, the cross-sectional area, and the heat-dissipation effects of the operating environment. Conductors operating in free air will dissipate heat more readily than conductors placed in a larger cable or in a raceway with other conductors will. Table 1.1 lists the principal parameters of common wire sizes.

1.3.1.1 Types of Conductors

Wire and cable designed for use in a power-distribution system can be roughly divided into two categories:

- Overhead conductors
- Underground cables

Each will be examined in the following sections.

1.3.1.2 Overhead Conductors

Many different types of conductors are used on overhead distribution lines [3]. They vary in both size and number, depending on the voltage level and the type of circuit. Copper, aluminum, and steel are the most commonly used materials for overhead lines. Copper is used in three forms: hard drawn, medium-hard drawn, and soft drawn or *annealed*. Hard-drawn copper has the greatest strength and is used for circuits of relatively long spans (200 ft or more). However, its inflexibility makes it harder to

Table 1.1 Characteristics of Copper Wire

Wire Size (AWG)	Diameter (mils)	Circular Mil Area	Ohms/1000 ft (20°C)	Current-Carrying Capacity at 700 C.M./A	Diameter (mm)
1	289.3	83,690	0.1239	119.6	7.348
2	257.6	66,370	0.1563	94.8	6.544
3	229.5	52,640	0.1970	75.2	5.827
4	204.3	41,740	0.2485	59.6	5.189
5	181.9	33,100	0.3133	47.3	4.621
6	162.0	26,250	0.3951	37.5	4.115
7	144.3	20,820	0.4902	29.7	3.665
8	128.5	16,510	0.6282	23.6	3.264
9	114.4	13,090	0.7921	18.7	2.906
10	101.9	10,380	0.9989	14.8	2.588
11	90.7	8,234	1.260	11.8	2.305
12	80.8	6,530	1.588	9.33	2.053
13	72.0	5,178	2.003	7.40	1.828
14	64.1	4,107	2.525	5.87	1.628
15	57.1	3,257	3.184	4.65	1.450
16	50.8	2,583	4.016	3.69	1.291
17	45.3	2,048	5.064	2.93	1.150
18	40.3	1,624	6.385	2.32	1.024
19	35.9	1,288	8.051	1.84	0.912
20	32.0	1,022	10.15	1.46	0.812
21	28.5	810	12.80	1.16	0.723
22	25.3	642	16.14	0.918	0.644

work with. The soft-drawn variety is the weakest of the copper conductors. Its use is limited to short spans. The medium-hard-drawn copper conductor has found widespread use in medium-range distribution circuits.

Steel wire is only about one tenth as good a conductor as copper and, hence, is rarely used alone. However, it offers an economic advantage over the other types of conductors. Also, because steel wire is much stronger than copper, it permits longer spans and requires fewer supports.

Aluminum is only 60 to 80% as good a conductor as copper and only half as strong as copper. However, its property of lighter weight, as compared to copper and steel, and its relative advantage in transmitting ac power because of reduced *skin effect* makes it suitable for overhead lines. Usually, the aluminum wires are stranded on a core of steel wire to form what is termed an *aluminum conductor steel-reinforced* (ACSR) conductor. The more strands in the ACSR conductor, the greater flexibility it will have. Hence, the larger conductors used today are all stranded and twisted in layers concentrically around a central steel wire.

Table 1.2 lists the characteristics of various conductors that are typically used on overhead distribution lines.

Table 1.2 General Characteristics of Overhead Conductors (*After* [5].)

Conductor	Type	Resistance (Ω / mi)	Diameter (in.)	Amperes
1,000,000	AA	0.1050	1.150	698
556,500	ACSR	0.1860	0.927	730
500,000	AA	0.2060	0.813	483
336,400	ACSR	0.3060	0.721	530
4/0	ACSR	0.5920	0.563	340
2/0	AA	0.7690	0.414	230
1/0	ACSR	1.1200	0.398	230
1/0	CU	0.6070	0.368	310
#2	AA	1.5400	0.292	156
#2	ACSR	1.6900	0.316	180
#4	ACSR	2.5500	0.257	140
#10	CU	5.9030	0.102	80
#12	CU	9.3750	0.081	75
#14	CU	14.8720	0.064	2

1.3.1.3 Underground Cables

Underground construction of distribution lines is designed mostly for urban areas and is dictated by economics, congestion, and density of population [3]. Although overhead lines have been ordinarily considered to be less expensive and easier to maintain, developments in underground cable and construction technology have narrowed the cost gap to the point where such systems are competitive in many urban and suburban residential installations.

The conductors used underground are different from overhead lines in that they are insulated for their entire length, and several of them may be combined under one protective sheath. The whole assembly is called an *electric cable*. These cables are either buried directly in the ground, or they may be installed in ducts buried in the ground. The conductors in cables are usually made of copper or aluminum and are usually stranded. They are made of soft-drawn copper because they do not have to support any appreciable weight. Cables can be either single conductor or multiple conductors enclosed in a single sheath for economy.

1.3.1.4 Skin Effect

The effective resistance offered by a conductor to high frequencies is considerably greater than the ohmic resistance measured with direct currents (dc). This is because of an action known as the *skin effect*, which causes the currents to be concentrated in certain parts of the conductor and leaves the remainder of the cross section to contribute little toward carrying the applied current.

When a conductor carries an alternating current, a magnetic field is produced that surrounds the wire. This field continually is expanding and contracting as the ac current wave increases from zero to its maximum positive value and back to zero, then through its negative half-cycle. The changing magnetic lines of force cutting the conductor induce a voltage in the conductor in a direction that tends to retard the normal flow of current in the wire. This effect is more pronounced at the center of the conductor. Thus, current within the conductor tends to flow more easily toward the surface of the wire. The higher the frequency, the greater the tendency for current to flow at the surface. The depth of current flow is a function of frequency and is determined from

$$d = \frac{2.6}{\sqrt{\mu f}} \tag{1.9}$$

where

d = Depth of current in mils
μ = Permeability (copper = 1, steel = 300)
f = Frequency of signal in MHz

It can be calculated that at a frequency of 100 kHz, current flow penetrates a conductor by 8 mils. At 1 MHz, the skin effect causes current to travel in only the top 2.6 mils in copper, and even less in almost all other conductors. Therefore, the series impedance of conductors at high frequencies is significantly higher than at low frequencies. Figure 1.8 shows the distribution of current in a radial conductor.

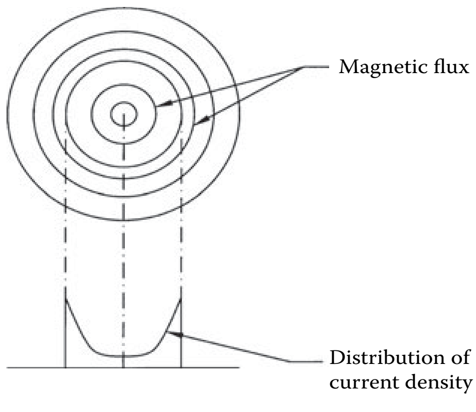


Figure 1.8 The skin effect on a conductor.

When a circuit is operating at high frequencies, the skin effect causes the current to be redistributed over the conductor cross section in such a way as to make most of the current flow where it is encircled by the smallest number of flux lines. This general principle controls the distribution of current regardless of the shape of the conductor involved. With a flat-strip conductor, the current flows primarily along the edges, where it is surrounded by the smallest amount of flux.

It is evident from Equation 1.9 that the skin effect is minimal at power-line frequencies for copper conductors. For steel conductors at high current, however, skin effect considerations are often important.

1.3.2 Dielectrics and Insulators

Dielectrics are materials that are used primarily to isolate components electrically from each other or ground or to act as capacitive elements in devices, circuits, and systems [6]. The insulating properties of dielectrics are directly attributable to their large energy gap between the highest filled valence band and the conduction band. The number of electrons in the conduction band is extremely low because the energy gap of a dielectric (5 to 7 eV) is sufficiently large to maintain most of the electrons trapped in the lower band. As a consequence, a dielectric subjected to an electric field will allow only an extremely small conduction or *loss current*. This current will be caused by the following:

- The finite number of free electrons available
- Other free charge carriers (ions) typically associated with contamination by electrolytic impurities
- Dipole orientation losses arising with polar molecules under ac conditions

Often, the two latter effects will tend to obscure the minuscule contribution of the relatively few free electrons available. Unlike solids and liquids, vacuum and gases (in their nonionized state) approach the conditions of a perfect insulator — i.e., they exhibit virtually no detectable loss or leakage current.

Two fundamental parameters that characterize a dielectric material are its *conductivity* σ and the value of the *real permittivity* or *dielectric constant* ε'. By definition, σ is equal to the ratio of the *leakage current density* J_l to the applied electric field E

$$\sigma = \frac{J_1}{E} \tag{1.10}$$

Because J_l is in A cm^{-2} and E is in V cm^{-1}, the corresponding units of σ are in S cm^{-1} or Ω^{-1} cm^{-1}.

Under ac conditions, *dielectric losses* arise mainly from the movement of free charge carriers (electrons and ions), space charge polarization, and dipole orientation. Ionic, space charge, and dipole losses are temperature and frequency dependent, a dependency that is reflected in the measured values of σ and ε'. This necessitates the introduction of a complex permittivity e defined by $\varepsilon = \varepsilon' - j\varepsilon''$, where ε'' is the imaginary value of the permittivity.

As the voltage is increased across a dielectric material, a point is ultimately reached beyond which the insulation will no longer be capable of sustaining any further rise in voltage and breakdown will ensue, causing a short circuit to develop between the electrodes. If the dielectric consists of a gas or liquid medium, the breakdown will be self-healing in the sense that the gas or liquid will support anew a reapplication of voltage. In a solid dielectric, however, the initial breakdown will result in a formation of a permanent conductive channel, which cannot support a reapplication of full voltage.

The breakdown strength of a dielectric under dc and impulse conditions tends to exceed that at ac fields, thereby suggesting the ac breakdown process is partially of a thermal nature. An additional factor, which may lower the ac breakdown strength, is that associated with the occurrence of partial discharges either in void inclusions or at the electrode edges. This leads to breakdown values much lower than the intrinsic value. In practice, breakdown values are generally of an extrinsic nature, and the intrinsic values are useful conceptually insofar as they provide an idea of an upper value that can be attained only under ideal conditions.

All insulating materials will undergo varying degrees of aging or deterioration under normal operating conditions. The rate of aging will be contingent upon the magnitude of the electrical, thermal, and mechanical stresses to which the material is subjected. It will also be influenced by the composition and molecular structure of the material itself, as well as the chemical, physical, and radiation environment under which the material must operate. The useful life of an insulating system will, thus, be determined by a given set and subset of aging variables. For example, the subset of variables in the voltage stress variable are the average and maximum values of the applied voltage, its frequency, and the recurrence rate of superposed impulse or transient voltage surges. For the thermal stress, the upper and lower ambient temperatures, the temperature gradient in the insulation, and the maximum permissible operating temperature constitute the subvariable set. In addition, the character of the mechanical stress will differ, depending upon whether torsion, compression, or tension and bending are involved.

Furthermore, the aging rate will be differently affected if all stresses (electrical, thermal, and mechanical) act simultaneously, separately, or in some predetermined sequence. The influence exerted on the aging rate by the environment will depend on whether the insulation system will be subjected to corrosive chemicals, petroleum fluids, water or high humidity, air or oxygen, ultraviolet radiation from the sun, and nuclear radiation. Organic insulations, in particular, may experience chemical degradation in the presence of oxygen. For example, polyethylene under temperature cycle will undergo both physical and chemical changes. These effects will be particularly acute at high operating temperatures (90 to 130°C). At these temperatures, partial or complete melting of the polymer will occur, and the increased diffusion rate will permit the oxygen to migrate to a greater depth into the polymer. Ultimately, the antioxidant will be consumed, resulting in an embrittlement of the polymer and, in extreme cases, in the formation of macroscopic cracks. Subjection of the polymer to many repeated overload cycles will be accompanied by repeated melting and recrystallization of the polymer — a process that will inevitably cause the formation of cavities, which, when subjected to sufficiently high voltages, will undergo discharge, leading eventually to electrical breakdown.

The 60 Hz breakdown strength of a 1 cm gap of air at 25°C at atmospheric pressure is 31.7 kV cm^{-1}. Although this is a relatively low value, air is a most useful insulating medium for large electrode separations, as is the case for overhead transmission lines. The only dielectric losses in the overhead lines are those resulting from corona discharges at the line conductor surfaces and leakage losses over the insulator surfaces. In addition, the highly reduced capacitance between the conductors of the lines ensures a small capacitance per unit length, thus rendering overhead lines an efficient means for transmitting large amounts of power over long distances.

1.3.2.1 Insulating Liquids

Insulating liquids are rarely used by themselves. Rather, they are intended for use mainly as impregnants with cellulose or synthetic papers [6]. The 60 Hz breakdown strength of practical insulating liquids exceeds that of gases; for a 1-cm gap separation, it is of the order of about 100 kV cm^{-1}. However, because the breakdown strength increases with decreasing gap length and the oils are normally evaluated using a gap separation of 0.254 cm, the breakdown strengths normally cited range from approximately 138 to 240 kV cm^{-1} (Table 1.3). The breakdown values are more influenced by the moisture and particle contents of the fluids than by their molecular structure.

Mineral oils have been extensively used in high-voltage electrical apparatus. They constitute a category of hydrocarbon liquids that are obtained by refining crude petroleum. Their composition consists of paraffinic, naphthenic, and aromatic constituents and is dependent upon the source of the crude as well as the refining procedure followed. The inclusion of the aromatic constituents is desirable because of their gas absorption and oxidation characteristics. Mineral oils used for cable and transformer applications have low polar molecule contents and are characterized by dielectric constants extending from about 2.10 to 2.25, with dissipation factors generally between 2×10^{-5} and 6×10^{-5} at room temperature, depending upon their viscosity and molecular weight. Their dissipation factors increase appreciably at higher temperatures when the viscosities are reduced. Oils may deteriorate in service because of oxidation and moisture absorption.

Alkyl benzenes are used as impregnants in high-voltage cables, often as substitutes for the low-viscosity mineral oils in self-contained, oil-filled cables. The electrical properties of alkyl benzenes are comparable to those of mineral oils, and they exhibit good gas inhibition characteristics. Because of their detergent character, alkyl benzenes tend to be more susceptible to contamination than mineral oils.

Since the discontinued use of the nonflammable *polychlorinated biphenyls* (PCBs), a number of unsaturated synthetic liquids have been developed for use in high-voltage capacitors, where, because of

Table 1.3 Electrical Properties of Common Insulating Liquids (*After* [6].)

Liquid	Viscosity cSt (37.8°C)	Dielectric Constant (at 60 Hz, 25°C)	Dissipation Factor (at 60 Hz, 100°C)	Breakdown Strength (kV cm^{-1})
Capacitor oil	21.00	2.20	0.00100	> 118
Pipe cable oil	170.00	2.15	0.00100	> 118
Self-contained cable oil	49.70	2.30	0.00100	> 118
Heavy cable oil	2365.00	2.23	0.00100	> 118
Transformer oil	9.75	2.25	0.00100	> 128
Alkyl benzene	6.00	2.10	0.00040	> 138
Polybutene pipe cable oil	110.00 (SUS)	2.14 (at 1 MHz)	0.00030	> 138
Polybutene capacitor oil	2200.00 (SUS at 100°C)	2.22 (at 1 MHz)	0.00050	> 138
Silicone fluid	50.00	2.70	0.00015	> 138
Castor oil	98.00 (100°C)	3.74	0.06000	> 138
$C_8F_{16}O$ fluorocarbon	0.64	1.86	< 0.00050	> 138

high stresses, evolved gases can readily undergo partial discharge. Most of these new synthetic capacitor fluids are, thus, gas-absorbing, low-molecular-weight derivatives of benzene, with permittivities ranging from 2.66 to 5.25 at room temperature (compared to 3.5 for PCBs). None of these fluids have the non-flammable characteristics of the PCBs; however, they do have high boiling points.

Silicone liquids consist of polymeric chains of silicon atoms alternating with oxygen atoms and with methyl side groups. For electrical applications, polydimethylsiloxane (PDMS) fluids are used, primarily in transformers as substitutes for the PCBs because of their inherently high flash and flammability points, and reduced environmental concerns.

1.3.2.2 Insulating Solids

Solid insulating materials can be classified into two main categories: organic and inorganic [13]. There are a large number of solid inorganic insulants available, including the following:

- *Alumina*, produced by heating aluminum hydroxide or oxyhydroxide; it is widely used as a filler for ceramic insulators. Further heating yields the *corundum structure*, which in its sapphire form is used for dielectric substrates in microcircuit applications.
- *Porcelain*, a multiphase ceramic material that is obtained by heating aluminum silicates until a *mullite* phase is formed. Because mullite is porous, its surface must be glazed with a high-melting-point glass to render it smooth and impervious to contaminants for use in overhead line insulators.
- *Electrical-grade glasses*, which tend to be relatively lossy at high temperatures. At low temperatures, however, they are suitable for use in overhead line insulators and in transformer, capacitor, and circuit breaker bushings. At high temperatures, their main application lies with incandescent and fluorescent lamps as well as electronic tube envelopes.
- *Mica*, a layer-type dielectric (mica films are obtained by splitting mica blocks). The extended two-dimensionally layered strata of mica prevents the formation of conductive pathways across the substance, resulting in a high dielectric strength. It has excellent thermal stability and, because of its inorganic nature, is highly resistant to partial discharges. It is used in sheet, plate, and tape forms in rotating machines and transformer coils.

Solid organic dielectrics consist of large polymer molecules, which generally have molecular weights in excess of 600. Primarily (with the notable exception of paper, which consists of cellulose that is comprised of a series of glucose units), organic dielectric materials are synthetically derived. Some of the more common insulating materials of this type include:

- *Polyethylene* (PE), perhaps one of the most common solid dielectrics. PE is extensively used as a solid dielectric extruded insulator in power and communication cables. Linear PE is classified as a low- (0.910 to 0.925), medium- (0.926 to 0.940), or high- (0.941 to 0.965) density polymer. Most of the PE used on extruded cables is of the cross-linked polyethylene type.
- *Ethylene-propylene rubber* (EPR), an amorphous elastomer that is synthesized from ethylene and propylene. It is used as an extrudent on cables where its composition has a filler content that

usually exceeds 50% (comprising primarily clay, with smaller amounts of added silicate and carbon black). Dielectric losses are appreciably enhanced by the fillers, and, consequently, EPR is not suitable for extra-high-voltage applications. Its use is primarily confined to intermediate voltages (< 69 kV) and to applications where high cable flexibility (due to its inherent rubber properties) may be required.

- *Polypropylene*, which has a structure related to that of ethylene with one added methyl group. It is a thermoplastic material having properties similar to high-density PE, although because of its lower density, polypropylene has also a lower dielectric constant. Polypropylene has many electrical applications, both in bulk form as molded and extruded insulations, as well as in film form in taped capacitor, transformer, and cable insulations.
- *Epoxy resins*, which are characterized by low shrinkage and high mechanical strength. They can also be reinforced with glass fibers and mixed with mica flakes. Epoxy resins have many applications, including insulation of bars in the stators of rotating machines, solid-type transformers, and spacers for compressed-gas-insulated busbars and cables.

Impregnated-paper insulation is one of the earliest insulating systems employed in electrical power apparatus and cables. Although many current designs use solid- or compressed-gas insulating systems, the impregnated-paper approach still constitutes one of the most reliable insulating techniques available. Proper impregnation of the paper results in a cavity-free insulating system, thereby eliminating the occurrence of partial discharges that inevitably lead to deterioration and breakdown of the insulating system. The liquid impregnants employed are either mineral oils or synthetic fluids.

Low-density cellulose papers have slightly lower dielectric losses, but the dielectric breakdown strength is also reduced. The converse is true for impregnated systems utilizing high-density papers. If the paper is heated beyond 200°C, the chemical structure of the paper breaks down, even in the absence of external oxygen, because the latter is readily available from within the cellulose molecule. To prevent this process from occurring, cellulose papers are ordinarily not used at temperatures above 100°C.

1.3.3 Control and Switching Systems

Specialized hardware is necessary to interconnect the elements of a power-distribution system. Utility control and switching systems operate under demanding conditions, including high voltage and current levels, exposure to lightning discharges, and 24-hour-a-day use. For reliable performance, large margins of safety must be built into each element of the system. The primary control and switching elements are high-voltage switches and protection devices.

High-voltage switches are used to manage the distribution network. Most disconnect switches function to isolate failures or otherwise reconfigure the network. Air-type switches are typically larger versions of the common *knife switch* device. To prevent arcing, air switches are changed only when power is removed from the circuit. These types of switches can be motor driven or manually operated.

Oil-filled circuit breakers are used at substations to interrupt current when the line is hot. The contacts usually are immersed in oil to minimize arcing. Oil-filled circuit breakers are available for operation at 500 kV and higher. Magnetic air breakers are used primarily for low-voltage indoor applications.

Protection devices include fuses and lightning arresters. Depending upon the operating voltage, various types of fuses can be used. Arc suppression is an essential consideration in the design and operation of a high-voltage fuse. A method must be provided to extinguish the arc that develops when the fuse element begins to open. Lightning arresters are placed at numerous points in a power-distribution system. Connected between power-carrying conductors and ground, they are designed to operate rapidly and repeatedly if necessary. Arresters prevent flashover faults between power lines and surge-induced transformer and capacitor failures. The devices are designed to extinguish rapidly, after the lightning discharge has been dissipated, to prevent power follow-on damage to system components.

A *fault* in an electrical power system is the unintentional and undesirable creation of a conducting path (a *short circuit*) or a blockage of current (an *open circuit*) [7]. The short-circuit fault is typically the most common and is usually implied when most people use the term "fault." The causes of faults include lightning, wind damage, trees falling across lines, vehicles colliding with towers or poles, birds shorting out lines, aircraft colliding with lines, vandalism, small animals entering switchgear, and line breaks resulting from excessive ice loading. Power system faults can be categorized as one of four types:

- Single line-to-ground
- Line-to-line
- Double line-to-ground
- Balanced three-phase

The first three types constitute severe unbalanced operating conditions.

It is important to determine the values of system voltages and currents during fault conditions so that protective devices can be set to detect and minimize their harmful effects. The time constants of the associated transients are such that sinusoidal steady-state methods can typically be used.

High-voltage insulators permit all of the foregoing hardware to be reliably interconnected. Most insulators are made of porcelain. The mechanical and electrical demands placed on high-voltage insulators are stringent. When exposed to rain or snow, the devices must hold off high voltages. They also must support the weight of heavy conductors and other components.

1.3.3.1 Fault Protection Devices

Fuses are designed to melt and disconnect the circuit within which they are placed should the current in the circuit increase above a specified thermal rating [3]. Fuses designed to be used in circuits operating above 600 V are classified as *fuse cutouts*. Oil-filled cutouts are mainly used in underground installations and contain the fusible elements in an oil-filled tank. Expulsion-type cutouts are the most common devices used on overhead primary feeders. In this class of device, the melting of the fusible element causes heating of a fiber fuse tube, which, in turn, produces deionizing gases to extinguish the arc. Expulsion-type cutouts are classified as:

- Open-fuse cutouts
- Enclosed-fuse cutouts
- Open-link-fuse cutouts

The *automatic recloser* is an overcurrent device that automatically trips and recloses a preset number of times to clear or isolate faults. The concept of reclosing is derived from the fact that most utility system faults are temporary in nature and can be cleared by de-energizing the circuit for a short period of time. Reclosers can be set for a number of operation sequences, depending on the action desired. These typically include instantaneous trip and reclose operation followed by a sequence of time-delayed trip operations prior to lockout of the recloser. The minimum pick-up for most reclosers is typically set to trip instantaneously at two times the nominal current rating.

An *automatic line recloser* is constructed of an interrupting chamber and the related contacts that operate in oil, a control mechanism to trigger tripping and reclosing, an operator integrator, and a lockout mechanism. An operating rod is actuated by a solenoid plunger that opens and closes the contacts in oil. Both single-phase and three-phase units are available.

The *line sectionalizer* is yet another overcurrent device. It is installed in conjunction with backup circuit breakers or reclosers. The line sectionalizer maintains coordination with the backup interrupting device and is designed to open after a preset number of tripping operations of the backup element. Line sectionalizers are installed on poles or crossarms in overhead distribution systems. The standard continuous current rating for sectionalizers ranges from 10 to 600 A. Sectionalizers also are available for both single-phase and three-phase systems.

The function of a circuit breaker is to protect a circuit from the harmful effects of a fault, in addition to energizing and de-energizing the same circuit during normal operation. Breakers are generally installed on both the incoming subtransmission lines and the outgoing primary feeders of a utility substation. These devices are designed to operate as quickly as possible (less than 10 cycles of the power frequency) to limit the impact of a fault on the distribution and control system. At the same time, the arc that forms between the opening contacts must be quenched rapidly. Several schemes are available to extinguish the arc, the most common being immersion of the contacts in oil. Some circuit breakers have no oil, but quench the arc by a blast of compressed air. These are referred to as *air circuit breakers*. Yet another type encloses the contacts in a vacuum or a gas, such as sulfur hexafluoride (SF_6).

Air circuit breakers are typically used when fault currents are relatively small. These devices are characteristically simple, are low cost, and require little maintenance. The fault current flows through coils, creating a magnetic field that tends to force the arc into ceramic chutes that stretch the arc, often with the aid of compressed air. When the arc is extinguished through vacuum, the breaker is referred to as a *vacuum circuit breaker*. Because a vacuum cannot sustain an arc, it can be an effective medium for this application. However, owing to imperfections present in a practical vacuum device, a small arc of short duration can be produced. The construction of vacuum circuit breakers is simple, but the maintenance is usually more complex than with other devices.

1.3.3.2 Lightning Arrester

A lightning arrester is a device that protects electrical apparatus from voltage surges caused by lightning [3]. It provides a path over which the surge can pass to ground before it has the opportunity to pass through and damage equipment. A standard lightning arrester consists of an air gap in series with a resistive element. The resistive element is usually made of a material that allows a low-resistance path to the voltage surge, but presents a high-resistance path to the flow of line energy during normal operation. This material is known as the *valve element*. Silicon carbide is a common valve element material. The voltage surge causes a spark that jumps across the air gap and passes through the resistive element to ground.

1.4 Utility AC Power System Architecture

The details of power distribution vary from one city or country to another, and from one utility company to another, but the basics are the same. Figure 1.9 shows a simplified distribution network. Power from a generating station or distribution grid comes into an area substation at 115 kV or higher. The substation consists of switching systems, step-down transformers, fuses, circuit breakers, reclosers, monitors, and control equipment. The substation delivers output voltages of approximately 60 kV to subtransmission circuits, which feed distribution substations. The substations convert the energy to approximately 12 kV and provide voltage regulation and switching provisions that permit patching around a problem. The 12 kV lines power pole- and surface-mounted transformers, which supply various voltages to individual loads. Typical end-user voltage configurations include:

- 120/208 V wye
- 277/480 V wye
- 120/240 V single phase
- 480 V delta

The circuits feeding individual customer loads are referred to as the *secondary system*, whereas the *primary system* is the network upstream from the secondary (Figure 1.9c). The secondary system originates at the distribution transformer and ends at the consumer loads. Each secondary main may supply groups of customers. In some instances, where service reliability is incorporated into the design, the secondary mains of several adjacent transformers may be connected through a fuse or a recloser. This is referred to as *secondary banking*. If an even higher service reliability factor is required, the secondary mains in an area can be connected in a mesh or a network, similar to the networking of the primary.

Fuses and circuit breakers are included at a number of points in the distribution system to minimize fault-caused interruptions of service. *Ground-fault interrupters* (GFIs) are also included at various points in the 12 kV system to open the circuit if excessive ground currents begin to flow on the monitored line. (GFIs are also known as *ground-fault current interrupters*, or GFCIs.) Reclosers may be included as part

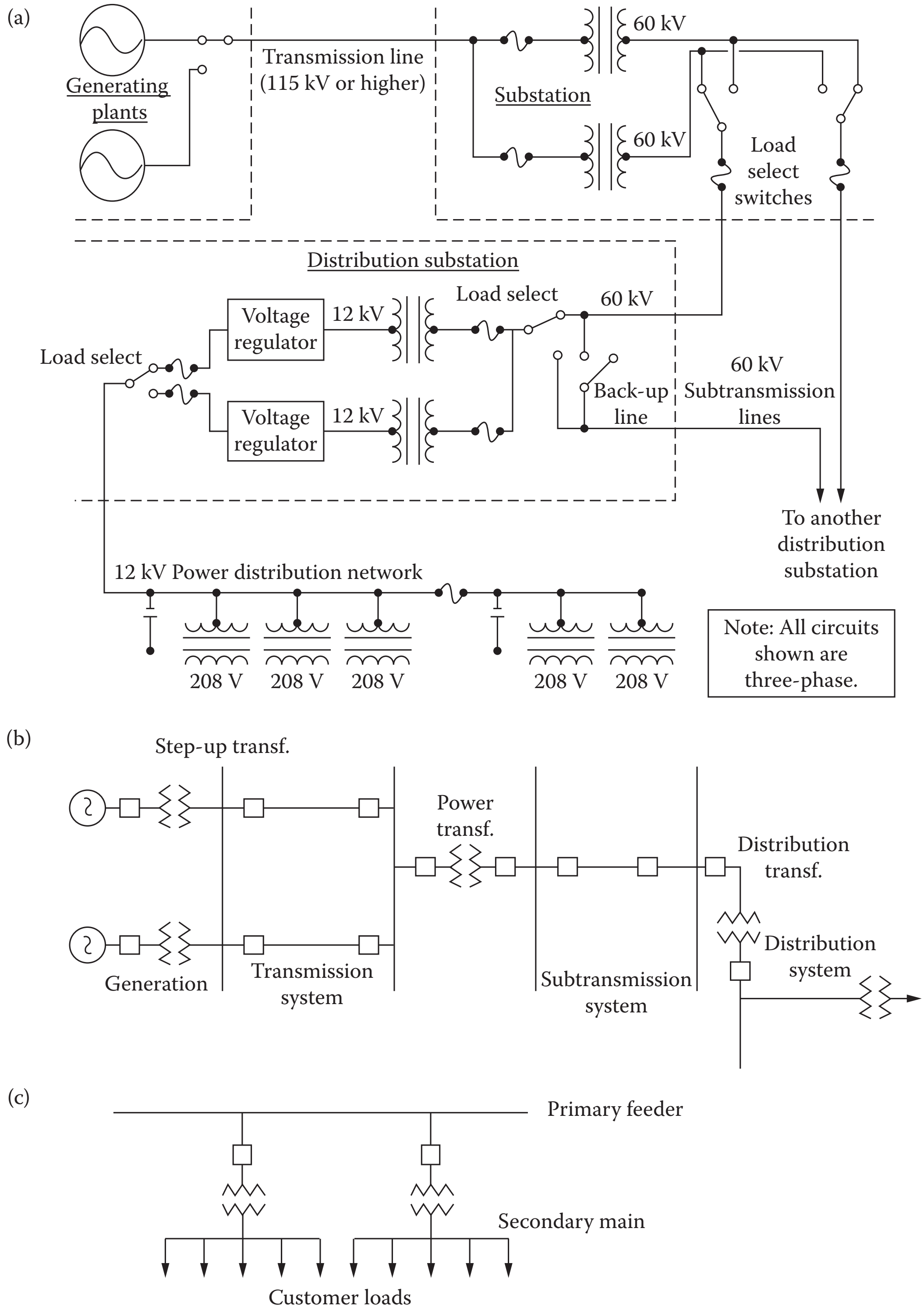


Figure 1.9 Simplified block diagram of a basic utility company power distribution system: (2) Overall network. The devices shown as fuses could be circuit breakers or reclosers. All circuits shown are three-phase. The capacitors perform power factor correction duty. (b) System terminology. (c) Distinction between the primary and secondary distribution systems. (b *and* c *from* [3]. *Used with permission.*)

of overcurrent protection of the 12 kV lines. They will open the circuit if excessive currents are detected and reclose after a preset length of time, as discussed in the previous section.

In some areas, the actions of circuit breakers, pole-mounted switches, and reclosers are controlled by two-way radio systems that allow status interrogation and switching of the remotely located devices from a control center. Some utilities use this method sparingly; others make extensive use of it.

Table 1.4 Standard Utility System Voltages (kV) (*After* [15].)

Category	Nominal Rating	Maximum Rating
High voltage	34.5	36.5
	46.0	48.3
	69.0	72.5
	115.0	121.0
	138.0	145.0
	161.0	169.0
	230.0	242.0
Extra-high voltage (EHV)	345.0	362.0
	400.0 (principally in Europe)	
	500.0	550.0
	765.0	800.0
Ultra-high voltage (UHV)	1100.0	1200.0

Depending on the geographic location, varying levels of lightning protection are included as part of the ac power-system design. Most service drop transformers (12 kV to 208 V) have integral lightning arresters. In areas of severe lightning, a ground (or *shield*) wire is strung between the top insulators of each pole, diverting the lightning to the ground wire, and away from the hot leads.

Standard transmission voltages are established in the U.S. by the American National Standards Institute (ANSI). There is no clear delineation between distribution, subtransmission, and transmission voltage levels. Table 1.4 lists the standard voltages given in ANSI Standards C84 and C92.2.

1.4.1 Power Distribution

The distribution of power over a utility company network is a complex process involving a number of power-generating plants, transmission lines, and substations. The physical size of a metropolitan power-distribution and control system is immense. Substations use massive transformers, oil-filled circuit breakers, huge strings of insulators, and high-tension conductors in distributing power to customers. Power-distribution and -transmission networks interconnect generating plants into an *area grid*, to which *area loads* are attached. Most utility systems in the U.S. are interconnected to one extent or another. In this way, power-generating resources can be shared as needed. The potential for single-point failure also is reduced in a distributed system.

A typical power-distribution network is shown in Figure 1.10. Power transmission lines operate at voltage levels from 2.3 kV for local distribution to 500 kV or more for distribution between cities or generating plants. Long-distance, direct current transmission lines also are used, with potentials of 500 kV and higher. Underground power lines are limited to short runs in urban areas. Increased installation costs and cable heat-management considerations limit the use of high-voltage underground lines. Wide variations in standard voltage levels can be found within any given system. Each link in the network is designed to transfer energy with the least I^2R loss, thereby increasing overall system efficiency. The following general classifications of power-distribution systems can be found in common use:

- *Radial system*. The simplest of all distribution networks, a single substation supplies power to all loads in the system. (See Figure 1.11.)
- *Ring system*. Distribution lines encircle the service area, with power being delivered from one or more sources into substations near the service area. Power is then distributed from the substations through the radial transmission lines. (See Figure 1.12.)
- *Network system*. A combination of the radial and ring distribution systems. Although such a system is more complex than either of the previous configurations, reliability is improved significantly. The network system, illustrated in Figure 1.13, is one of the most common power-distribution configurations.

1.4.2 Distribution Substations

Distribution substations serve as the source for primary distribution feeders [3]. They receive bulk electric power at high voltages and reduce the voltage to distribution primary values. Also associated with a substation are provisions for protection from faults, for voltage regulation, and for data acquisition and monitoring. The equipment generally installed in a distribution substation includes:

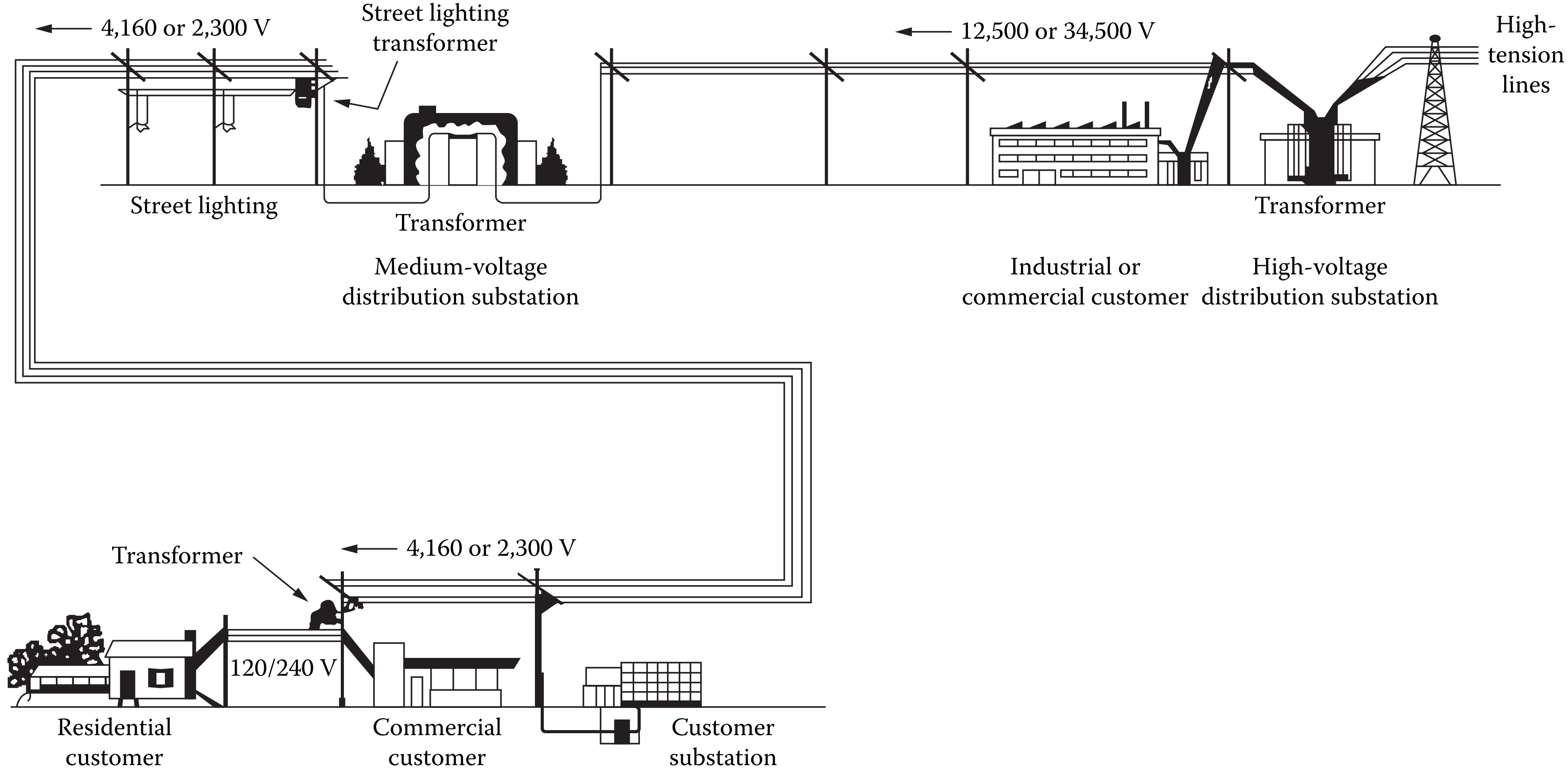


Figure 1.10 Simplified power-distribution architecture.

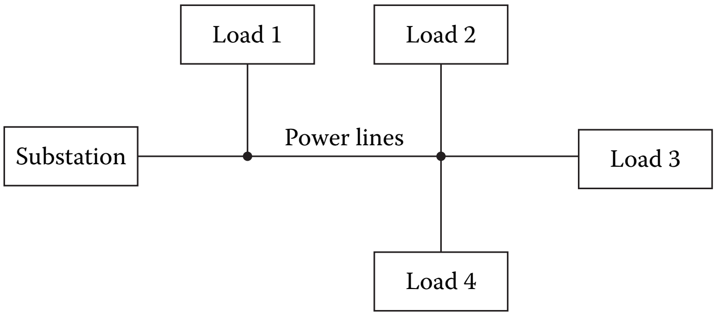


Figure 1.11 Radial power-transmission system.

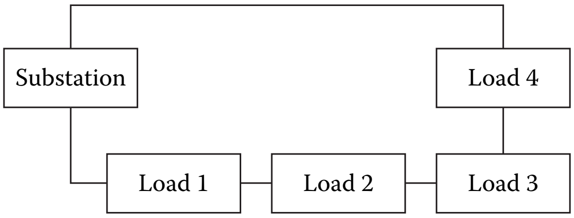


Figure 1.12 Ring power-transmission system.

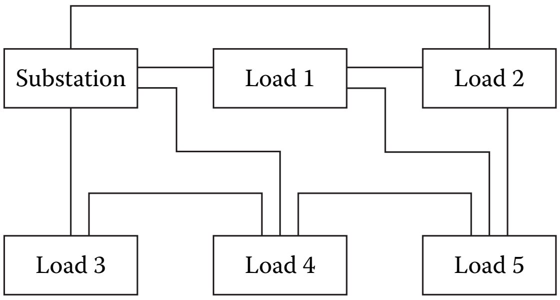


Figure 1.13 Network power-transmission system.

- Power transformers
- Oil or air circuit breakers
- Voltage regulators
- Protective relays
- Air break and disconnect switches
- Surge arresters
- Measuring instruments
- Storage batteries and capacitors (in some installations)

Some substations are entirely enclosed in buildings, whereas others are built entirely in the open with all equipment enclosed in one or more metal-clad units. The final design of the type of substation depends on economic factors; future load growth; and environmental, legal, and social issues.

1.4.2.1 Breaker Schemes

The circuit breaker scheme used at a substation provides for varying degrees of reliability and maintainability on both the input and output sides [3]. Each additional circuit breaker provides greater reliability and flexibility in maintaining the bus energized during a fault or during maintenance. However, the cost also increases with each circuit breaker. Hence, the selection of a particular substation scheme depends on safety, reliability, economy, and simplicity. The most commonly used circuit breaker schemes are [9]:

- The *single-bus*, shown in Figure 1.14*a*
- *Double-bus/double-breaker*, shown in Figure 1.14*b*

- *Main-and-transfer bus*, shown in Figure 1.14*c*
- *Breaker-and-a-half*, shown in Figure 1.14*d*
- *Ring bus*, shown in Figure 1.14*e*

Of these designs, the single-bus scheme costs the least; however, it possesses rather low reliability because the failure of the bus or any circuit breaker results in a total shutdown of the substation. The most expensive arrangement is the double-bus/double-breaker scheme. Each circuit is provided with two circuit breakers, and thus, any breaker can be taken out of service for maintenance without disruption of service at the substation. In addition, feeder circuits can be connected to either bus. The main-and-transfer bus requires an extra breaker for the bus tie between the main and the auxiliary buses. The breaker-and-a-half scheme provides the most flexible operation with high reliability. The relaying and automatic reclosing, however, are somewhat complex.

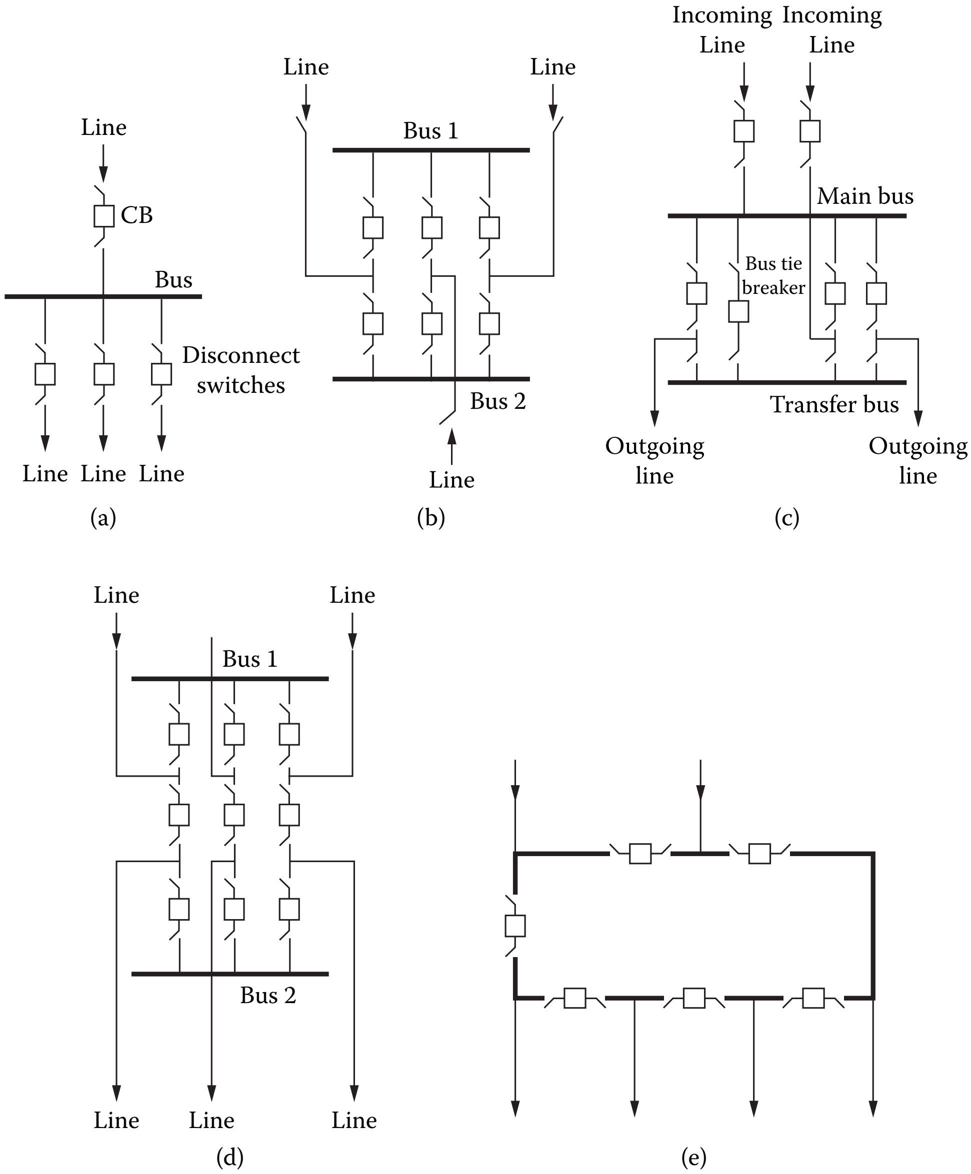


Figure 1.14 Substation bus and breaker arrangements: (*a*) single-bus; (*b*) double-bus/double-breaker; (*c*) main-and-transfer bus; (*d*) breaker-and-a-half; (*e*) ring bus. (*From* [3]. *Used with permission.*)

1.4.3 Voltage Analysis

Distribution systems are designed to maintain service voltages within specified limits during normal and emergency conditions. Typical voltage limits are [3]:

- For service to residential customers, the voltage at the point of delivery shall not exceed 5% above or below the nominal voltage. This is equivalent to the band between 114 and 126 V for most utilities in the United States.
- For service to commercial or industrial customers, the voltage at the point of delivery shall not exceed 7.5% above or below the nominal voltage.
- The maximum allowable voltage imbalance for a three-phase service shall be 2.5%.

The goal of voltage analysis is to determine whether the voltages on different line sections remain within the specified limits under varying load conditions. Thus, voltage analysis facilitates the effective placement of capacitors, voltage regulators, and other voltage regulation devices on the distribution system. *Load flow analysis* is a computer-aided tool that is typically used in this planning task. Load flows determine feeder voltages under steady-state conditions and at different load conditions.

Voltage analysis begins with an accurate representation, or map, of the feeder circuits, starting at the substation. The map generally consists of details and electrical characteristics (such as kVA ratings, impedances, and other parameters) of the conductors and cables on the system, substation and distribution transformers, series and shunt capacitors, voltage regulators, and related devices.

Before the analysis can begin, feeder loading must be known. Several different methods can be used for this task. If the utility maintains a database on each customer connected to a distribution transformer, it can use the billing data to determine the kilowatt-hours supplied by each transformer for a given month. Methods can then be used to convert the kilowatt-hours to a noncoincident peak kilovoltampere demand for all distribution transformers connected on the feeder. If this information is not available, the kilovoltampere rating of the transformer and a representative power factor can be used as the load. With the metered demand at the substation, the transformer loads can be allocated, for each phase, such that the allocated loads plus losses will equal the metered substation demand.

Accurately representing the load types or models is an important issue in voltage analysis. Several load models are available, including:

- Spot and distributed loads
- Wye and delta connected loads
- Constant power, constant current, constant impedance, or a combination of these methods

1.4.4 High-Voltage DC Transmission

High-voltage dc (HVDC) transmission offers several advantages over alternating current for long-distance power transmission and asynchronous interconnection between two ac systems, including the ability to precisely control the power flow without inadvertent *loop flows* that can occur in an interconnected ac system [9]. HVDC transmission can be classified into one of three broad categories:

- *Back-to-back* systems
- *Two-terminal*, or *point-to-point*, systems
- *Multiterminal* systems

In a back-to-back dc system, shown in Figure 1.15, both the rectifier and the inverter are located in the same station, usually in the same building. The rectifier and inverter are usually integrated with a reactor, which is generally an air-core design. A back-to-back dc system is used to tie two *asynchronous* ac systems (systems that are not in synchronism). The two ac systems can be of different operating frequencies, for example, one 50 Hz and the other 60 Hz. Back-to-back dc links are also used to interconnect two ac systems that are of the same frequency but are not operating in synchronism. In North America, for example, Eastern and Western systems may not be synchronized, and Quebec and Texas may not be

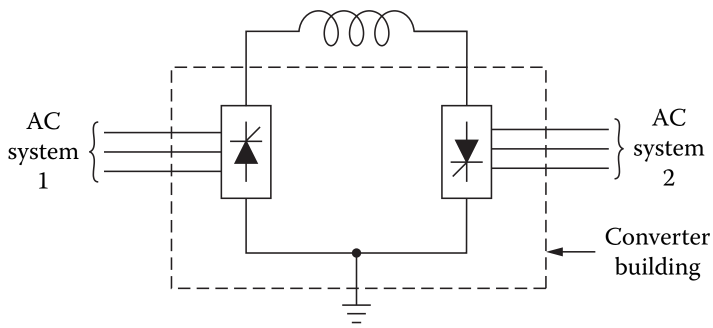


Figure 1.15 The back-to-back system of dc transmission. (*From* [9]. *Used with permission.*)

synchronized with their neighboring systems. A dc link offers a practical solution to interconnecting these nonsynchronous networks.

Two-terminal dc systems can be either *bipolar* or *monopolar*. The bipolar configuration, shown in Figure 1.16*a*, is the commonly used arrangement for systems with overhead lines. In this configuration, there are two conductors, one for each polarity (positive and negative) carrying nearly equal currents. Only the difference of these currents, which is usually small, flows through the ground return. A monopolar system has one conductor, either of positive or negative polarity, with current returning through either ground or another metallic return conductor. The monopolar ground return current configuration, shown in Figure 1.16*b*, has been used for undersea cable systems, where current returns through the sea. This configuration can also be used for short-term emergency operation for a two-terminal dc line system in the event of a pole outage. However, concerns about corrosion of underground metallic structures and interference with telephone and other utilities restrict the duration of such operation. The total ampere-hour operation per year is usually the restricting criterion. In a monopolar metallic return system, shown in Figure 1.16*c*, return current flows through a conductor, thus avoiding the problems associated with ground return current. This method is generally used as a contingency mode of operation for a normal bipolar transmission system in the event of a partial converter (one-pole equipment) outage. In the case of outage of a one-pole converter, the conductor of the affected pole will be used as the return current conductor. A metallic return transfer breaker is opened, diverting the return current from the ground path and into the pole conductor. This conductor is grounded at one end and insulated at the other end. This system can transmit half the power of the normal bipolar system capacity, and can be increased if overload capacity is available. However, the percentage of losses will be doubled compared to the normal bipolar operation.

There are two basic configurations in which dc systems can be operated as *multiterminal systems*:

- Parallel configuration
- Series configuration

The parallel configuration can be either radial-connected (Figure 1.17*a*) or mesh-connected (Figure 1.17*b*). In a parallel-connected multiterminal dc system, all converters operate at the same nominal dc voltage, similar to ac system interconnections. In this mode of operation, one converter determines the operating voltage, and all other terminals operate in a current-controlling mode.

In a series-connected multiterminal dc system, shown in Figure 1.18, all converters operate at the same current. One converter sets the current that will be common to all converters in the system. Except for the converter that sets the current, the remaining converters operate in a voltage control mode (constant firing angle or constant extinction angle). The converters operate almost independently without the requirement for high-speed communication between them. The power output of a noncurrent-controlling converter is varied by changing its voltage. At all times, the sum of the voltages across the rectifier stations must be larger than the sum of voltages across the inverter stations. Disadvantages of a series-connected system include the following:

- Reduced efficiency because full line insulation is not used at all times.

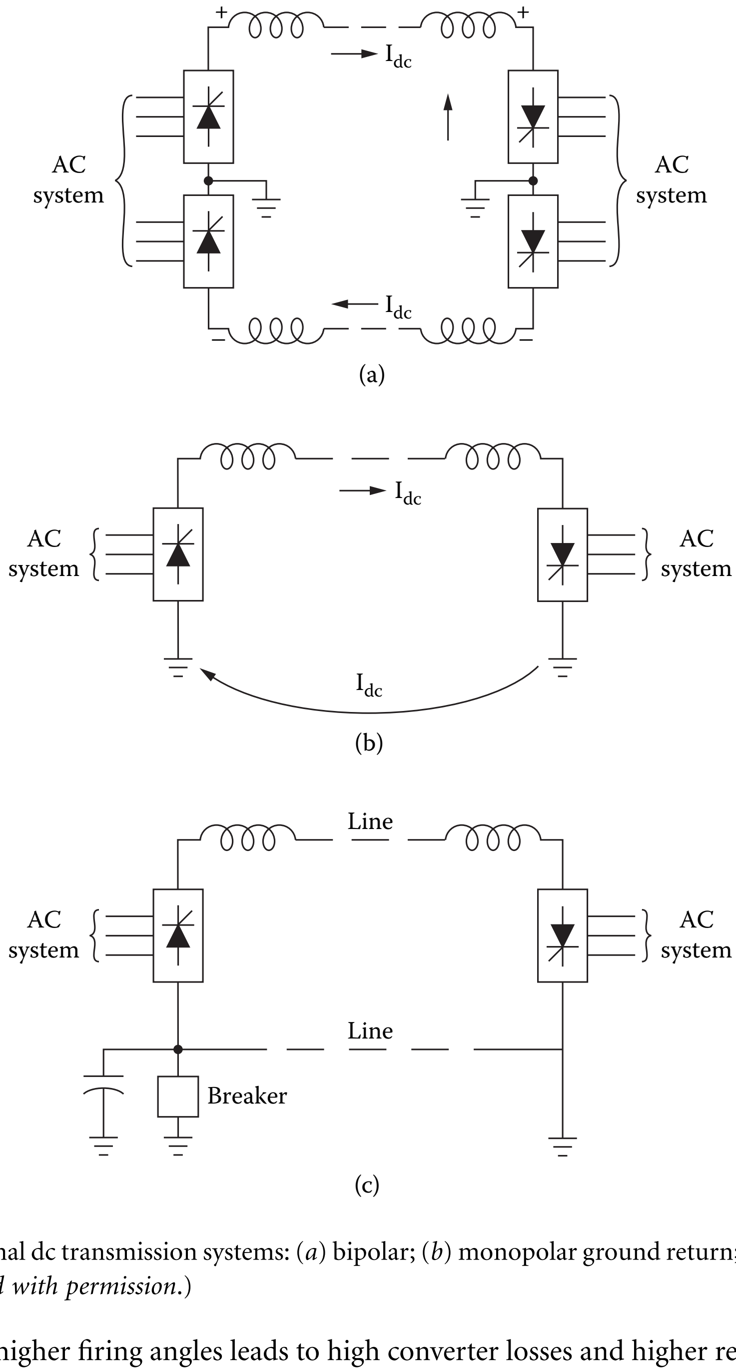


Figure 1.16 Two-terminal dc transmission systems: (*a*) bipolar; (*b*) monopolar ground return; (*c*) monopolar metallic return. (*From* [9]. *Used with permission.*)

- Operation at higher firing angles leads to high converter losses and higher reactive power requirements from the ac system.

1.4.4.1 AC vs. DC Transmission

In cases where HVDC is selected on technical considerations, it may be the only practical option, as in the case of an asynchronous interconnection [9]. However, for long-distance power transmission, where both ac and HVDC are practical, the final decision is dependent on the total costs of each alternative. The total cost of a transmission system includes the line costs (conductors, insulators, and towers) plus the right-of-way (R-o-W) costs. A dc line with two conductors can carry almost the same amount of power as a three-phase ac line with the same size of line conductors. However, dc towers with only two conductors are simpler and cheaper than three-phase ac towers. Hence, the per-mile costs of line and R-o-W will be lower for a dc line. Power losses in the dc line are also lower than for ac for the same power transmitted. However, the HVDC system requires converters at each end of the line; hence, the terminal costs for dc are higher than for ac. The variation of total costs for ac and dc as a function of line length is shown in Figure 1.19. As illustrated, there is a break-even distance beyond which the total costs of the dc option

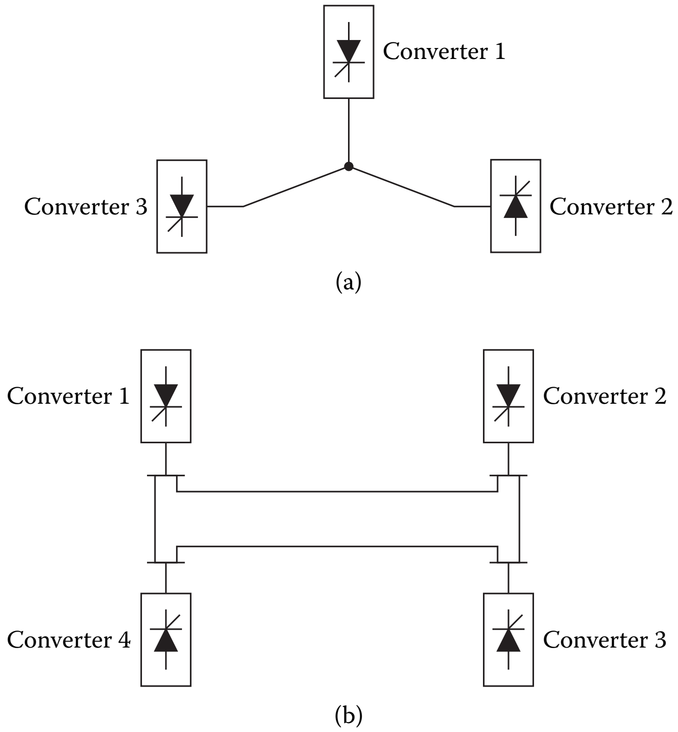


Figure 1.17 Multiterminal dc transmission systems: (*a*) parallel-connected radial; (*b*) parallel connected mesh-type. (*From* [9]. *Used with permission.*)

will be lower than the ac transmission option. This is in the range of 500 to 800 km for overhead lines, but much shorter for cables. The break-even point is between 20 and 50 km for submarine cables and twice as far for underground cables.

1.4.4.2 DC Circuit Breakers

The process of interrupting the current in an ac system is aided by the fact that ac current goes through zero every half-cycle, or approximately every 8 ms in a 60 Hz system [9]. The absence of a natural *current zero* in dc makes it difficult to develop a dc circuit breaker. There are three principal problems that must be addressed:

- Forcing current zero in the interrupting element
- Controlling the overvoltages caused by large changes in current as a function of time (*di*/*dt*) in a highly inductive circuit
- Dissipating large amounts of energy (tens of megajoules is not uncommon)

The second and third problems are solved by the application of zinc oxide varistors connected line to ground and across the breaking element. The first is the major problem, and several different solutions have been adopted by different manufacturers. Basically, current zero is achieved by inserting a *counter voltage* into the circuit.

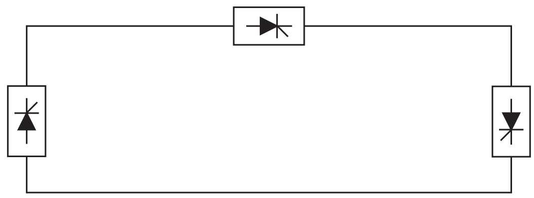


Figure 1.18 Series connected multiterminal dc system. (*From* [9]. *Used with permission.*)

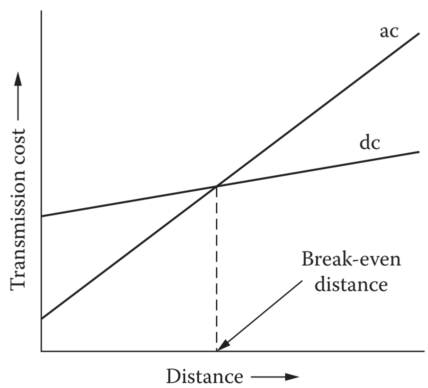


Figure 1.19 Transmission system cost as a function of line length for ac and dc systems. (*From* [9]. *Used with permission.*)

In the circuit shown in Figure 1.20, opening CB (an air-blast circuit breaker) causes current to be commutated to the parallel LC tank. The commutating circuit will be oscillatory, which creates current zero in the circuit breaker. The opening of CB increases the voltage across the commutating circuit, which will be limited by the zinc oxide varistor ZnO_1 by entering into conduction. The resistance *R* is the closing resistor in series with switch *S*.

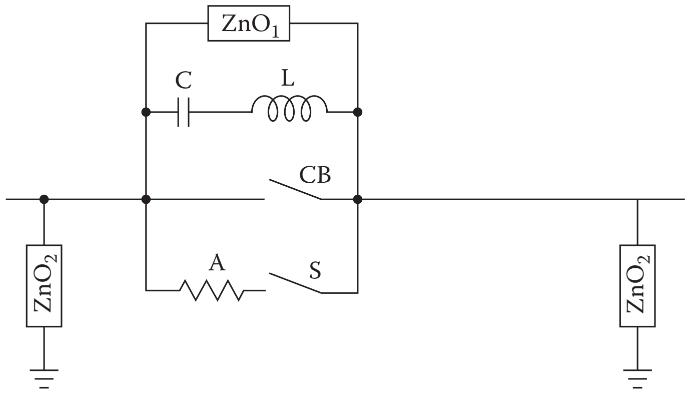


Figure 1.20 Block diagram of a dc circuit breaker (one module). (*From* [9]. *Used with permission.*)

1.4.5 Utility Company Interfacing

Most utility company-to-customer connections are the delta-wye type shown in Figure 1.21. This transformer arrangement usually is connected with the delta side facing the high voltage and the wye side facing the load. This configuration provides good isolation of the load from the utility and somewhat retards the transmission of transients from the primary to the secondary windings. The individual three-phase loads are denoted in the figure by Z_1, Z_2, and Z_3. They carry load currents as shown. For a wye-connected system, it is important that the building neutral lead is connected to the midpoint of the transformer windings, as shown. The neutral line provides a path for the removal of harmonic currents that may be generated in the system as a result of rectification of the secondary voltages.

In some areas, an open-delta arrangement is used by the utility company to supply power to customers. The open-delta configuration is shown in Figure 1.22. Users often encounter problems when operating sensitive three-phase loads from such a connection because of poor voltage-regulation characteristics during varying load conditions. The open-delta configuration is also subject to high third-harmonic content and transient propagation. The three loads and their respective load currents are shown in the diagram.

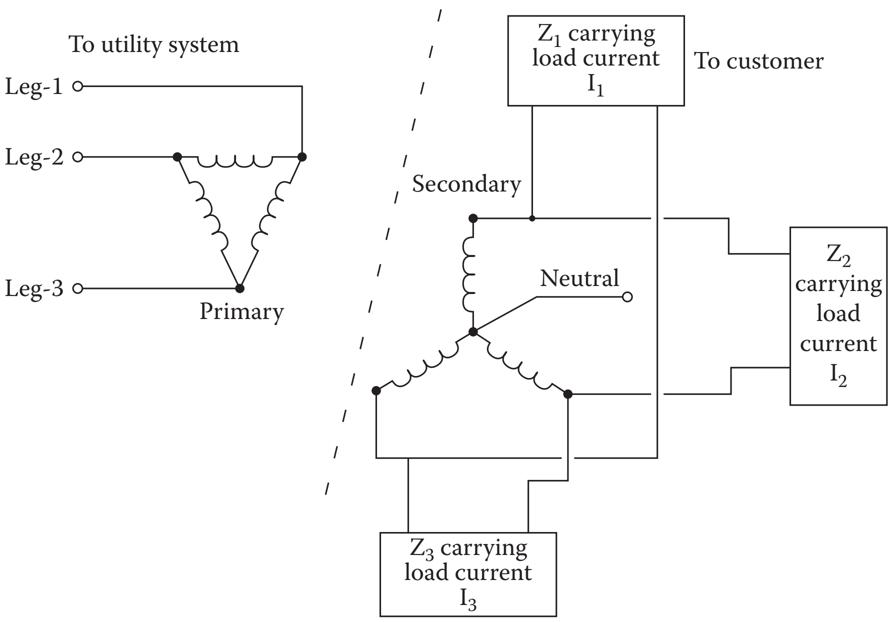


Figure 1.21 Delta-wye transformer configuration for utility company power distribution. This common type of service connection transformer provides good isolation of the load from the high-voltage distribution-system line.

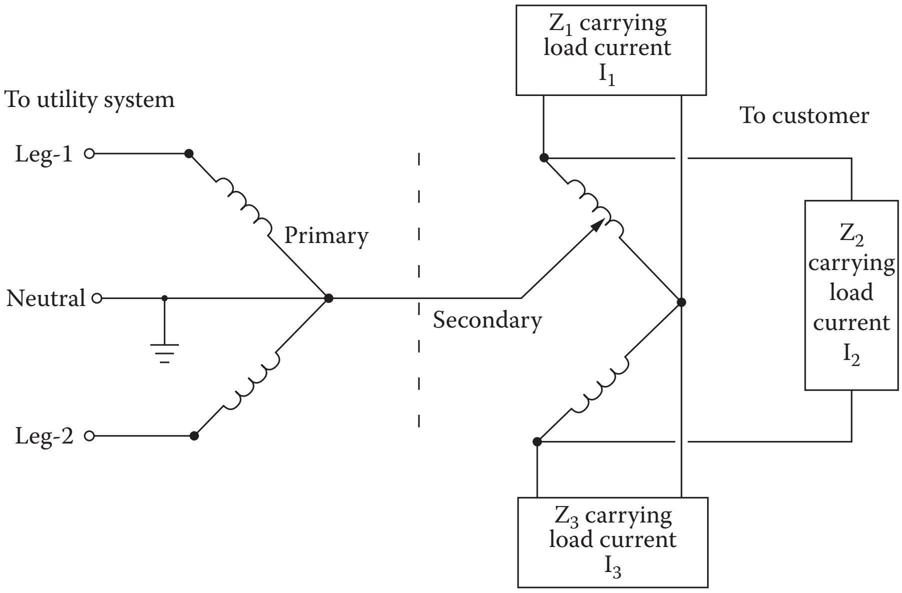


Figure 1.22 The open-delta (or V-V) utility company service connection transformer. This configuration is not recommended because of its poor voltage regulation under varying load, high third-harmonic content, and transient disturbance propagation characteristics.

Other primary power connection arrangements are possible, such as wye-to-wye or delta-to-delta. Like the delta-to-wye configuration, they are not susceptible to the problems that may be experienced with the open-delta (or V-V) service.

The open-delta system can develop a considerable imbalance among the individual phases in either voltage or phase or both. This can introduce a strong 120 Hz ripple frequency in three-phase power supplies, which are designed to filter out a 360 Hz ripple. The effects of this 120 Hz ripple can be increased noise in the supply and possible damage to protection devices across the power-supply chokes. Depending on the loading of an open-delta transformer, high third-harmonic energy can be transferred to the load, producing transients of up to 300% of the normal voltage. The result could be severely strained rectifiers, capacitors, and inductors in the power supply as well as additional output noise of the supply.

1.4.5.1 Phase-to-Phase Balance

The phase-to-phase voltage balance of a utility company line is important at most types of facilities, not only because of the increased power-supply ripple that it can cause, but also because of the possible heating effects. Even simple three-phase devices such as motors should be operated from a power line that is well balanced, preferably within 1%. Studies have shown that a line imbalance of only 3.5% can produce a 25% increase in the heat generated by a three-phase motor. A 5% imbalance can cause a 50% increase in heat, which is potentially destructive. Similar heating also can occur in the windings of three-phase power transformers used in industrial equipment.

Phase-to-phase voltage balance can be measured accurately over a period of several days with a slow-speed chart recorder or electronic utility-line analyzer. The causes of imbalanced operation are generally large, single-phase power users on local distribution lines. Uneven currents through the utility company power-distribution system will result in uneven line-to-line voltages at the customer's service drop entrance.

1.4.6 Load Fault Protection

Fuses and circuit breakers are the two most common methods used in electronic equipment to prevent system damage in the event of a component failure. Although it is hardly new technology, there are still a lot of misconceptions about fuse and circuit-breaker ratings and operation.

1.4.6.1 Fuses

Fuses are rated according to the current they can pass safely. This may give the wrong idea — that excessive current will cause a fuse to blow. Rather, the cause is power dissipation in the form of heat. Put in more familiar terms, it is the I^2R loss across the fuse element that causes the linkage to melt. The current rating of a given device, however, is not the brick-wall-protection value that many service people think it is. Consider the graph shown in Figure 1.23, which illustrates the relationship of rated current across a fuse to the blowing time of the device.

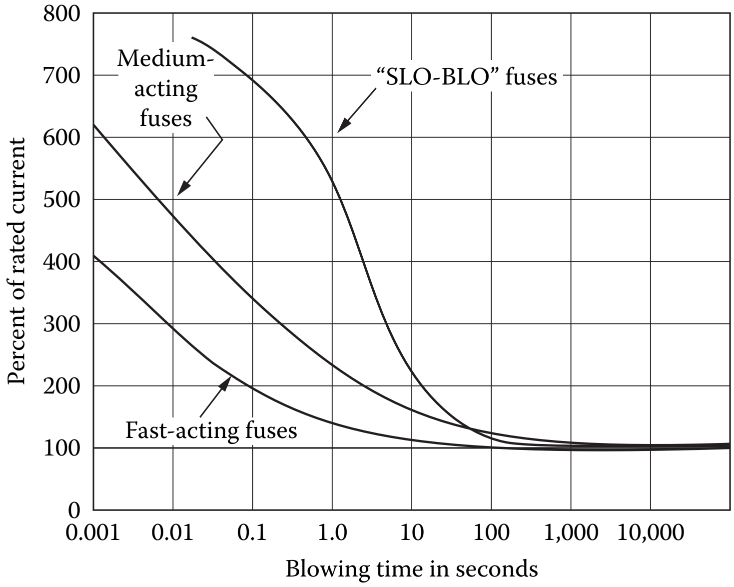


Figure 1.23 The relationship between the rated current of a fuse and its blowing time. Curves are given for three types of devices: fast-acting, medium-acting, and slow-blow.

Fuse characteristics can be divided into three general categories: fast-acting, medium-acting, and slow-blow. Circuit protection for each type of device is a function of both current and time. For example, a slow-blow fuse will allow approximately 6 times the rated current through a circuit for a full second before opening. Such delay characteristics have the benefit of offering protection against nuisance blowing because of high inrush currents during system startup. This feature, however, comes with the price of possible exposure to system damage in the event of a component failure.

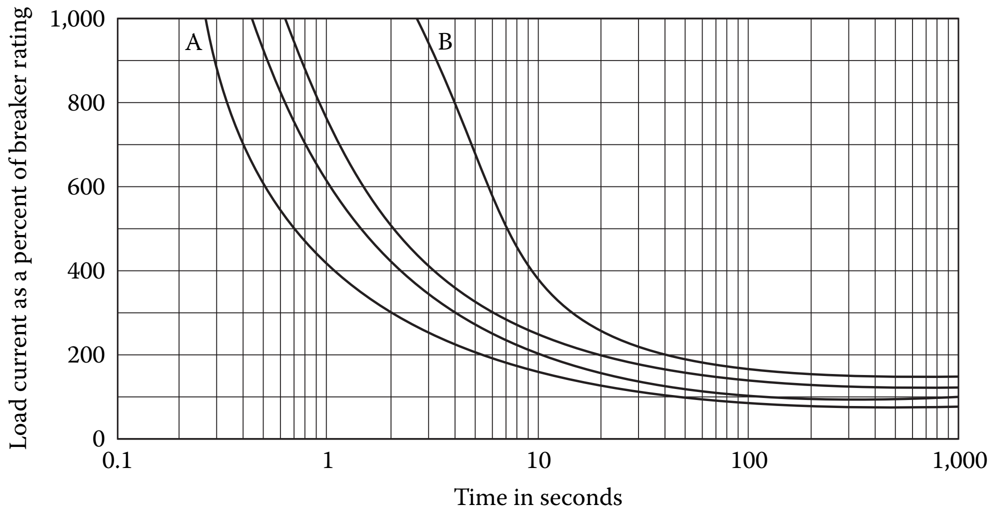
1.4.6.2 Circuit Breakers

Circuit breakers are subject to similar current let-through constraints. Figure 1.24 illustrates device load current as a percentage of breaker rating vs. time. The A and B curves refer to breaker load capacity product divisions. Note the variations possible in trip time for the two classifications. The minimum clearing time for the A group (the higher classification devices) is 1 s for a 400% overload. Similar to fuses, these delays are designed to prevent nuisance tripping caused by normally occurring current surges from (primarily) inductive loads. Most circuit breakers are designed to carry 100% of their rated load continuously without tripping. They normally are specified to trip at between 101 and 135% of rated load after a period of time determined by the manufacturer. In this example, the *must-trip point* at 135% is 1 hour.

Circuit breakers are available in both thermal and magnetic designs. Magnetic protectors offer the benefit of relative immunity to changes in ambient temperature. Typically, a magnetic breaker will operate over a temperature range of –40°C to +85°C without significant variation of the trip point. Time delays usually are provided for magnetic breakers to prevent nuisance tripping caused by startup currents from inductive loads. Trip-time delay ratings range from near instantaneous (under 100 ms) to slow (10 to 100 s).

1.4.6.3 Semiconductor Fuses

The need for a greater level of protection for semiconductor-based systems led to the development of semiconductor fuses. Figure 1.25 shows the clearing characteristics of a typical fuse of this type. The total clearing time of the device consists of two equal time segments: the *melting time* and the *arcing time*. The rate of current decrease during the arcing time must be low enough that high induced voltages, which could destroy some semiconductor components, are not generated.



(A) 5A to 50A models

Overload Trip Times	
100%	No trip
135%	Trip in 1 hour
200%	6–22 sec
600%	0.45–1.5 sec
1,000%	0.25–0.6 sec

(B) 0.5A to 4A models

Overload Trip Times	
100%	No trip
135%	Trip in 1 hour
200%	11–30 sec
600%	1.0–5.5 sec
1,000%	0.4–2.5 sec

Figure 1.24 The relationship between the rated current of a circuit breaker and its blowing time. Curves A and B represent different product current ranges, as shown.

1.4.6.4 Application Considerations

Although fuses and circuit breakers are a key link in preventing equipment damage during the occurrence of a system fault, they are not without some built-in disadvantages. Lead alloy fuses work well and are the most common protection device found, but because the current-interrupting mechanism is dependent on the melting of a metal link, their exact blow point is not constant. The interrupting current may vary, depending on the type and size of fuse clip or holder, conductor size, physical condition of the fuse element, extent of vibration present, and ambient temperature. Figure 1.26 illustrates the effects of ambient temperature on blowing time and current-carrying capacity.

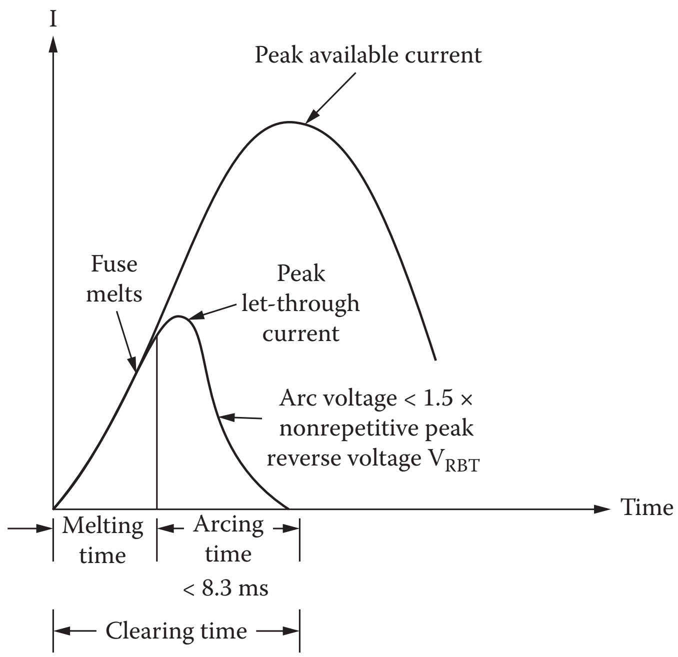


Figure 1.25 The current let-through characteristics of a semiconductor fuse. Note that the clearing time of the device is less than 8.3 ms in this example.

1.4.6.5 Transient Currents

Trip delays for fuses and circuit breakers are necessary because of the high startup or inrush currents that occur when inductive loads or tungsten filament lamps are energized. The resistance of a tungsten lamp is high when it is hot, but low when it is cold. A current surge of as much as 15 times the rated steady-state value may occur when the lamp is energized (pulse duration approximately 4 ms).

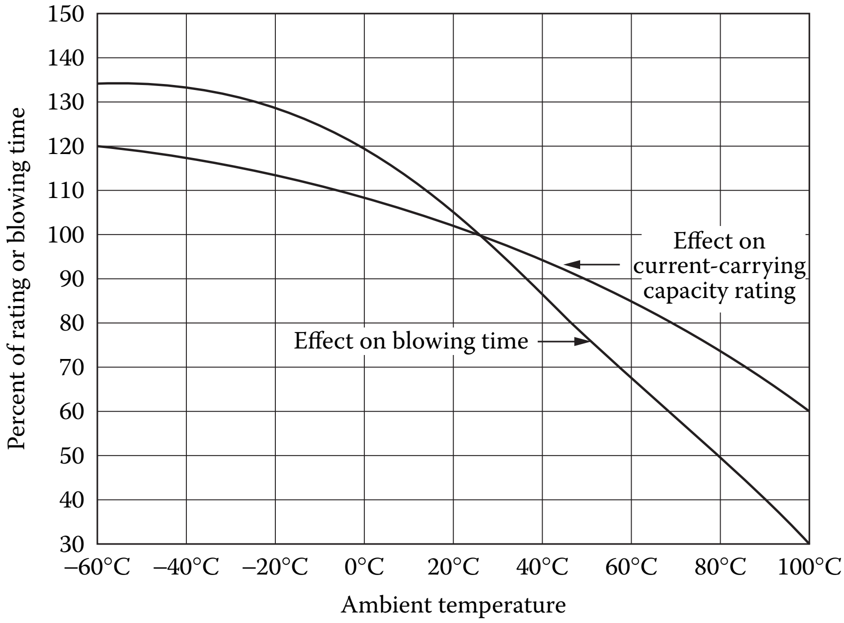


Figure 1.26 The effects of ambient temperature on fuse-blowing time and current-carrying capacity.

Transformer inrush currents can measure as high as 30 times the normal rated current for newer types of transformers that have grain-oriented high silicon steel cores. These transformer designs are attractive because of their favorable size and weight characteristics. Older transformers of more conventional design typically exhibit an inrush current approximately 18 times greater than the steady-state value. This transient current surge reaches its peak in the first half-cycle of applied ac power and decreases with each successive half-cycle. Such transients are relatively insensitive to the load placed on the secondary. The transient may, in fact, be smaller when the transformer is loaded than unloaded. A worst-case turn-on current surge will not occur every time the transformer is energized. Among the determining factors involved is the magnitude of the applied voltage at the instant the transformer is connected. Minimum transient energy occurs when the transformer is switched on at the zero-crossing point of the sine wave.

The magnitude of the turn-on current surge of an ac-to-dc power supply is determined mainly by the transformer transient and the capacitive load placed after the rectifier elements. Large filter capacitors commonly found in low-voltage, high-current supplies can place severe stress on the rectifiers and transformer. A fully discharged capacitor appears as a virtual short circuit when power is first applied. Some form of surge-limiting circuit often is provided for power supplies containing more than 10,000 μF total capacitance.

The surge current of an ac motor is spread over tenths of a second, rather than milliseconds, and varies considerably with the load connected to the unit. Table 1.5 lists typical motor surge currents for various types of devices. Note that the single-phase induction motor has the highest surge rating (7 times the running value for a period of 750 ms). Three-phase motors exhibit a relatively low-surge current during startup (350% for 167 ms).

1.4.6.6 Delay-Trip Considerations

The occurrence of turn-on surges for inductive loads, ac-to-dc power supplies, and tungsten filament lamps dictates the installation of protective devices that exhibit delayed-trip characteristics that match the given load. The problem, however, is that high-surge currents of brief duration — not related to turn-on activities — can occur without tripping the circuit breaker or opening the fuse element. The result may be damage to other circuit devices, such as semiconductors. To provide full protection to an electronic system, the overload withstand characteristics of all components should match. This is not always an easy goal to accomplish.

Table 1.5 Starting Surge Current Characteristics for Various Types of ac Motors Selected from a Random Test Group

Motor Type	Start Current (peak amplitude, rms)	Duration of Start Surge (s)	Load-s (% I × t s)
Shaded pole	150%	2.000	0.30
Split phase no. 1	600%	0.116	0.70
Split phase no. 2	425%	0.500	2.00
Capacitor (loaded) no. 1	400%	0.600	2.40
Capacitor (no load)	300%	0.100	0.30
Capacitor (loaded) no. 2	420%	0.500	2.10
Induction	700%	0.750	5.00
Three phase	350%	0.167	0.60
Capacitor-start split-phase run	290%	0.083	0.24

For example, consider a simple SCR-controlled ac-to-dc power supply. The transformer will set the upper limit on surge current presented to the protective device and the SCR (assuming light capacitive loading). If that surge is 18 times the normal steady-state current for a period of 8 ms, then a protective device must be selected that will allow the surge to pass without tripping. An SCR must be selected for the circuit, therefore, that can withstand at least 18 times the normal rated current for 8 ms. If not, the SCR will become the weak link in the system, not the protective device.

1.4.7 Measuring AC Power

Measuring the average power delivered to a load requires measurement of the rms values of voltage and current, as well as the power factor [10]. This is accomplished by an electro-dynamometer-type wattmeter, shown in Figure 1.27. The current in the high-resistance pivoted coil is proportional to the voltage across the load. The current to the load and the pivoted coil together through the energizing coil of the electromagnet establishes a proportional magnetic field across the cylinder of rotation of the pivoted coil. The torque on the pivoted coil is proportional to the product of the magnetic field strength and the current in the pivoted coil. If the current in the pivoted coil is negligible compared to that in the load, then the torque becomes essentially proportional to the product of the voltage across the load (equal to that across the pivoted coil) and the current in the load (essentially equal to that through the energizing coil of the electromagnet). The dynamics of the pivoted coil together with the restraining spring, at ac power frequencies, ensures that the angular displacement of the pivoted coil is proportional to the average of the torque or, equivalently, the average power.

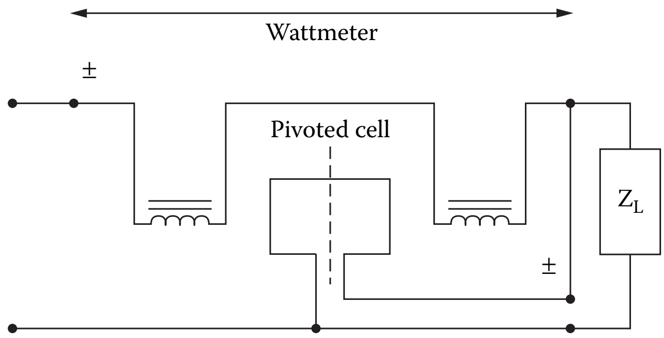


Figure 1.27 A wattmeter connected to a load. (*From* [10]. *Used with permission.*)

One of the most common electrical instruments is the induction-type watt-hour meter, which measures the energy delivered to a load. In this design, the pivoted coil is replaced by a rotating conducting (usually aluminum) disk, as shown in Figure 1.28. An induced eddy current in the disk replaces the pivoted coil current in its interaction with the load-current-established magnetic field. After compensating for the less-than-ideal nature of the electrical elements making up this type of meter, the result is that the disk rotates at a

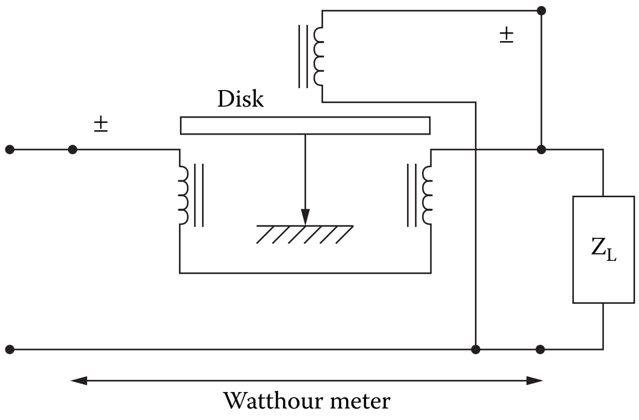


Figure 1.28 A watt-hour meter connected to a load. (*From* [10]. *Used with permission.*)

rate proportional to the average power of the load, and the rotational count is proportional to the energy delivered to the load.

At frequencies above the ac power frequency, and — in some instances — at the ac power frequencies, electronic instruments are used to measure power and energy. These systems are based on a variety of basic digital measurement techniques.

1.4.7.1 Digital Measurement Techniques

Figure 1.29 shows a generalized block diagram of a digital voltmeter/ammeter. Conversion of an input voltage to a digital equivalent can be accomplished in one of several ways. The *dual-slope conversion* method (also know as *double-integration*) is one of the more popular techniques. Figure 1.30 illustrates the dual-slope conversion process. V_{in} represents the input voltage (the voltage to be measured). V_{REF} is a reference voltage with a polarity opposite that of the measured voltage, supplied by the digital conversion circuit. Capacitor C1 and operational amplifier U1 constitute an integrator. S1 is an electronic switch that is initially in the position shown. When the meter terminals are first connected to the circuit, the sample voltage is applied to the input of the integrator for a specified period of time, called the *integration period*. The integration period is usually related to the 60 Hz line frequency; integration periods of 1/60th of a second are common. S1 is an electronic switch that is initially in the position shown. When the meter terminals are first connected to the circuit, the sample voltage is applied to the input of the integrator for a specified period of time, called the *integration period*. The integration period is usually related to the 60 Hz line frequency; integration periods of 1/60th of a second and 1/10th of a second are common. The output signal of the integrator is a voltage determined by the resistor-capacitor (RC) time constant of R1 and C1. Because of the nature of the integrator, the maximum voltage (the voltage at the end of the integration period) is proportional to the voltage being measured. At the end of the integration period, switch S1 is moved to the other position (V_{REF}) and a voltage of opposite polarity to the measured voltage is applied. The capacitor is then discharged to zero. As shown in the figure, the discharge interval is directly proportional to the maximum voltage, which, in turn, is proportional to the applied voltage at the input terminals.

At the same time that the integration interval ends and the discharge interval begins, a counter in the meter begins counting pulses generated by a clock circuit. When the voltage reaches zero, the counter stops. The number of pulses counted is, therefore, proportional to the discharge period. This count is converted to a digital number and displayed as the measured quantity. Although this method works well, it is somewhat slow, so many microcomputer-based meters use a variation called *multislope integration*.

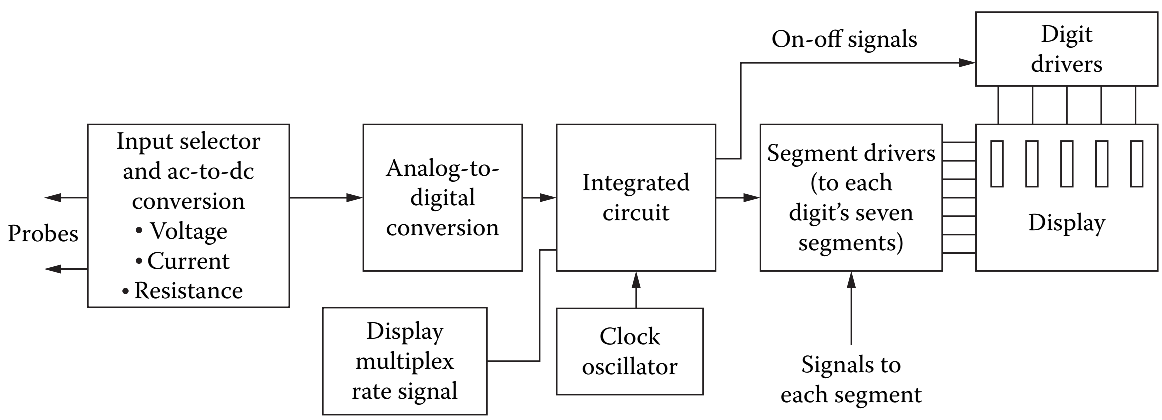


Figure 1.29 Block diagram of a basic digital voltage and current measuring device. It should be noted that advances in integrated circuit technology have reduced most of the individual elements shown to a single device.

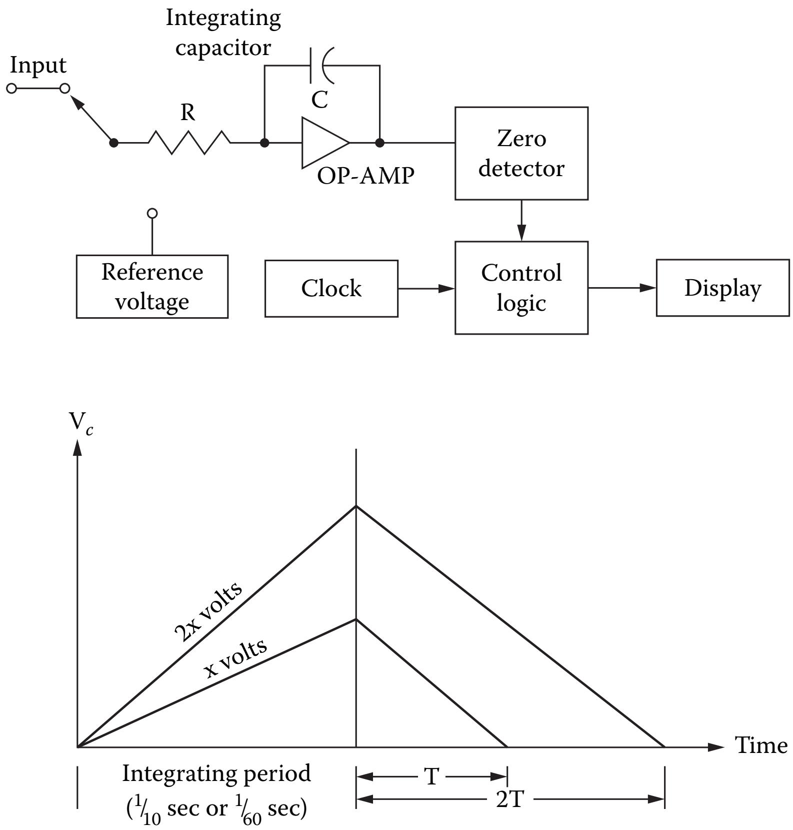


Figure 1.30 The analog-to-digital conversion process: (*a*) the basic circuitry involved; (*b*) graph of V_c vs. time. Because the slope of the discharge curve is identical regardless of the ultimate voltage reached by the integrator, the discharge period and, therefore, the number of counts recorded by the logic circuitry are proportional to the input voltage.

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2

Power-Generation Systems

2.1 Introduction

Any ac power system begins with a generating source. Electric generators are devices that convert energy from a mechanical form into an electrical form. This process, known as *electromechanical energy conversion*, involves magnetic fields that act as an intermediate medium. The input to the generating machine can be derived from a number of energy sources. For example, in the generation of large-scale electric power, coal can produce steam that drives the shaft of the machine. Typically, for such a thermal process, only about 1/3 of the raw energy (i.e., from coal) is converted into mechanical energy. The final step of the energy conversion is quite efficient, with efficiency close to 100%.

2.2 Fundamental Concepts

A simplified diagram of a three-phase generator is shown in Figure 2.1. Note that poles A', B', and C' represent the start of each of the phase windings, whereas poles A, B, and C represent the ends of each of the windings. As with transformers, the windings of the generator can be connected in either of two ways:

- *Wye configuration.* A circuit arrangement in which the schematic diagram of the windings forms a Y.
- *Delta configuration.* A circuit arrangement in which the schematic diagram of the windings forms a delta.

Figure 2.2 illustrates the connection arrangements.

The generator shown in Figure 2.1 is a rotating-field type of device. A magnetic field is developed by an external dc voltage. Through electromagnetic induction, a current is induced into each of the stationary (*stator*) coils of the generator. Because each of the phase windings is separated by 120°, the output voltage of the generator also is offset for each phase by 120° (Figure 2.3). Three-phase power is used almost exclusively for power distribution because it is an efficient method of transporting electrical energy.

2.2.1 Operating Principles

The operation of a generator is based on Faraday's law of electromagnetic induction [1]: If a coil (or winding) is linked to a varying magnetic field, then an electromotive force (emf or voltage) is induced across the coil. Thus, generators have two essential parts: one that creates a magnetic field, and the other where the emf energies are induced. The magnetic field is typically generated by electromagnets; thus, the field intensity can be adjusted for control purposes. These windings are referred to as *field windings* or *field circuits*. The coils where the emf energies are induced are called *armature windings* or *armature circuits*. One of these two components is stationary (the stator), and the other is a rotational part (the rotor) driven by an external torque. Conceptually, it is immaterial which of the two components is intended to rotate because, in either case, the armature circuits always experience a varying magnetic field. However, practical considerations lead to the common design that for ac generators, the field windings are mounted on the rotor and the armature windings on the stator.

Today, most electric power is produced by synchronous generators that rotate at a constant speed (the *synchronous speed*). This speed is dictated by the operating frequency of the system and the machine

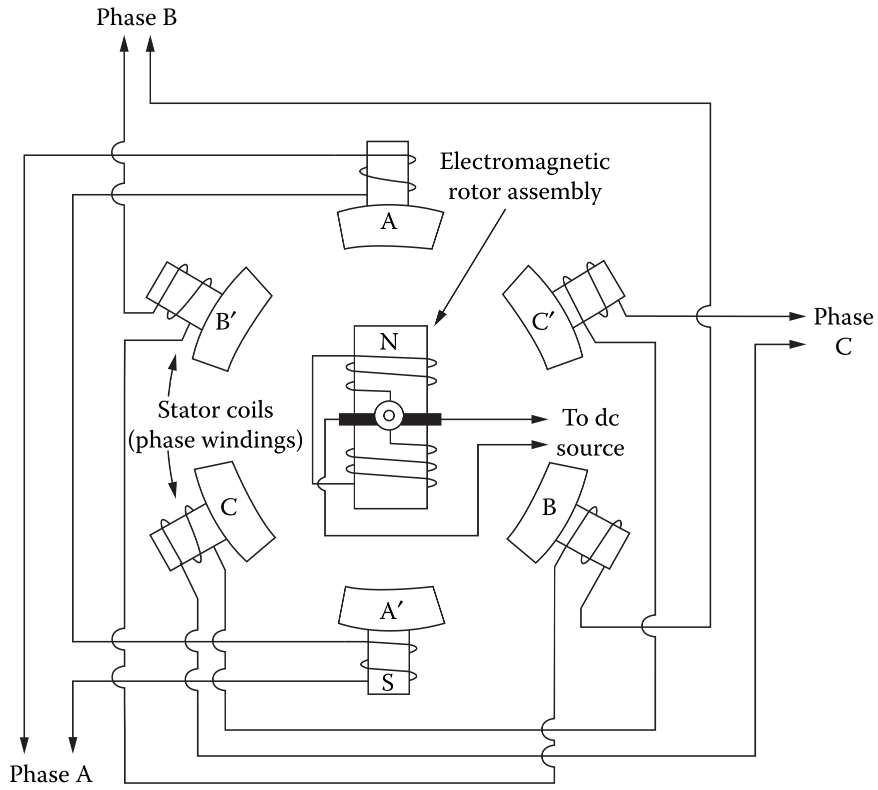

Figure 2.1 Simplified diagram of a three-phase ac generator.

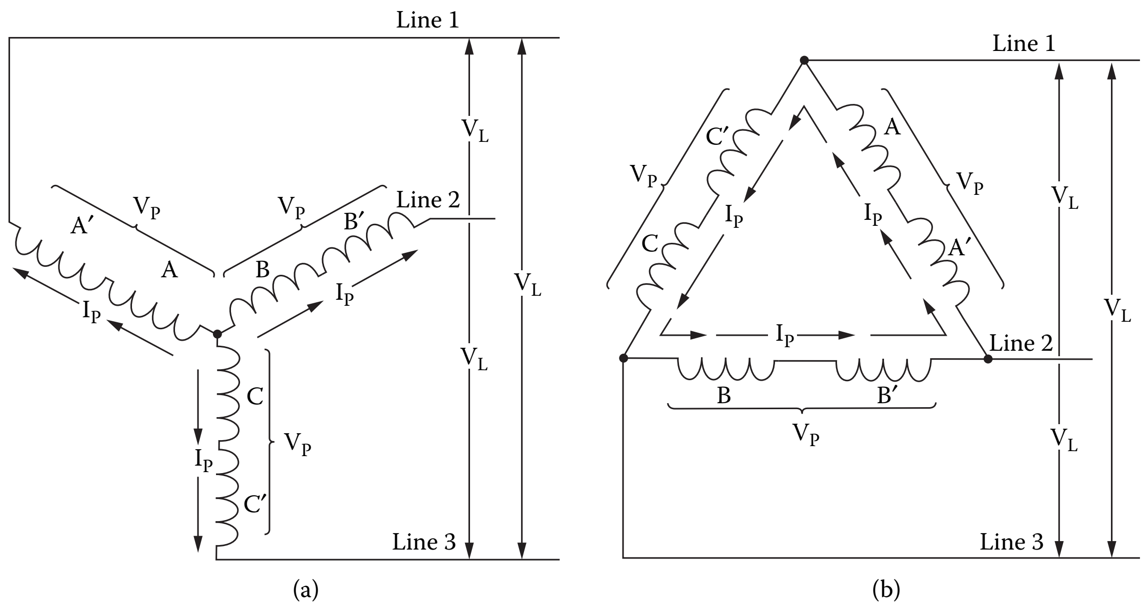

Figure 2.2 Generator circuit configurations: (*a*) wye; (*b*) delta.

structure. AC generators are also used that do not necessarily rotate at a fixed speed, such as those found in windmills (*induction generators*); these generators, however, account for only a small percentage of the power generated today.

For a better understanding of the principles of operation, see Figure 2.4, which shows a cross section of a basic ac machine. The rotor consists of a winding wrapped around a steel body. A dc current is made to flow in the rotor winding (or field winding), and this results in a magnetic field (rotor field). When the rotor is made to rotate at a constant speed, the three stationary windings *aa*', *bb*', and *cc*' experience a periodically varying magnetic field. Thus, an emf is induced across these windings in accordance with Faraday's law. These forces are ac and periodic; each period corresponds to one revolution of the rotor. Thus, for 60 Hz electricity, the rotor must spin at 3600 revolutions per minute (rpm); this is the synchronous speed of the machine. Because the windings *aa*', *bb*', and *cc*' are displaced equally in space from each other (by 120°), their emf waveforms are displaced in time by one third of a period. In other words, the machine is capable of generating three-phase electricity.

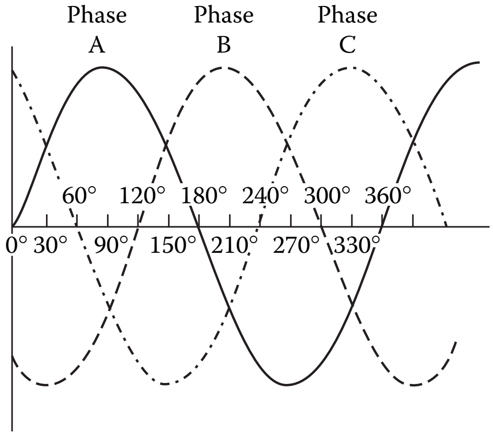

Figure 2.3 Output waveform of a three-phase generator.

When the stator windings are connected to an external (electrical) system to form a closed circuit, the steady-state currents in the windings are also periodic. This revolving field arises from the space displacements of the windings and the phase differences of their currents. The combined magnetic field has two poles and rotates at the same speed and direction as the rotor. It is important to observe that the armature circuits are in fact exposed to two rotating fields, one of which (the armature field) is caused by and tends to counter the effect of the other (the rotor field). The end result is that the induced emf in the armature can be reduced when compared with an unloaded machine (i.e., open-circuited stator windings). This phenomenon is referred to as *armature reaction.*

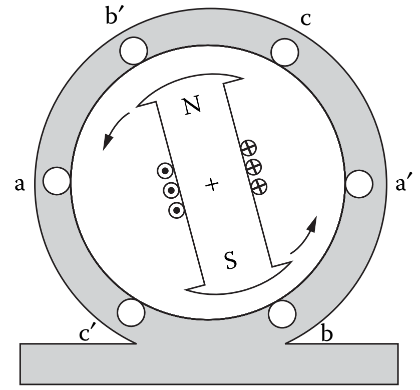

Figure 2.4 Cross section of a simple two-pole synchronous machine. (*From* [1]. *Used with permission.*)

It is possible to build a machine with *p* poles, where *p* = 4, 6, 8, … (even numbers). For example, the cross-sectional view of a four-pole machine is illustrated in Figure 2.5. For the specified direction of the (dc) current in the rotor windings, the rotor field has two pairs of north and south poles, arranged as shown. The emf induced in a stator winding completes one period for every pair of north and south poles sweeping by; thus, each revolution of the rotor corresponds to two periods of the stator emf. If the machine is to operate at 60 Hz, then the rotor needs to rotate at 1800 rpm. In general, a *p*-pole machine operating at 60 Hz has a rotor speed of 3600/(*p*/2) rpm. That is, the lower the number of poles, the higher the rotor speed must be. In practice, the number of poles is dictated by the mechanical system (the *prime mover*) that drives the rotor. Steam turbines operate best at a high speed; thus, two- or four-pole machines are suitable. Machines driven by hydro turbines usually have more poles and operate at lower speeds.

The stator windings are typically arranged so that the resulting armature field has the same number of poles as the rotor field. In practice, there are many possible ways to arrange these windings. The essential idea, however, can be understood by studying the arrangement shown in Figure 2.5. Each phase consists of a pair of windings and thus occupies four slots on the stator structure. For example, those for phase *a* are labeled a_1a_1' and a_2a_2'. Geometry suggests that, at any time instant, equal electromotive forces are induced across the windings of the same phase. If the individual windings are connected in series, as shown in Figure 2.5, their energies add up to form the phase voltage.

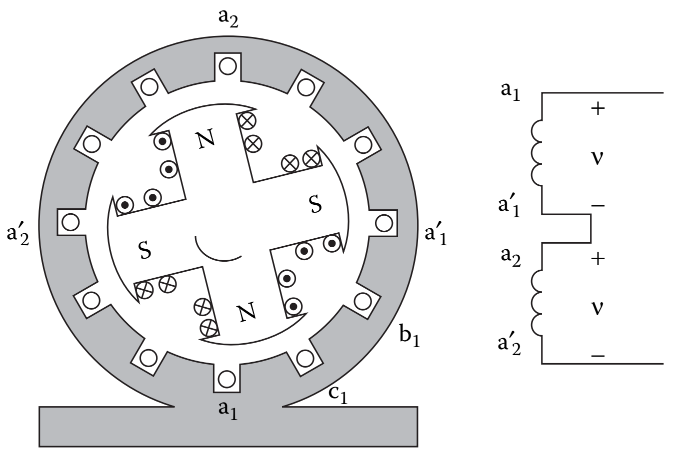

Figure 2.5 A four-pole synchronous machine: (*a*) cross section of the machine; (*b*) schematic diagram for the phase *a* windings. (*From* [1]. *Used with permission.*)

In addition to the basic components of a synchronous generator (the rotor, stator, and their windings), auxiliary devices are used to help maintain the machine's operation within acceptable limits. These devices include the following:

- *Governor*. The function of the governor is to control the mechanical power input to the generator. The control is via a feedback loop where the speed of the rotor is constantly monitored. For instance, if this speed falls behind the synchronous speed, the input is insufficient and has to be increased. This is accomplished by opening a valve to increase the amount of steam for turbogenerators or the flow of water through the penstock for hydrogenerators. Governors are mechanical systems and, therefore, usually have some significant time lags (many seconds) compared to other electromagnetic parameters associated with the machine.
- *Damper windings* (*armortisseur windings*). These windings are special conducting bars buried in notches on the rotor surface (the rotor resembles a squirrel-cage-rotor induction machine). The damper windings provide an additional stabilizing force for the machine during certain periods of operation. As long as the machine is in a steady state, the stator field rotates at the same speed as the rotor, and no currents are induced in the damper windings. However, when the speeds of the stator field and the rotor become different (because of a load disturbance), currents are induced in the damper windings in such a way as to keep the two speeds from separating.
- *Excitation control system*. Modern excitation systems are fast and efficient. An excitation control system is a feedback loop designed to maintain the voltage at the machine terminals at a set level. Figure 2.6 illustrates the mechanisms at work. Assume that a disturbance occurs in the system, and as a result, the machine terminal voltage V_t drops. The excitation system boosts the internal voltage E_F. This action can increase the voltage V_t and also tends to increase the reactive power output.

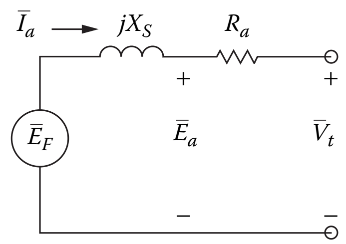

Figure 2.6 The per-phase equivalent circuit of a round-rotor synchronous machine. E_F is the internal voltage (phasor form) and V_t is the terminal voltage. (*From* [1]. *Used with permission.*)

From a system viewpoint, the two controlling mechanisms of excitation and the governor rely on local information (the machine terminal voltage and rotor speed). In other words, they are *decentralized controls*. For large-scale systems, such designs do not always guarantee stable behavior because the effects of the interconnection system and other elements in the network are not taken into account. An analysis of the operation of centralized control systems is beyond the scope of this book; however, it is instructive to examine some of the principles of decentralized control systems. Many of these principles apply in a modified form to centralized control techniques.

2.2.2 Control Techniques

Reliable electric power service implies that the loads are fed at a constant voltage and frequency at all times [1]. A stable power system is one in which the synchronous machines, if perturbed, will return to their original state if there is no net change in power, or stabilize at a new state without loss of synchronization. The machine rotor angle is used to quantify stability; that is, if the difference in the angle between machines increases or oscillates for an extended period of time, the system is considered unstable. The *swing equation,* given by

$$J\delta_m = J\omega_m = T_a \tag{2.1}$$

governs the motion of the machine rotor. J is moment of inertia, δ_m is mechanical torque angle with respect to a rotating reference, ω_m is shaft angular velocity, and T_a is the accelerating torque. Two factors that act as criteria for the stability of a generating unit are the angular swing of the machine during and following fault conditions, and the time it takes to clear the transient swing.

The mechanical torque of the prime mover — team or hydraulic — for a large generator depends on rotor speed. In an unregulated machine, the torque speed characteristic is linear over the rated range of speeds. The prime mover speed of a machine will drop in response to an increased load, and the valve position must be opened to increase the speed of the machine. In a regulated machine (governor controlled), the speed control mechanism controls the throttle valves to the steam turbine or the gate position for a water turbine.

Automatic voltage regulation can be used to adjust the field winding current, thus changing E_g as the load on the machine is varied (Figure 2.7). If the power output of a generator is to be increased while an automatic voltage regulator holds the bus voltage at a constant value, then the field winding current must be increased. The maximum voltage output of a machine is limited by the maximum voltage of the excitor supplying the field winding. Figure 2.8 illustrates control of a power-generating unit.

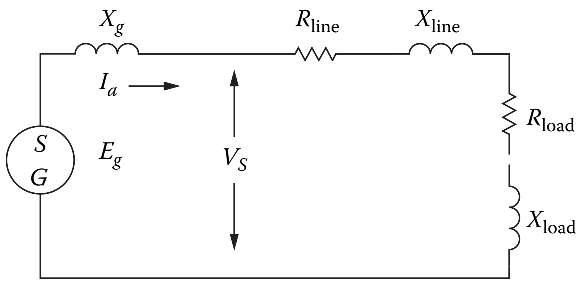

Figure 2.7 The basic power circuit of a generating system; $V_s = E_g - I_a X_g$. (*From* [1]. *Used with permission.*)

The performance of a transmission system can be improved by reactive compensation of a series or parallel type. Series compensation consists of banks of capacitors placed in series with each phase conductor of the line and is used to reduce the series impedance of the line, which is the principal cause of voltage drop. Shunt compensation consists of inductors placed from each line to neutral and is used to reduce the shunt susceptance of the line.

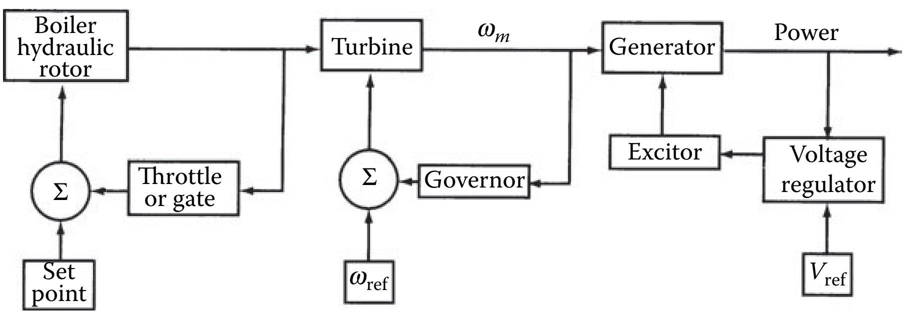

Figure 2.8 Block diagram of a generating control system *(From [1]. Used with permission.)*

2.3 Power-Generating Systems

Electrical power can be produced in many ways, including chemical reactions, heat, light, or mechanical energy. Most electrical power produced today is through hydroelectric plants and nuclear energy, and by burning coal, oil, or natural gas. Fossil fuel and nuclear-fission plants use steam turbines to deliver the mechanical energy required to rotate large three-phase generators, which produce massive quantities of electrical power. Generators used in such facilities usually are classified as high-speed units, operating at 3600 rpm to produce a 60 Hz output frequency. Hydroelectric systems use hydraulic turbines, mounted vertically to intercept the flow of water to produce electrical energy. Most hydroelectric facilities use low-speed generators, operating at from 120 to 900 rpm to produce 60 Hz. It follows that a larger number of poles are required for a low-speed generator.

Fossil fuels, used as a source of heat, are burned to produce steam in a boiler system. The steam then drives one or more generators. Coal and coke are used commonly to produce energy in this manner. Other fossil fuel sources include oil and natural gas.

A nuclear power plant is basically a fossil fuel facility with a nuclear power source to produce heat and then steam. Nuclear fission is a complex process that results in the division of the nucleus of an atom into two nuclei. This splitting of the atom is initiated by bombardment of the nucleus with neutrons, gamma rays, or other charged particles.

A hydroelectric system is the simplest of all power plants. Flowing water from a reservoir is channeled through a control gate that directs water to the blades of a hydraulic turbine. The turbine, in turn, drives one or more generators. Although simple in design and efficient in operation, hydroelectric systems are limited by the availability of a water reservoir.

Concern about the burning of fossil fuels and the safety of nuclear power has led to the development of alternative fuel sources for turbine-driven power plants. Power-generating systems now in operation include:

- Geothermal systems, which utilize the heat of a molten mass in the interior of the earth to produce steam, which drives a turbine generator. Such systems are efficient and simple, but their placement is limited to areas of geothermal activity.
- Wind systems, which use a number of small generators mounted on supports and attached to propeller-type blades to intercept prevailing winds. Naturally, generator output is determined by wind activity, limiting the use of these systems on any large scale.

Significant variations in load requirements must be satisfied at different times by a generating plant. Because of wide variations in load demands, much of the generating capability of a facility may be unused during low-demand periods. Two mathematical ratios commonly are used to measure utility service:

- *Load factor*. The average load for a given period divided by the peak load for that same period.
- *Capacity factor*. The average load for a given period divided by the output capacity of the power plant.

Under ideal conditions, both the load factor and the capacity factor are unity (100%). Commercial power systems use a number of three-phase generators connected in parallel, and synchronized in phase, to supply the load requirements.

Table 2.1 lists general technical details for different types of common power plants.

2.3.1 Fossil Fuel Power Plants

The most frequently used fuels for large-scale power generation are oil, natural gas, and coal [3]. Figure 2.9 illustrates the principal elements of a fossil fuel power plant. Fuel handling includes transport by rail, on ships, or through pipelines. A power plant usually maintains several days of fuel reserve at any one

Table 2.1 Power Plant Technical Data (*After* [2].)

Power Generation Type	Typical Size (MW)	Capitalized Plant Cost ($/kW)	Construction Lead Time (Yr)	Heat Rate (BTU/kWh)	Fuel Type
Nuclear	1,200	2,400	10	10,400	Uranium
Pulverized coal/steam	500	1,400	6	9,900	Coal
Atmospheric fluidized bed	400	1,400	6	9,800	Coal
Gas turbine	100	350	2	11,200	Natural gas
Combined-cycle	300	600	4	7,800	Natural gas
Coal-gasification combined-cycle	300	1,500	6	9,500	Coal
Pumped storage hydro	300	1,200	6	–	–
Conventional hydro	300	1,700	6	–	–

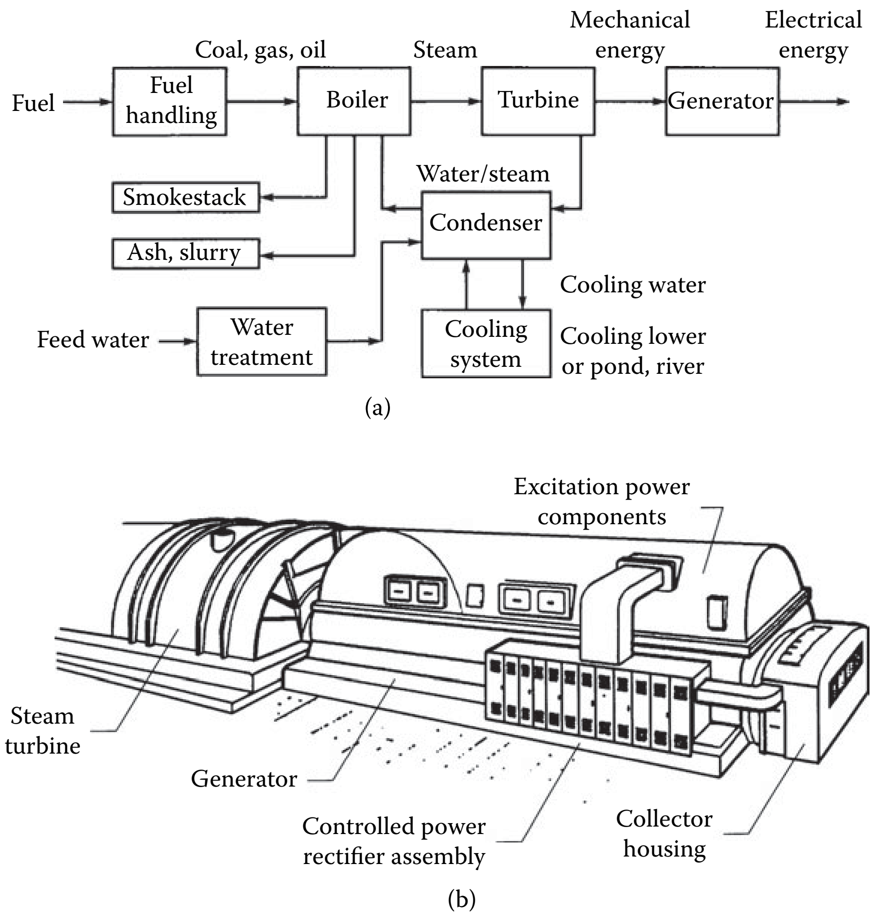

Figure 2.9 Primary components of a fossil fuel power plant: (*a*) system block diagram; (*b*) common configuration of turbine/generator system. (*From* [3]. *Used with permission.*)

time. Oil and gas are stored in large metal tanks, and coal is kept in open yards. The temperature of the coal layer must be monitored carefully to avoid self-ignition.

Oil is pumped and gas is fed to the burners of the boiler. Coal is pulverized in large mills, and the powder is mixed with air and transported by air pressure, through pipes, to the burners. The coal transport from the yard to the mills requires automated transporter belts, hoppers, and sometimes manually operated bulldozers.

Two types of boilers are used in modern power plants: the *subcritical* water-tube drum-type and the *supercritical* once-through type. The former operates around 2500 psi, which is below the water critical pressure of 3208.2 psi. The latter operates above that pressure, at approximately 3500 psi. The superheated steam temperature is about 1000°F (540°C) because of turbine temperature limitations.

A typical subcritical water-tube drum-type boiler has an inverted-U shape, as illustrated in Figure 2.10. On the bottom of the rising part is the furnace where the fuel is burned. The walls of the furnace are

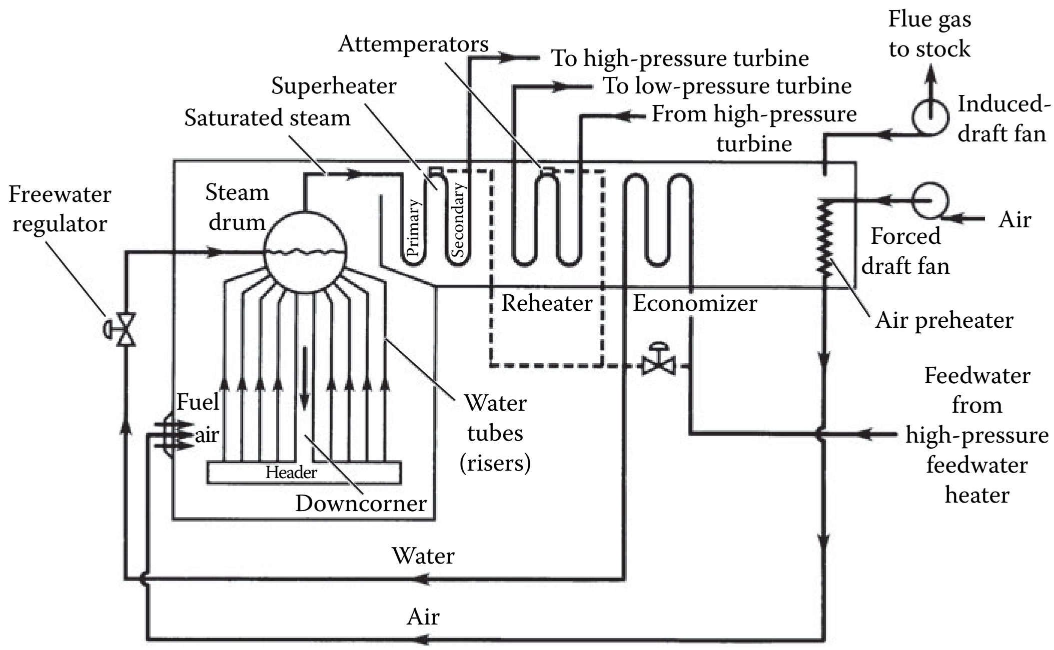

Figure 2.10 Flow diagram of a typical drum-type steam boiler. (*From* [4]. *Used with permission.*)

covered by water pipes. The drum and the superheater are at the top of the boiler. The falling part of the U houses the reheaters, economizer (water heater), and air preheater, which is supplied by the forced-draft fan. The induced-draft fan forces the flue gases out of the system and sends them up the stack, which is located behind the boiler. This steam generator has three major systems:

- **Fuel system.** Fuel is mixed with air and injected into the furnace through burners. The burners are equipped with nozzles, which are supplied by preheated air and carefully designed to assure the optimum air-fuel mix. The fuel mix is ignited by oil or gas torches. The furnace temperature is around 3000°F.
- **Air-flue gas system.** Ambient air is driven by the forced-draft fan through the air preheater, which is heated by the high-temperature (600°F) flue gases. The air is mixed with fuel in the burners and enters the furnace, where it supports the fuel burning. The hot combustion flue gas generates steam and flows through the boiler to heat the superheater, reheaters, economizer, and other related systems. Induced-draft fans, located between the boiler and the stack, increase the flow and send the 300°F flue gases to the atmosphere through the stack.
- **Water-steam system.** Large pumps drive the feedwater through the high-pressure heaters and the economizer, which further increases the water temperature (400 to 500°F). The former is heated by steam removed from the turbine; the latter is heated by the flue gases. The preheated water is fed to the steam drum. Insulated tubes called *downcomers* are located outside the furnace and lead the water to a header. The header distributes the hot water among the *risers*. These water tubes line the furnace walls. The water tubes are heated by the combustion gases through both connection and radiation. The steam generated in these tubes flows to the drum, where it is separated from the water. Circulation is maintained by the density difference between the water in the downcomer and the water tubes. Saturated steam, collected in the drum, flows through the superheater. The superheater increases the steam temperature to about 1000°F. Dry superheated steam drives the high-pressure turbine. The exhaust from the high-pressure turbine goes to the reheater, which again increases the steam temperature. The reheated steam drives the low-pressure turbine.

The typical supercritical once-through-type boiler concept is shown in Figure 2.11. The feedwater enters through the economizer to the boiler, which consists of riser tubes that line the furnace wall. All the water is converted to steam and fed directly to the superheater. The latter increases the steam temperature above the critical temperature of the water and drives the turbine. The construction of these steam generators is more expensive than the drum-type units but has a higher overall operating efficiency.

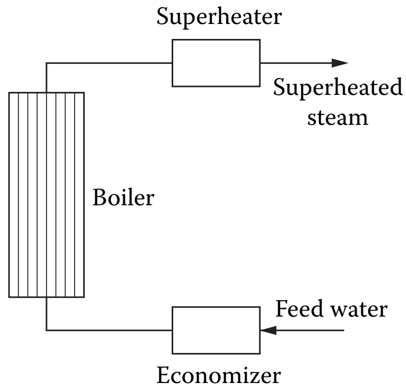

Figure 2.11 Block diagram of a once-through-type steam generator. (*From* [3]. *Used with permission.*)

The turbine converts the heat energy of the steam into mechanical energy. Modern power plants typically use one high-pressure and one or two lower-pressure turbines. High-pressure steam enters the high-pressure turbine to flow through and drive the turbine. The exhaust is reheated in the boiler and returned to the lower-pressure units. Both the rotor and the stationary part of the turbine have blades. The length of the blades increases from the steam entrance to the exhaust. Figure 2.12 shows the blade arrangement of an impulse-type turbine. Steam enters through nozzles and flows through the first set of moving rotor blades. The following stationary blades change the direction of the flow and direct the steam into the next set of moving blades. The nozzles increase the steam speed and reduce pressure, as shown in the figure. The impact of the high-speed steam, generated by the change of direction and speed in the moving blades, drives the turbine.

In a fossil fuel plant, the generator converts mechanical energy from the turbines into electrical energy. The stator typically has a laminated and slotted silicon steel iron core. The stacked core is clamped and held together by insulated axial through bolts. The stator winding is placed in the slots and consists of a copper-strand configuration with woven glass insulation between the strands and mica flakes, mica mat, or mica paper groundwall insulation. To avoid insulation damage caused by vibration, the groundwall insulation is reinforced by asphalt, epoxy-impregnated fiberglass, or Dacron. Most frequently, the stator is hydrogen-cooled; however, small units may be air-cooled, and very large units may be water-cooled. The solid steel rotor has slots milled along the axis. The multiturn copper rotor winding is placed in the slots and cooled by hydrogen. Cooling is enhanced by subslots and axial cooling passages. The rotor winding is restrained by wedges inserted in the slots.

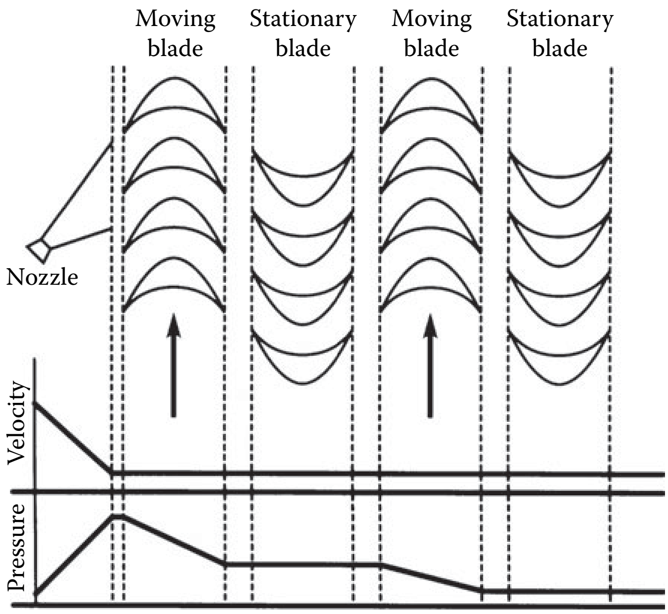

Figure 2.12 Velocity and pressure variation in an impulse turbine. (*From* [3]. *Used with permission.*)

The rotor winding is supplied by dc current, either directly by a brushless excitation system or through collector rings. The nondrive-end bearing is insulated to avoid shaft current generated by stray magnetic fields. The hydrogen is cooled by a hydrogen-to-water heat exchanger mounted on the generator or installed in a closed-loop cooling system.

The condenser condenses turbine exhaust steam to water, which is pumped back to the steam generator through various water heaters. This condensation produces a vacuum, which is necessary to exhaust the steam from the turbine. The condenser usually is a shell-and-tube heat exchanger, where steam condenses on water-cooled tubes. Cold water is obtained from the cooling towers or other cooling systems. The condensed water is fed through a deaerator, which removes absorbed gases from the water. Next, the gas-free water is mixed with the feedwater and returned to the boiler. The gases absorbed in the water may cause corrosion and increase condenser pressure, adversely affecting efficiency. Older plants use a separate deaerator heater, whereas deaerators in modern plants are usually integrated in the condenser, where injected steam jets produce a pressure drop and remove absorbed gases.

2.3.2 Nuclear Power Plants

There are approximately 500 nuclear power plants operating around the world [3]. Close to 300 operate *pressurized water reactors* (PWRs), more than 100 are built with *boiling-water reactors* (BWRs), about 50 use gas-cooled reactors, and the rest are *heavy-water reactors*. In addition, a few *fast breeder reactors* are in operation. These reactors are built for better utilization of uranium fuel. The modern nuclear plant size varies from 100 to 1200 MW.

The general arrangement of a PWR power plant is shown in Figure 2.13*a*. The reactor heats the water from about 550 to approximately 650°F. High pressure, at about 2235 psi, prevents boiling. Pressure is maintained by a pressurizer, and the water is circulated by a pump through a heat exchanger. The heat exchanger evaporates the feedwater and generates steam, which supplies a system similar to a conventional power plant. The advantage of this two-loop system is the separation of the potentially radioactive reactor cooling fluid from the water-steam system.

The reactor core consists of fuel and control rods. Grids hold both the control and fuel rods. The fuel rods are inserted in the grid following a predetermined pattern. The fuel elements are Zircaloy-clad rods filled with UO_2 pellets. The control rods are made of a silver, cadmium, and indium alloy protected by stainless steel. The reactor operation is controlled by the position of the rods. In addition, control rods are used to shut down the reactor. The rods are released and fall in the core when emergency shutdown is required. Cooling water enters the reactor from the bottom, flows through the core, and is heated by nuclear fission.

In the BWR, shown in Figures 2.13*b* and 2.14, the pressure is low (about 1000 psi). The nuclear reaction heats the water directly to evaporate it and produce wet steam at about 545°F. The remaining water is recirculated and mixed with feedwater. The steam drives a turbine that typically rotates at 1800 rpm. The

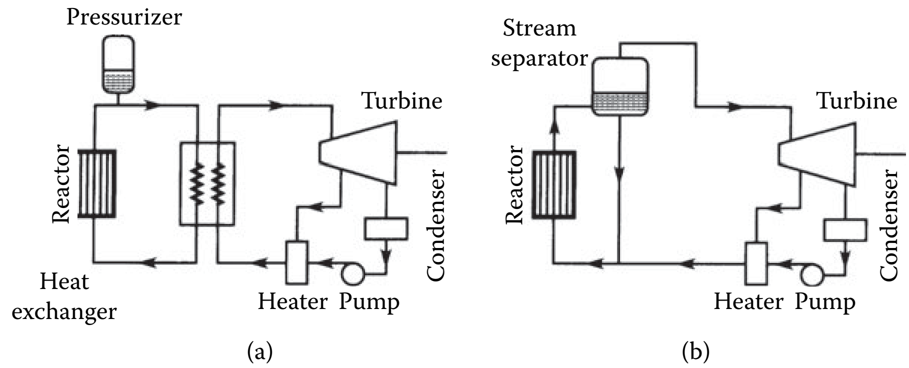

Figure 2.13 Types of nuclear power plants: (*a*) pressurized water reactor; (*b*) boiling-water reactor. (*From* [3]. *Used with permission.*)

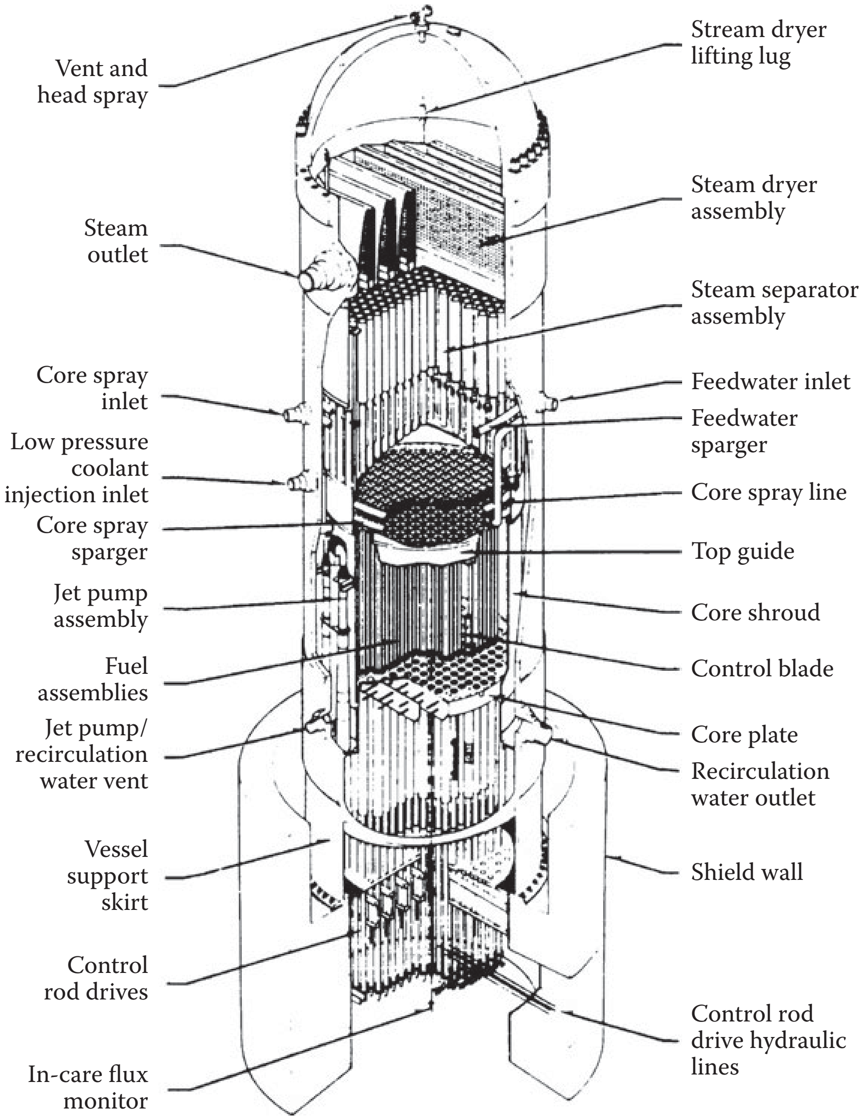

Figure 2.14 Typical configuration of a boiling-water reactor. (*Courtesy of General Electric Company.*)

rest of the plant is similar to a conventional power plant. Figure 2.14 shows all the major components of the reactor. The fuel and control rod assembly is located in the lower part. The steam separators are above the core, and the steam dryers are at the top of the reactor. The reactor is enclosed by a concrete dome.

2.3.3 Hydroelectric Power Plants

Hydroelectric power plants convert energy produced by a *water head* into electric energy [3]. The head is produced by building a dam across a river, which forms the upper-level reservoir. In the case of *low head*, the water forming the reservoir is fed to the turbine through the intake channel or the turbine is integrated in the dam. The latter arrangement is shown in Figure 2.15. Penstock tubes or tunnels are used for medium-head and high-head plants, as shown in Figure 2.16 and Figure 2.17, respectively. The spillway regulates the excess water in the reservoir by opening gates at the bottom of the dam or permitting overflow on the spillway section of the dam. The water discharged from the turbine flows to the lower or *tail water* reservoir, which is usually a continuation of the original water channel.

High-head plants are built with impulse turbines, where the head-generated water pressure is converted into velocity by nozzles and the high-velocity water jets drive the turbine runner. Low- and medium-head installations are built with reaction-type turbines, where the water pressure is mostly converted to velocity in the turbine. The two basic classes of reaction turbines are the propeller or *Kaplan*

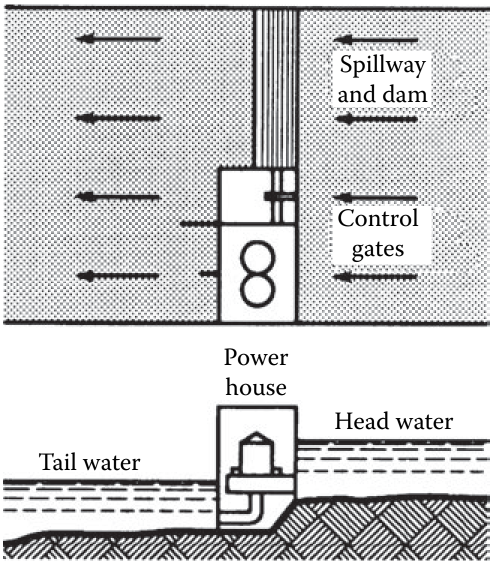

Figure 2.15 Low-head hydroelectric power plant. (*From* [4]. *Used with permission.*)

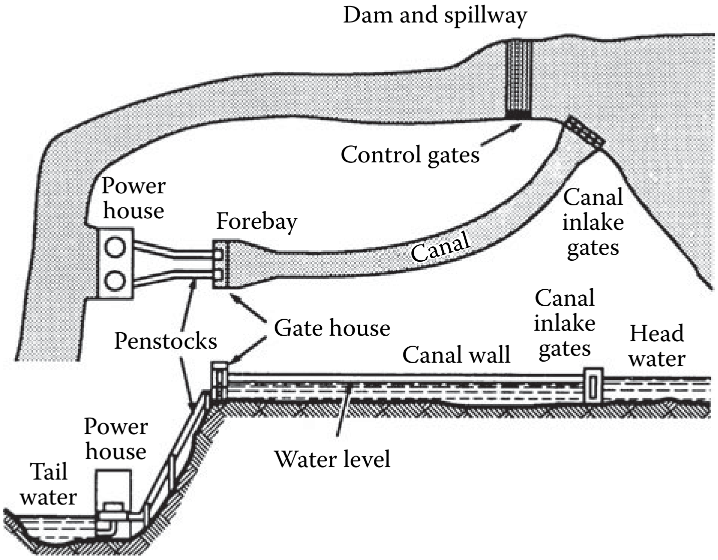

Figure 2.16 Medium-head hydroelectric power plant. (*From* [4]. *Used with permission.*)

type, mostly used for low-head plants, and the *Francis* type, primarily used for medium-head plants. The cross section of a typical low-head Kaplan turbine is shown in Figure 2.18.

The vertical shaft turbine and generator are supported by a thrust bearing immersed in oil. The generator is in the upper, watertight chamber. The turbine runner has 4 to 10 propeller types and adjustable-pitch blades. The blades are regulated from 5 to 35° by an oil-pressure-operated servomechanism. The water is evenly distributed along the periphery of the runner by a concrete spiral case and regulated by adjustable wicket blades. The water is discharged from the turbine through an elbow-shaped draft tube. The conical profile of the tube reduces the water speed from the discharge speed of 10 to 30 ft/s to 1 ft/s to increase turbine efficiency.

The hydrogenerator is a low-speed (usually 120 to 360 rpm) salient-pole machine with a vertical shaft. The typical number of poles ranges from 20 to 72. They are mounted on a pole spider, which is a welded, spoked wheel. The spider is mounted on the forged steel shaft. The poles are built with a laminated iron core and stranded copper winding. Damper bars are built in the pole faces. The stator is built with a slotted, laminated iron core that is supported by a welded steel frame. Windings are made of stranded conductors insulated between the turns by fiberglass or Dacronglass. The ground insulation is formed from multiple layers of mica tape impregnated with epoxy or polyester resins. Older machines use asphalt and mica tape insulation, which is sensitive to corona-discharge-caused insulation deterioration.

Direct water cooling is used for very large machines, whereas the smaller ones are air- or hydrogen-cooled. Some machines use forced-air cooling with an air-to-water heat exchanger. A braking system is installed in larger machines to stop the generator rapidly when necessary.

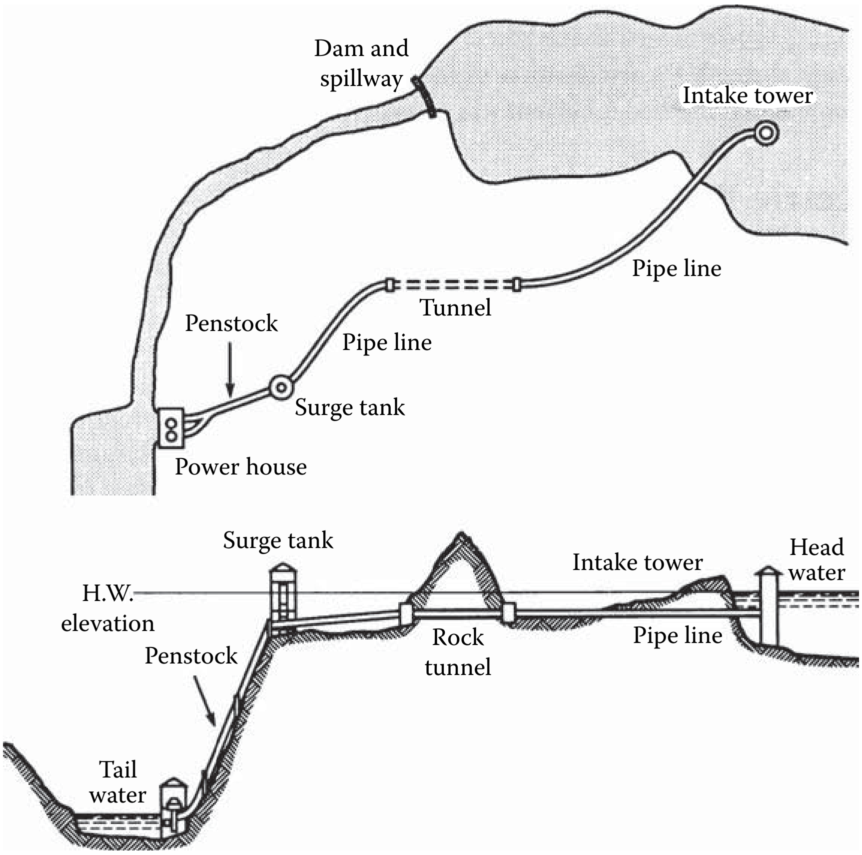

Figure 2.17 High-head hydroelectric power plant. (*From* [4]. *Used with permission.*)

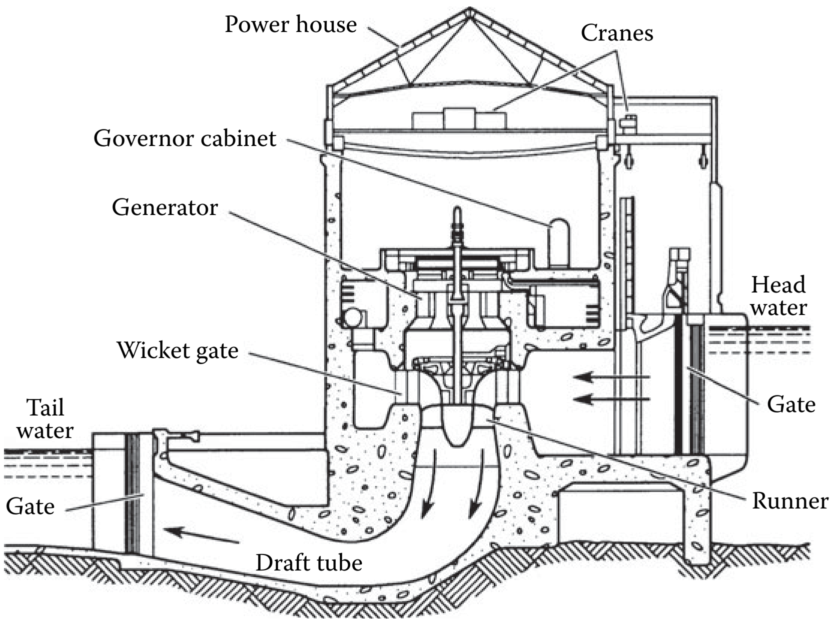

Figure 2.18 Typical low-head hydroelectric power plant with a Kaplan turbine. (*From* [4]. *Used with permission.*)

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3

Power Factor

3.1 Introduction

Power factor (PF) is an important, but often misunderstood, element of ac power system design and operation. It is defined as the ratio of *true power* to *apparent power*, generally expressed as a percentage. (PF also may be expressed as a decimal value.) Reactive loads (inductive or capacitive) act on power systems to shift the current out of phase with the voltage. The cosine of the resulting angle between the current and voltage is the power factor.

3.2 Fundamental Principles

A utility line that is feeding an inductive load (which is most often the case) is said to have a *lagging* power factor, whereas a line feeding a capacitive load has a *leading* power factor. (See Figure 3.1.) A poor power factor will result in excessive losses along utility company feeder lines because more current is required to supply a given load with a low power factor than the same load with a power factor close to unity.

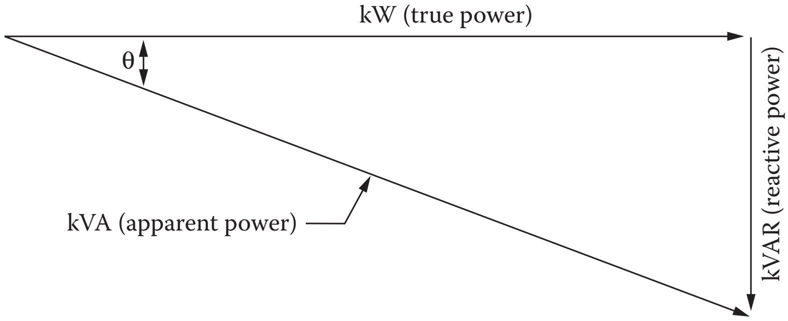
For example, a motor requiring 5 kW from the line is connected to the utility service entrance. If it has a power factor of 86%, the apparent power demanded by the load will be 5 kW divided by 86%, or more than 5.8 kW. The true power is 5 kW, and the apparent power is 5.8 kW. The same amount of work is being done by the motor, but the closer the power factor is to unity, the more efficient the system. To expand upon this example, for a single-phase electric motor, the actual power is the sum of several components, namely:

- The work performed by the system, specifically lifting, moving, or otherwise controlling an object
- Heat developed by the power that is lost in the motor winding resistance
- Heat developed in the motor iron through eddy-current and hysteresis losses
- Frictional losses in the motor bearings
- Air friction losses in turning the motor rotor

All these values are expressed in watts or kilowatts, and can be measured with a wattmeter. They represent the actual power. The apparent power is determined by measuring the current and voltage with an ammeter and a voltmeter, then calculating the product of the two. In the single-phase motor example, the apparent power thus obtained is greater than the actual power. The reason for this is the power factor.

The PF reflects the differences that exist between different types of loads. A soldering iron is a purely resistive load that converts current directly into heat. The current is called actual current because it contributes directly to the production of actual power. On the other hand, single-phase electric motor represents a partially inductive load. The motor current consists of actual current that is converted into actual power and a *magnetizing current* that is used to generate the magnetic field required for operation of the device. This magnetizing current corresponds to an exchange of energy between the power source and the motor, but it is not converted into actual power. This current is identified as the reactive current in the circuit.

As illustrated in Figure 3.2, in a resistive circuit, the current is in phase with the voltage. In a purely inductive circuit, the current lags the voltage by 90°. This relationship can be represented graphically by vectors, as shown in the figure. For a circuit with both inductive and resistive components, as in the motor example, the two conditions exist simultaneously. The distribution between the actual power and the reactive power is illustrated in Figure 3.3. The power factor, which has been defined previously as the ratio between actual power and apparent power, is also the cosine of the angle θ. The greater the angle θ becomes, the lower the power factor.



$$\text{Cos } \theta = \frac{\text{kW}}{\text{kVA}} = \text{PF}$$

$$\text{Sin } \theta = \frac{\text{kVAR}}{\text{kVA}}$$

θ = The phase angle, a measure of the net amount of inductive reactance in the circuit.

kW = The true power that performs the “real work” done by the electrical circuit (measured in kilowatts).

kVA = The apparent power drawn by a reactive load (measured in kilowatts).

kVAR = The kilovolt-ampers-reactive component of an inductive circuit. The kVAR component (also known as the *phantom power*) provides the magnetizing force necessary for operation of inductive loads.

Figure 3.1 The mathematical relationships of an inductive circuit as they apply to power factor (PF) measurements. Reducing the kVAR component of the circuit causes θ to diminish, improving the PF. When kW is equal to kVA, the phase angle is zero and the power factor is unity (100%).

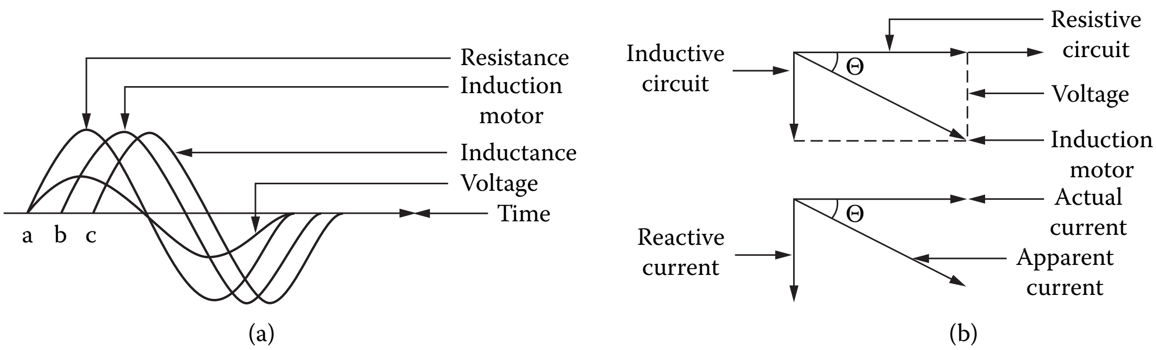


Figure 3.2 The effects of inductance in a circuit: (*a*) waveforms for resistive and inductive loads; (*b*) vector diagrams of inductive loads.

Determining the power factor for a given element of a power-distribution system is complicated by the variety of loads typically connected. Different loads present different PF components:

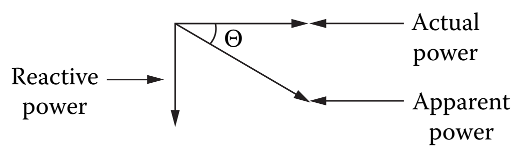


Figure 3.3 Vector diagram showing that apparent power is the vector sum of the actual and the reactive power in a circuit.

- **Lighting.** The PF for most incandescent lamps is unity. Fluorescent lamps usually have a low power factor; 50% is typical. Fluorescent lamps sometimes are supplied with compensation devices to correct for low power factor. Mercury vapor lamps have a low PF; 40 to 60% is typical. Again, such devices can be supplied with compensation devices.
- **Electric motors.** The PF of an induction motor varies with the load, as shown in Figure 3.4. Unloaded or lightly loaded motors exhibit a low PF. Figure 3.5 illustrates the variation of PF and reactive power for varying loads on a three-phase induction motor. Synchronous motors provide

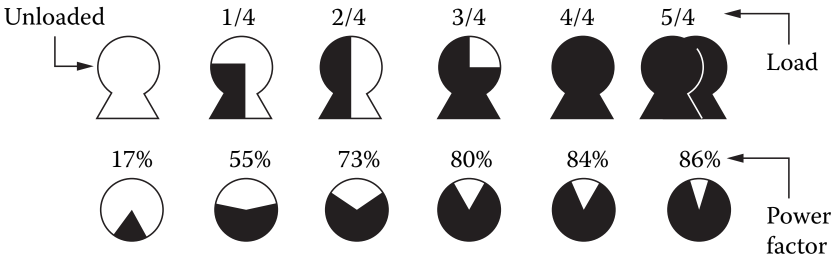


Figure 3.4 Changes in power factor for an induction motor as a function of motor loading.

good PF when their excitation is adjusted properly. Synchronous motors also can be *overexcited* to exhibit a leading power factor and, therefore, can be used to improve the power factor of a facility.

- **Heating systems.** Most heating systems used in ovens or dryers present a PF of close to unity.
- **Welding equipment.** Electric arc welders usually have a low PF; 60% is typical.
- **Distribution transformers.** The PF of a transformer varies considerably as a function of the load applied to the device, as well as the design of the transformer. An unloaded transformer would be highly inductive and, therefore, would exhibit a low PF.

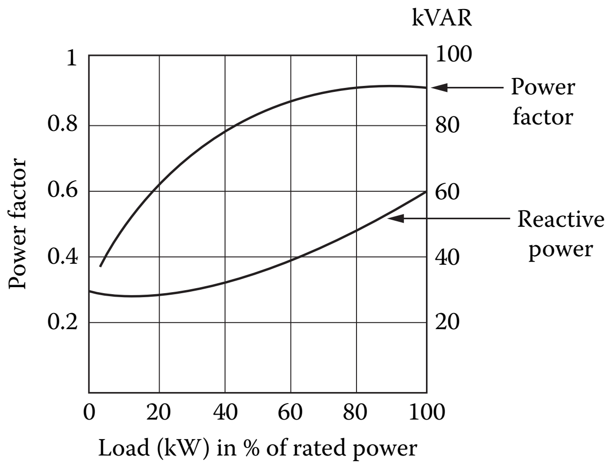


Figure 3.5 The relationship of reactive power and power factor to percentage of load for a 100 kW, three-phase induction motor.

Power factor, in the classical power triad representation presented here, is more appropriately referred to as *displacement power factor* (DPF). DPF is that portion of the power factor that is attributable to phase displacement between the source voltage and the load current at the fundamental frequency [1]. The vector diagram power triangle models real and reactive power at the fundamental frequency of the electrical power system. Displacement power factor does not consider that portion of the power factor attributable to harmonic load current.

The *total power factor* (TPF) can be derived by revisiting the definition of power factor as a measurement of efficiency. TPF, then, is the ratio of real power to total power consumed in the system:

$$TPF = \frac{KW}{kVA_{total}} \tag{3.1}$$

where

TPF = Total power factor
KW = Real power consumed by the electrical system
kVA_{total} = Total power (composed of real, reactive, and harmonic power)

The TPF in a system can be low because of high reactive power consumption or high harmonic power consumption, resulting in high apparent power in the denominator. DPF is always greater than TPF when harmonic load currents exist.

3.3 PF Correction Techniques

The term *compensation* is used to describe the intentional insertion of reactive power devices, either capacitive or inductive, to achieve one or more desired effects in an electric power system. These effects include improved voltage profiles, enhanced stability, and increased transmission capacity. The devices are either in series or in shunt (parallel) with the load(s) at one or more points in the power circuit.

To keep the power factor as close as possible to 100%, utility companies place capacitor banks in parallel with the load at various locations in the distribution system, offsetting the inductive loading (lagging power factor) of most user equipment. The goal is to create an equal amount of leading PF in the system to match the lagging PF of the load. When balanced, the power factor is 100%. In practice, this is seldom attainable because loads are switched on and off at random times, but utilities routinely maintain an overall power factor of approximately 99%. To accomplish this, capacitor banks are switched automatically to compensate for changing load conditions. In addition, *static capacitors* are used for power factor correction. These devices are similar to conventional oil-filled, high-voltage capacitors. Operating voltages range from 230 V to 13.8 kV and higher for pole-mounted applications.

The PF correction capacitors are connected in parallel, with the utility lines as close as practical to the low-PF loads. The primary disadvantage of static PF correction capacitors is that they cannot be adjusted for changing power factor conditions. Remotely operated relays can be used, however, to switch capacitor banks in and out of the circuit as required. Synchronous capacitors, on the other hand, can be adjusted to provide varying capacitance to correct for varying PF loads. The capacitive effect of a synchronous capacitor is changed by varying the dc excitation voltage applied to the rotor of the device.

Utilities usually pass on to customers the costs of operating low-PF loads. Power factor can be billed as one, or a combination, of the following:

- A penalty for PF below a predetermined value or a credit for PF above a predetermined value
- An increasing penalty for decreasing PF
- A charge on monthly kVAR hours
- A straight charge for the maximum value of kVA used during the month

Aside from direct costs from utility companies for low-PF operation, the end user experiences a number of indirect costs, as well. When a facility operates with a low overall PF, the amount of useful electrical energy available inside the plant at the distribution transformer is reduced considerably because of the amount of reactive energy that the transformer(s) must carry. Figure 3.6 illustrates the reduction in available power from a distribution transformer when presented with varying PF loads. Figure 3.7 illustrates the increase in I^2R losses in feeder and branch circuits with varying PF loads. These conditions result in the need for oversized cables, transformers, switchgear, and protection circuits.

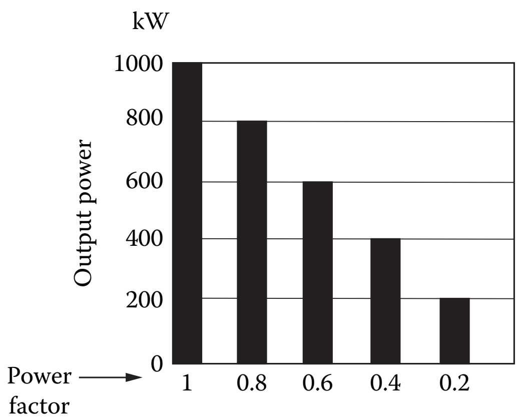


Figure 3.6 The effects of power factor on the output of a transmformer.

The *copper losses* in a system are proportional to the square of the load current. The installation of PF correction capacitors near offending low PF loads decreases the reactive power and load current drawn from the utility [17]. This reduced load current translates into lower conductor losses throughout the electrical system. As copper losses are reduced, voltage levels increase throughout the system. This rise can be described by

$$VR = \frac{kVAR_{cb} \times Z_t}{kVA_t} \tag{3.2}$$

where

VR = percent voltage rise
$kVAR_{cb}$ = sum of capacitor kVAR ratings
Z_t = percent reactance of the supply transformer(s)
kVA_t = kVA rating of the supply transformer(s)

When individual capacitors are installed at large motors or at a motor control center with several smaller motors attached, the individual capacitor reactive power ratings can be arithmetically summed and the resulting value inserted into Equation 3.2.

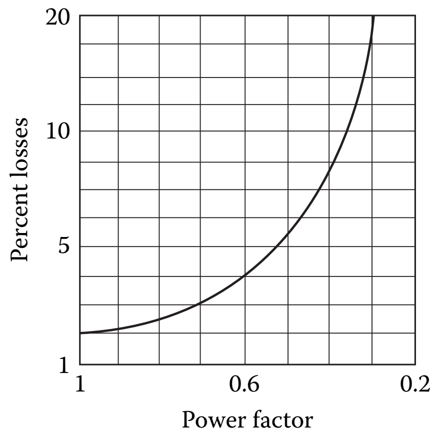


Figure 3.7 The relationship between power factor and percentage losses in system feeder and branch circuits.

3.3.1 On-Site Power Factor Correction

The first step in correcting for low PF is to determine the existing situation at a given facility. Clamp-on power factor meters are available for this purpose. Power factor can be improved in two ways:

- Reduce the amount of reactive energy by eliminating low PF loads, such as unloaded motors and transformers
- Apply external compensation capacitors or other devices to correct the low-PF condition

PF correction capacitors perform the function of an energy-storage device. Instead of transferring reactive energy back and forth between the load and the power source, the magnetizing current reactive energy is stored in a capacitor at the load. Capacitors are rated in kVARs, and are available for single- and multiphase loads. Usually, more than one capacitor is required to yield the desired degree of PF correction. The capacitor rating required in a given application can be determined by using lookup tables provided by PF capacitor manufacturers. Installation options include:

- Individual capacitors placed at each machine
- A group or bank installation for an entire area of the plant
- A combination of the two approaches

Figure 3.8*a* shows a simple circuit with shunt capacitor compensation applied at the load. The line current I_L is the sum of the motor load current I_M and the capacitor current I_C. From the current phasor diagram of Figure 3.8*b*, it can be seen that the line current is reduced with the insertion of the shunt capacitor. Figure 3.8*c* displays the corresponding voltage phasors. The effect of the shunt capacitor is to increase the voltage source to V_{S1} from V_{S0}.

When rectifier loads that generate harmonic load current are the cause of a low-PF condition, the addition of PF correcting capacitors will not necessarily provide the desired improvement. The capacitors, in some cases, may actually raise the line current and fail to improve the power factor. Harmonic currents generally are most apparent in the neutral of three-phase circuits. Conductors supplying three-phase rectifiers using a neutral conductor require a neutral conductor that is as large as the phase conductors. A reduced neutral should not be permitted. When adding capacitors for PF correction, be careful to avoid any unwanted voltage resonances that might be excited by harmonic load currents.

If a delta/wye-connected power transformer is installed between the power source and the load, the power factor at the transformer input generally will reflect the average PF of the load on the secondary. This conclusion works on the assumption that the low PF is caused by inductive and capacitive reactances in the loads. However, if the load current is rich in harmonics from rectifiers and switching regulators, some of the harmonic currents will flow no farther toward the power source than the transformer delta winding. The third harmonic and multiples of three will flow in the delta winding and will be significantly reduced in amplitude. By this means, the transformer will provide some improvement in the PF of the total load.

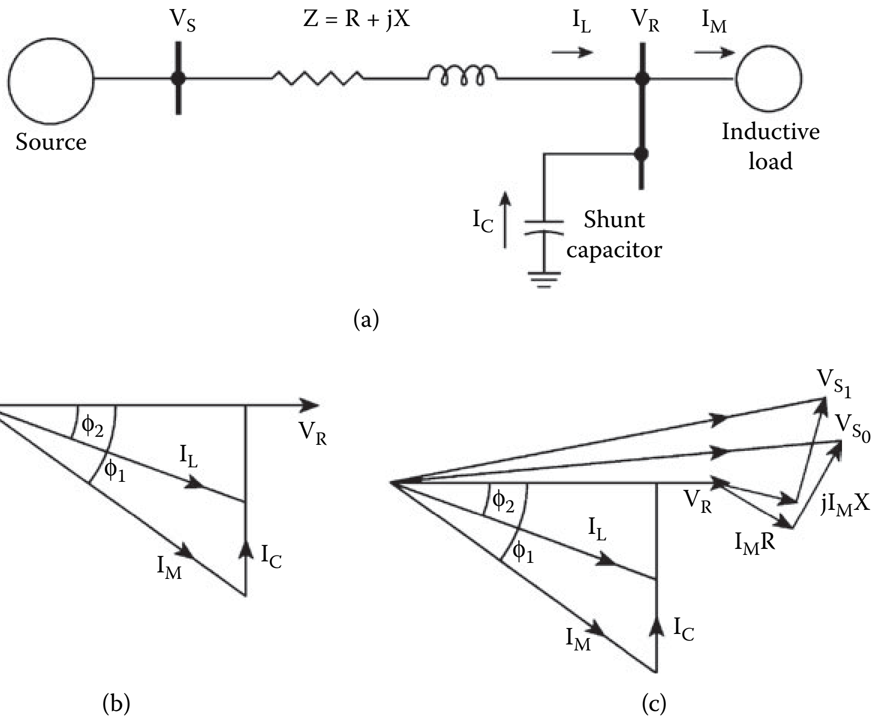


Figure 3.8 Shunt-capacitor compensation: (*a*) schematic diagram; (*b*) current phasor diagram; (*c*) voltage phasor diagram. (*From* [1]. *Used with permission.*)

An economic evaluation of the cost versus benefits, plus a review of any mandatory utility company limits that must be observed for PF correction, will determine how much power factor correction, if any, may be advisable at a given facility. Figure 3.9 shows a "before" and "after" comparison of a hypothetical facility. Correction to 85% will satisfy many requirements. No economic advantage is likely to result from correcting to 95% or greater. Overcorrecting a load by placing too many PF correction capacitors can reduce the power factor after reaching unity and cause uncontrollable overvoltages in low-kVA-capacity power sources.

PF correcting capacitors usually offer some benefits in absorbing line-voltage impulse-type noise spikes. However, if the capacitors are switched on and off, they will create significant impulses of their own. Switching can be accomplished with acceptably low disturbance using soft-start or preinsertion

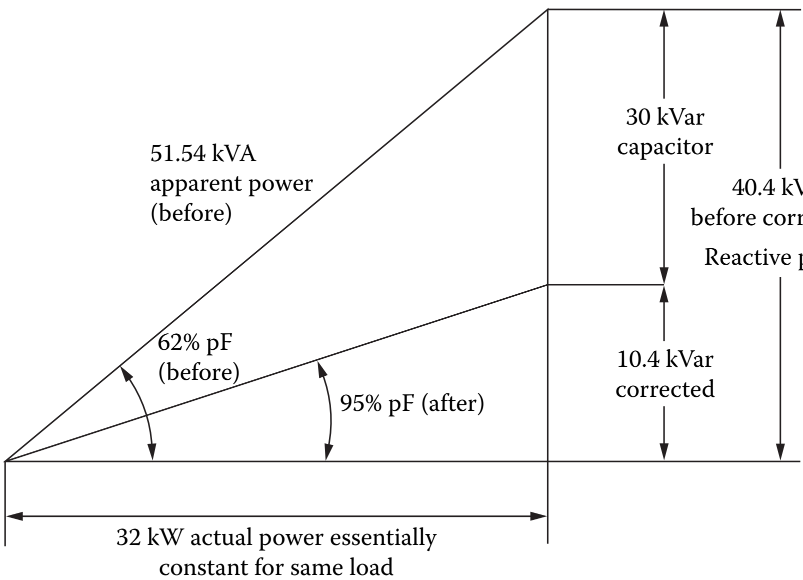


Figure 3.9 Illustration of the results of on-site power factor correction.

resistors. Such resistors are connected momentarily in series with the capacitors. After a brief delay (0.5 s or less), the resistors are short-circuited, connecting the capacitors directly across the line.

Installation of PF correction capacitors at a facility is a complicated process that requires a knowledgeable consultant and licensed electrician. The local utility company should be contacted before any effort is made to improve the PF of a facility.

3.3.2 Shunt Reactors

Shunt reactor compensation is typically required under conditions that are the opposite of those requiring shunt capacitor compensation [1]. Such a case is illustrated in Figure 3.10. Shunt reactors are usually installed to remedy utility company power-generation and transmission issues, including the following:

- Overvoltages that occur during low load periods at utility substations served by long lines as a result of the inherent capacitance of the line
- Leading power factors at generating plants resulting in lower transient and steady-state stability limits
- Open-circuit line charging kVA requirements in extra-high-voltage systems that exceed the available generation capabilities

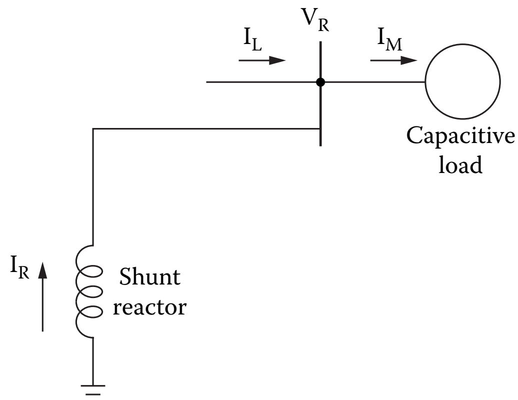


Figure 3.10 Shunt-reactor-compensated load. (*From* [1]. *Used with permission.*)

It should also be noted that coupling from nearby energized lines can cause severe resonant overvoltages across the shunt reactors of unenergized compensated lines.

3.3.3 Unwanted Resonance Conditions

At a specific frequency, the inductive reactance of an electrical distribution system will equal the capacitive reactance; this is the definition of resonance. Resonance takes on one of two forms, parallel or series, depending upon the circuit configurations. The application of PF correction capacitors at a facility must be carefully planned to avoid unwanted harmonic resonances in the ac distribution system [2].

When a system is in parallel resonance, the impedance of the transformer and capacitor is maximized. Harmonic currents at or near the resonant frequency can create high harmonic voltages across the high parallel impedance. When a system is in series resonance, the impedance of the transformer and capacitor is minimized. During series resonance, the only impedance to current flow is the pure resistance of the distribution circuit, which is normally quite low.

Nonlinear loads often behave as harmonic current generators, operating on the 60 Hz source voltage and producing harmonic-rich disturbances on the distribution system. By spreading the load current across the harmonic spectrum, nonlinear loads significantly increase the likelihood of resonances within a distribution system that includes PF correction capacitors. High harmonic voltages and currents can result, therefore, from nonlinear load operation that excites a resonant condition.

Harmonic-related problems include overheating of equipment, blown fuses, and equipment failure. Excessive harmonic voltages and current in capacitors results in increased losses in iron, insulation, and conductors, with a corresponding increase in temperature [3].

Simple equations can be used to determine whether the installation of capacitors on an electrical distribution system might lead to a resonant condition. The short-circuit kVA available from the utility must be determined first, and is given by

$$kVA_{sc} = \frac{\sqrt{3} \times V \times I}{1000} \tag{3.3}$$

where

kVA_{sc} = The available short-circuit kVA from the utility
V = System operating voltage
I = Available short-circuit current

Next, the building or facility distribution system short-circuit capacity must be calculated, as given by

$$kVA_{sys} = \frac{kVA_t \times kVA_{sc}}{kVA_t + (\mathbf{Z} \times kVA_{sc})} \tag{3.4}$$

where

kVA_{sys} = The short circuit capacity of the secondary electrical system
kVA_t = kVA rating of the substation transformer(s)
kVA_{sc} = Available short-circuit kVA from the utility
$\mathbf{Z}_t$ = Impedance of the substation transformer(s)

The resonant harmonic of the distribution system under analysis is given by

$$h_r = \sqrt{\frac{kVA_{sys} + kVA_{mc}}{kVAR_c}} \tag{3.5}$$

where

h_r = The resonant harmonic
kVA_{sys} = Available short-circuit kVA from the distribution system
kVA_{mc} = available short-circuit kVA from motor contribution
$kVAR_c$ = sum of capacitor kVAR ratings

A resonant harmonic on the order of 50 or greater does not usually represent a potential resonant condition; because the distribution-system inductive reactance increases proportionally with frequency, higher order harmonic currents are significantly attenuated. Additionally, harmonic analysis may reveal negligible harmonic current magnitudes at or near the resonant frequency. In either case, harmonic mitigation techniques may not be required to prevent resonance within the distribution system.

When Equation 3.5 indicates a relatively low resonant harmonic, and spectrum analyses indicate that the magnitude of harmonic currents are significant at or near the resonant frequency, the most likely solution will be to install harmonic filters. In fact, low total power factor (TPF) can be principally the result of harmonic currents generated by the load. In such instances, the TPF may be improved by installing filters or traps alone [4]. In most cases, a combination of harmonic filters and capacitors designed to operate at the fundamental frequency are required to improve the TPF to acceptable levels in systems in which harmonic currents are present.

Active harmonic filters are available for facility applications that sense the load parameters and inject currents onto the distribution system that cancel the harmonics generated by nonlinear loads. In lieu of active filters, strategic placement of static filters to trap harmonics near the resonant frequency and to attenuate higher order harmonics can effectively protect the entire electrical system from damaging harmonic current and voltage magnitudes. Capacitor banks can be specified as integral components of a harmonic filter, tuned at or near the resonant frequency. Harmonic filters may provide a single package that will mitigate distribution-system resonant frequency problems and simultaneously improve the total power factor [4, 5].

3.3.4 Series Capacitor Compensation

Series capacitors are employed to neutralize part of the inductive reactance of a power circuit [1]. (See Figure 3.11.) From the phasor diagram of Figure 3.12, it can be seen that the load voltage is higher with the capacitor inserted than without the capacitor. Such application of a series capacitor facilitates an increase in the circuit transmission capacity and enhanced stability of the distribution network. Other useful by-products include:

- Improved load distribution
- Control of overall transmission losses
- Control over reactive power throughout the system

It should be noted, however, that the reduction in the circuit inductive reactance gained through the use of series-capacitor-compensation also increases the short-circuit current levels over those for the noncompensated system.

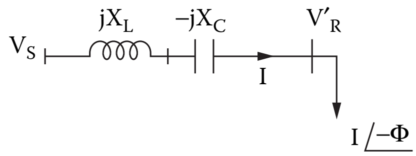


Figure 3.11 A distribution line with series-capacitor-compensation applied. (*From* [1]. *Used with permission.*)

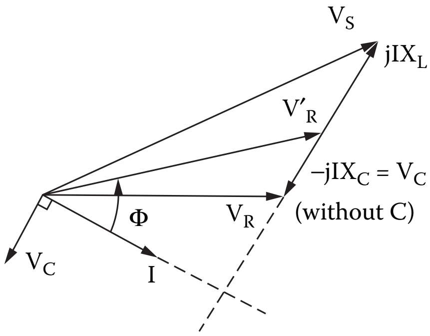


Figure 3.12 Phasor diagram corresponding to the circuit shown in Figure 3.11. (*From* [7]. *Used with permission.*)

Another consideration involves the interaction between a series-capacitor-compensated ac transmission system in electrical resonance and a turbine-generator mechanical system in torsional mechanical resonance. These resonances result in the phenomenon of *subsynchronous resonance* (SSR). In this mode, energy is exchanged between the electrical and mechanical systems at one or more natural frequencies of the combined system below the synchronous frequency of the system. The resulting mechanical oscillations can increase until mechanical failure occurs. A number of measures can be taken to reduce or eliminate SSR, as described in Reference 1.

3.3.5 Static Compensation Devices

Advances in thyristor technology for power-system applications have led to the development of the *static VAR compensator* (SVC) [1]. This class of devices contains standard shunt elements (reactors and capacitors) that are controlled by thyristors. Static VAR devices are used to address two common problems encountered in practical power systems:

- Load compensation, where there is a need to reduce or cancel the reactive power demand of large and fluctuating industrial loads. Because heavy industrial loads are normally concentrated in one plant and served from one network terminal, they can usually be handled by a local compensator connected to the same terminal.
- Balancing the real power drawn from the ac supply lines. This type of compensation is related to the voltage support of transmission lines at a given terminal in response to disturbances of both the load and the supply. This voltage support is achieved by rapid control of the SVC reactance and, thus, its reactive power output.

The main objectives of such VAR compensation schemes are:

- To increase the stability limit of the ac power system
- To decrease terminal voltage fluctuations during load changes
- To limit overvoltages resulting from large system disturbances

SVCs are essentially thyristor-controlled reactive power devices, usually designed around one of two basic configurations:

- *Thyristor-switched shunt capacitor* (TSC). As illustrated in Figure 3.13*a*, this configuration splits a capacitor bank into small steps and switches those steps on and off individually. This approach offers stepwise control, virtually no transients, and no harmonic generation. The average delay for executing a command from the regulator is one half-cycle.
- *Thyristor-switched shunt reactor* (TSR). Shown in Figure 3.13*b*, the fundamental frequency current component through the reactor is controlled by delaying the closing of the thyristor switch with respect to the natural zero crossing of the current. In this case, harmonic currents are generated from the phase-angle-controlled device.

In many applications, the arrangement of the SVC consists of a few large steps of thyristor-switched capacitors and one or two thyristor-controlled reactors, as shown in Figure 3.13*c*.

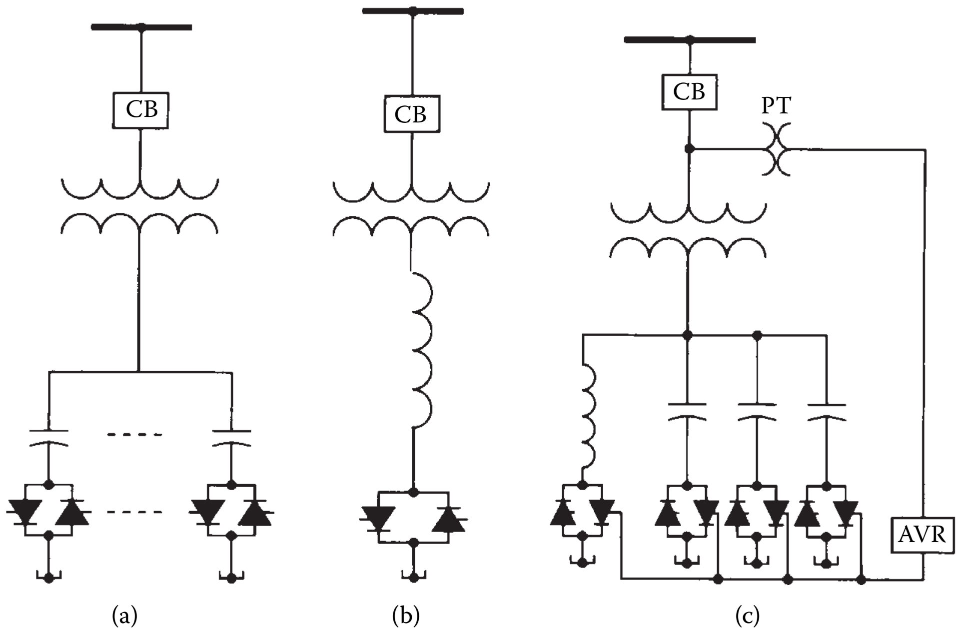


Figure 3.13 Basic static VAR compensator configurations: (*a*) thyristor-switched shunt capacitors (TSC); (*b*) thyristor-switched shunt reactors (TSRs); (*c*) combined TSC/TSR. (*From* [1]. *Used with permission.*)

3.4 References

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4

Power Transformers

4.1 Introduction

The transformer forms the basis of all ac power-distribution systems. In the most basic definition, a transformer is a device that magnetically links two or more circuits for time-varying voltage and current. Magnetic coupling has a number of intrinsic advantages, including:

- DC isolation between the circuits
- The ability to match the voltage and current capability of a source to a load
- The ability to change the magnitude of the voltage and current from one side of the transformer to the other
- The ability to change the phases of voltage and current from one side of the device to the other

4.2 Inductive Properties[1]

Inductance is, primarily, a geometrical property of a current-carrying element in an electrical circuit [1]. A circuit element with this property may be termed an *inductor*. The magnitude and, for that matter, the frequency dependence of inductance also depend on the material environment of that element. Similar remarks to these could — of course — be used to define capacitance; inductance and capacitance are invariably intimately related in electronic circuits. One reason is that both are (electrical) energy storage devices in time-varying electronic systems. Capacitance is, however, a measure of the capability of a (potential) circuit element to store charge and, thereby, electric field energy; inductance, by contrast, is a measure of a circuit element's ability to store magnetic field energy. Because a magnetic field is derived from current flow, inductance is always associated with current-carrying circuit elements. This dichotomy extends also to the matter of frequency dependence. At zero signal frequency, for example, an (ideal) capacitor has infinite impedance, whereas the inductor has zero impedance; at infinite frequency, the opposite is true.

The concept of inductance or, more correctly, *self-inductance* is, perhaps, best illustrated by the example of a current-carrying conducting coil of N circular turns (see Figure 4.1). When a current I flows through this circuit, as described, a magnetic field is generated inside and around the coil turns, in accordance with Ampere's law. Flux linkage Λ is defined by how much of the total magnetic flux ϕ threads all of the turns of the coil, multiplied by the total numbers of turns N. Thus, in simple algebraic terms:

$$\Lambda = N\phi = N \iint_A B \, dA \quad (\approx N \; B \; A) \tag{4.1}$$

where, because of incomplete linkage by the magnetic flux, in actuality A will typically be slightly less than the cross-sectional area of the coils. The inductance L of this coil is defined as the flux linkage per unit current and is defined as [2]

$$L = \frac{\Lambda}{I} = \frac{N\left(\iint_A B \, dA\right)}{I} \tag{4.2}$$

[1]This section was adapted from Parker, M. R., and W. E. Webb, "Magnetic Materials for Inductive Processes," in *The Electronics Handbook*, 2nd ed., J. C. Whitaker (Ed.), CRC Press, Boca Raton, FL, 2005. Used with permission.

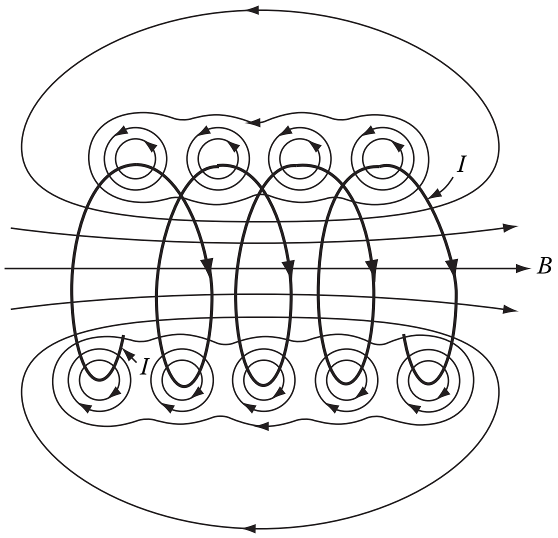

Figure 4.1 A magnetic field produced by a current through a coil. (*After* [2]. *From* [1]. *Used with permission.*)

The SI unit of inductance is the *henry* (H) if I is in amperes, Λ in webers, A in square meters, and B in teslas (webers/square meter). The inductance of some current-carrying elements of comparatively simple geometry is described in approximate form next.

4.2.1 Coils

The long solenoid is a longer, more tightly wound version of the simple coil shown in Figure 4.1 with a relatively large number of turns, as illustrated in Figure 4.2 [1]. The B-field inside a long solenoid is fairly uniform and given by

$$\frac{\mu_0 NI}{l} \tag{4.3}$$

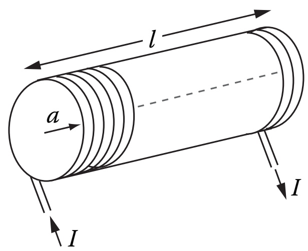

Figure 4.2 A long solenoid. (*From* [1]. *Used with permission.*)

where l is its length. The inductance is given by

$$L = \frac{\mu_0 N^2 A}{l} \tag{4.4}$$

where $\mu_0 = 4p \times 10^{-7}\ H/m$ is the *permeability* of free space.

Similarly, for a short solenoid of N turns, also of length l and of radius a, it can be shown that

$$B = \frac{\mu_0 NI}{(l^2 + 4a^2)^{1/2}} \tag{4.5}$$

Once again, from Equation 4.3 and Equation 4.5, it follows that

$$L = \frac{\mu_0 N^2 A}{\left(l^2 + 4a^2\right)^{1/2}} \tag{4.6}$$

Note that, in the limit of a becoming vanishingly small, the short solenoid takes on the appearance of a long solenoid and Equation 4.6 reduces to Equation 4.4.

In the limit of l approaching zero in Equation 4.6, we have a flat coil of N turns, radius a, whose inductance is approximately

$$L = \frac{\mu_0 N^2 a}{2} \tag{4.7}$$

where A (Equation 4.6) has been replaced by a. Note that the special case of a single loop is derived from Equation 4.7, simply by making $N = l$, leading to

$$L = \frac{\mu_0 a}{2} \tag{4.8}$$

4.2.2 The Toroid

Another simple classic geometry (Figure 4.3) is the toroid [1]. This doughnut-shaped winding is a close relative of the long solenoid. Indeed, it may be viewed as a long solenoid whose ends have been joined. Accordingly, the B-field inside the toroid may be given, approximately, by Equation 4.4, with the modification that the length l is replaced by $2r$, where r is the (mean) radius of the toroid. A crude approximation for the inductance of the toroid, when r is much greater than the radius of the individual windings, is, therefore,

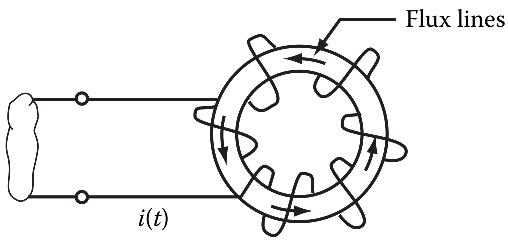

Figure 4.3 A toroid inductor. (After [3]. *From* [1]. *Used with permission.*)

$$L = \frac{\mu_0 N^2 A}{2r} \tag{4.9}$$

When the dimensions of the windings compare in size with the toroid radius, the simple expression of Equation 4.9 is inadequate. To illustrate the point, consider the rectangularly cross-sectioned toroid of Figure 4.4. It is easy to show analytically [4] that, for this geometry,

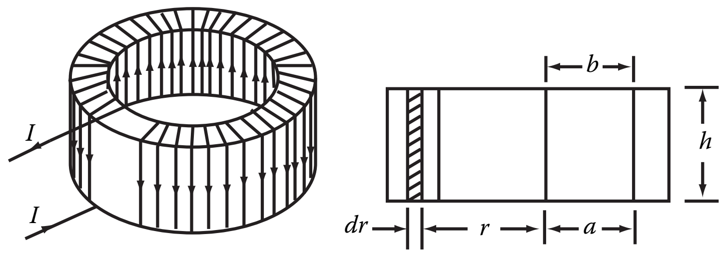

Figure 4.4 A closely wound toroidal coil. (*After* [4]. *From* [1]. *Used with permission.*)

$$L = \frac{\mu_0 N^2 h(\ln b/a}{2} \tag{4.10}$$

4.2.3 Circuit Description of Self-Inductance

It is a relatively simple matter to describe the voltage drop across a simple self-inductance such as the coil of Figure 4.5. For a steady-state current I, in the coils, the voltage drop is simply IR, as dictated by Ohm's law, where R is the coil resistance. On the other hand, if the current $i(t)$ is time varying, then it follows quite simply from a combination of Faraday's law of electromagnetic induction and equations for magnetic flux and flux density that the (time-varying) voltage drop v across a self-inductance is

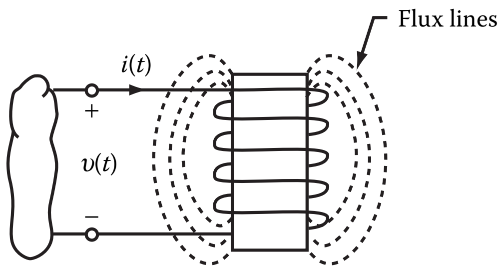

Figure 4.5 A circuit illustrating self-inductance (*After* [3]. *From* [1]. *Used with permission.*)

$$v = L\frac{di}{dt} + Ri \tag{4.11}$$

Given that magnetic field energy density is expressible [2] as

$$w_m = B \times H \tag{4.12}$$

it follows that for any of the simple inductive windings described, the total magnetic field energy (that is, the stored energy of any inductor) is

$$W_m = \frac{1}{2}Li^2 \tag{4.13}$$

Note that L may be defined from Equation 4.13, thus,

$$L = \left(\frac{2W_m}{i^2}\right)^{1/2} \tag{4.14}$$

4.2.4 Magnetic Materials

All of the preceding described current elements were characterized by air-filled windings [1]. In fact, the formulas of the preceding equations are essentially valid if the windings encompass any condensed matter other than a magnetic (i.e., ferromagnetic/ferrimagnetic, etc.) material. If, however, any of the described windings are constructed around a magnetic material of *permeability* μ, then in each of the formulas of Equation 4.4 through Equation 4.10, μ_0 is replaced by μ. Now, for magnetic materials μ is, typically, much greater than μ_0. The actual value of μ depends crucially on: (1) the current signal frequency, and (2) the chemical identity and temperature of the magnetic material comprising the inductive element as well as on the details of its microstructure.

In inductive devices, one will typically find *soft* magnetic materials employed as the core medium. Here, a soft magnetic material is one in which the *relative permeability* μ_r, defined as

$$\mu_r = \frac{\mu}{\mu_0} \tag{4.15}$$

is, numerically, >> 1. (See Table 4.1.) For the magnetic materials of Table 4.1 and the like, μ_r is: (1) a nonanalytical function of magnetic field intensity (see, for example Figure 4.6), and (2) a complex quantity of the form

$$\mu = \mu' + j\mu'' \tag{4.16}$$

where μ'' is, typically, significant only at high frequencies.

4.3 Basic Principles of the Transformer

In 1831, English physicist Michael Faraday demonstrated the phenomenon of electromagnetic induction. The concept is best understood in terms of lines of force, a convention Faraday introduced to describe the direction and strength of a magnetic field. The lines of force for the field generated by a current in a loop of wire are shown in Figure 4.7. When a second, independent loop of wire is immersed in a changing magnetic field, a voltage will be induced in the loop. The voltage will be proportional to the time rate of change of the number of force lines enclosed by the loop. If the loop has two turns, such induction occurs in each turn, and twice the voltage results. If the loop has three turns, three times the voltage results, and so on. The concurrent phenomena of *mutual induction* between the coils and *self-induction* in each coil form the basis of transformer action.

For a power transformer to do its job effectively, the coils must be coupled tightly and must have high self-induction. That is, almost all the lines of force enclosed by the primary also must be enclosed by the secondary, and the number of force lines produced by a given rate of change of current must be high. Both conditions can be met by wrapping the primary and secondary coils around an iron core, as Faraday did in his early experiments. Iron increases the number of

Table 4.1 Properties of Magnetic Materials and Magnetic Alloys (*After* [2].

Material (Composition)	Initial Relative Permeability, μ_i/μ_0	Maximum Relative Permeability, μ_{max}/μ_0	Coercive Force, H_e, A/m (Oe)	Residual Field, B_r, Wb/m^2 (G)	Saturation Field B_s, Wb/m^2 (G)	Electrical Resistivity, $\rho \times 10^{-8}$ Ω m	Uses
Commercial iron (0.2 imp.)	250	9,000	≈ 80 (1)	0.77 (7,700)	2.15 (21,500)	10	Relays
Purified iron (0.05 imp.)	10,000	200,000	4.00 (0.05)	—	2.15 (21,500)	10	
Silicon-iron (4 Si)	1,500	7,000	20.00 (0.25)	0.5 (5,000)	1.95 (19,500)	60	Transformers
Silicon-iron (3 Si)	7,500	55,000	8.00 (0.1)	0.95 (9,500)	2.00 (20,000)	50	Transformers
Silicon-iron (3 Si)	—	116,000	4.80 (0.06)	1.22 (12,200)	2.00 (20,100)	50	Transformers
Mu metal (5 Cu, 2 Cr, 77 Ni)	20,000	100,000	4.00 (0.05)	0.23 (2,300)	0.65 (6,500)	62	Transformers
78 Permalloy (78.5 Ni)	8,000	100,000	4.00 (0.05)	0.60 (6,000)	1.08 (10,800)	16	Sensitive relays
Supermalloy (79 Ni, 5 Mo)	100,000	1,000,000	0.16 (0.002)	0.50 (5,000)	0.79 (7,900)	60	Transformers
Permendur (50 Cs)	800	5,000	160.00 (2)	1.40 (14,000)	2.45 (24,500)	7	Electromagnets
Mn-Zn ferrite	1,500	2,500	16 .00(0.2)	—	0.34 (3,400)	20×10^6	Core material coils
Ni-Zn ferrite	2,500	5,000	8.00 (0.1)	—	0.32 (3,200)	10^{11}	Core material coils

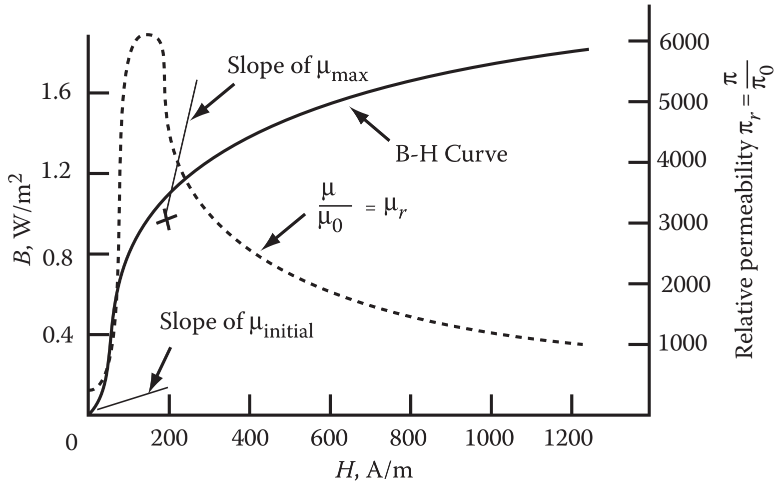

Figure 4.6 Magnetization curve of commercial iron. Permeability is given by the ratio *B*/*H*. (*After* [2]. *From* [1]. *Used with permission*.)

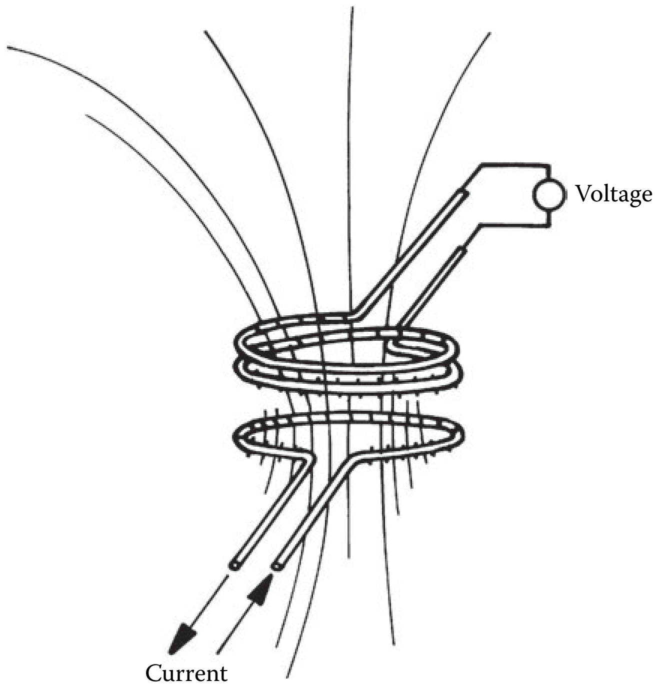

Figure 4.7 The basic principles of electromagnetic induction.

lines of force generated in the transformer by a factor of about 10,000. This property of iron is referred to as *permeability*. The iron core also contains the lines so that the primary and secondary coils can be separated spatially and still closely coupled magnetically.

With the principles of the transformer firmly established, American industrialist George Westinghouse and his associates made several key refinements that made practical transformers possible. The iron core was constructed of thin sheets of iron cut in the shape of the letter E. Coils of insulated copper wire were wound and placed over the center element of the core. Straight pieces of iron were laid across the ends of the arms to complete the magnetic circuit. This construction still is common today. Figure 4.8 shows a common E-type transformer. Note how the low-voltage and high-voltage windings are stacked on top of each other. An alternative configuration, in which the low-voltage and high-voltage windings are located on separate arms of a core box, is shown in Figure 4.9.

In an ideal transformer, all lines of force pass through all the turns in both coils. Because a changing magnetic field produces the same voltage in each turn of the coil, the total voltage induced in a coil is

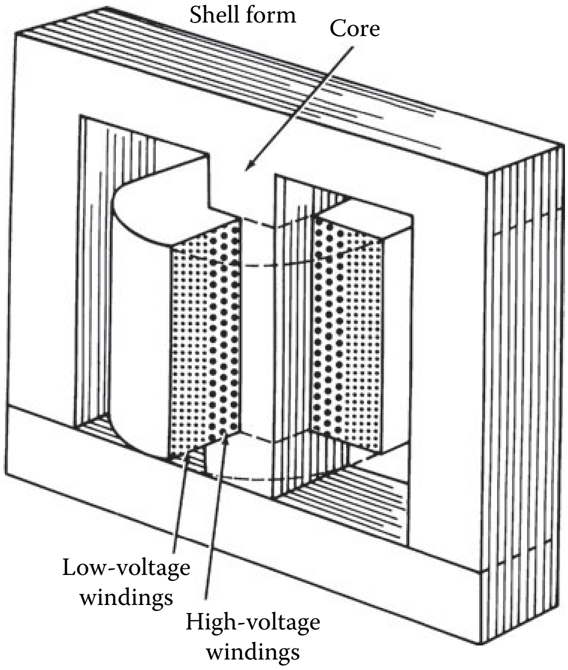

Figure 4.8 Physical construction of an E-shaped core transformer. The low- and high-voltage windings are stacked as shown.

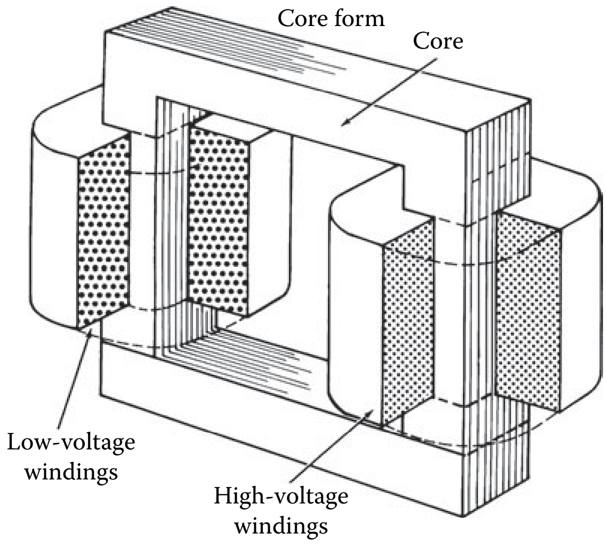

Figure 4.9 Transformer construction using a box core with physical separation between the low- and high-voltage windings.

proportional to the total number of turns. If no energy is lost in the transformer, the power available in the secondary is equal to the power fed into the primary. In other words, the product of current and voltage in the primary is equal to the product of current and voltage in the secondary. Thus, the two currents are inversely proportional to the two voltages and therefore, inversely proportional to the turns ratio between the coils. This expression of power and current in a transformer is true only for an ideal transformer. Practical limitations prevent the perfect transformer from being constructed.

The key properties of importance in transformer core design include:

- Permeability
- Saturation
- Resistivity
- Hysteresis loss

Permeability, as discussed previously, refers to the number of lines of force a material produces in response to a given magnetizing influence. Saturation identifies the point at which the ability of the core to carry a magnetic force reaches a limiting plateau. These two properties define the power-handling capability of the core element. Electrical resistivity is desirable in the core because it minimizes energy losses resulting from *eddy currents*. In contrast, hysteresis undermines the efficiency of a transformer. Because of the interactions among groups of magnetized atoms, losses are incurred as the frequency of the changing magnetic field is increased. Throughout the history of transformer development, the goal of the design engineer has been to increase permeability, saturation, and resistivity, while decreasing hysteresis losses. A variety of core materials, including silicon iron in various forms, have been used.

Transformer efficiency is defined as

$$E = \frac{P_{out}}{P_{in}} \times 100 \tag{4.17}$$

where:

E = Efficiency in percent
P_{out} = Transformer power output in watts
P_{in} = Transformer power input in watts

Losses in a transformer are the result of copper losses in the windings and core losses. The copper losses vary with the square of the current; the core losses vary with the input voltage magnitude and frequency. Because neither of these quantities depend on the power being consumed by the load, power transformers are rated by the voltamperes (VA) that flow through them.

The regulation specification of a power transformer is a measure of the transformer's ability to maintain a constant output voltage under varying loads. The primary voltage is held constant at the value required to produce the rated voltage on the secondary at full load:

$$R = \frac{V_{s0} - V_{sfl}}{V_{sfl}} \times 100 \tag{4.18}$$

where

R = Regulation in percent
V_{s0} = Secondary voltage under no load
V_{sfl} = Secondary voltage under full load

Also bearing on transformer performance are electrical insulation and the cooling system used. These two elements are intimately related because the amount of heat that the core and conductors generate determines the longevity of the insulation; the insulation itself — whether solid, liquid, or gas — serves to carry off some portion of the heat produced. Temperatures inside a commercial transformer may reach 100°C, the boiling point of water. Under such conditions, deterioration of insulating materials can limit the useful lifetime of the device. Although oils are inexpensive and effective as insulators and coolants, some oils are flammable, making them unacceptable for units placed inside buildings. Chlorinated hydrocarbon liquids (PCBs) were used extensively from the 1930s to the late 1970s, but evidence of long-term toxic effects prompted a ban on their use. Some transformers rely on air- or nitrogen-gas-based insulators. Such devices can be installed indoors. The breakdown strength of gas sometimes is enhanced through the addition of small quantities of fluorocarbons. Other dry transformers depend on cast-resin insulation made of polymerizing liquids that harden into high-integrity solids. Progress in heat removal is largely responsible for reducing the overall size of the transformer assembly.

Modern high-power commercial transformers may operate at voltages of 750 kV or more and can handle more than 1000 kVA. The expected lifetime of a commercial power transformer ranges from 24 to 40 years. A typical three-phase oil-cooled transformer is shown in Figure 4.10.

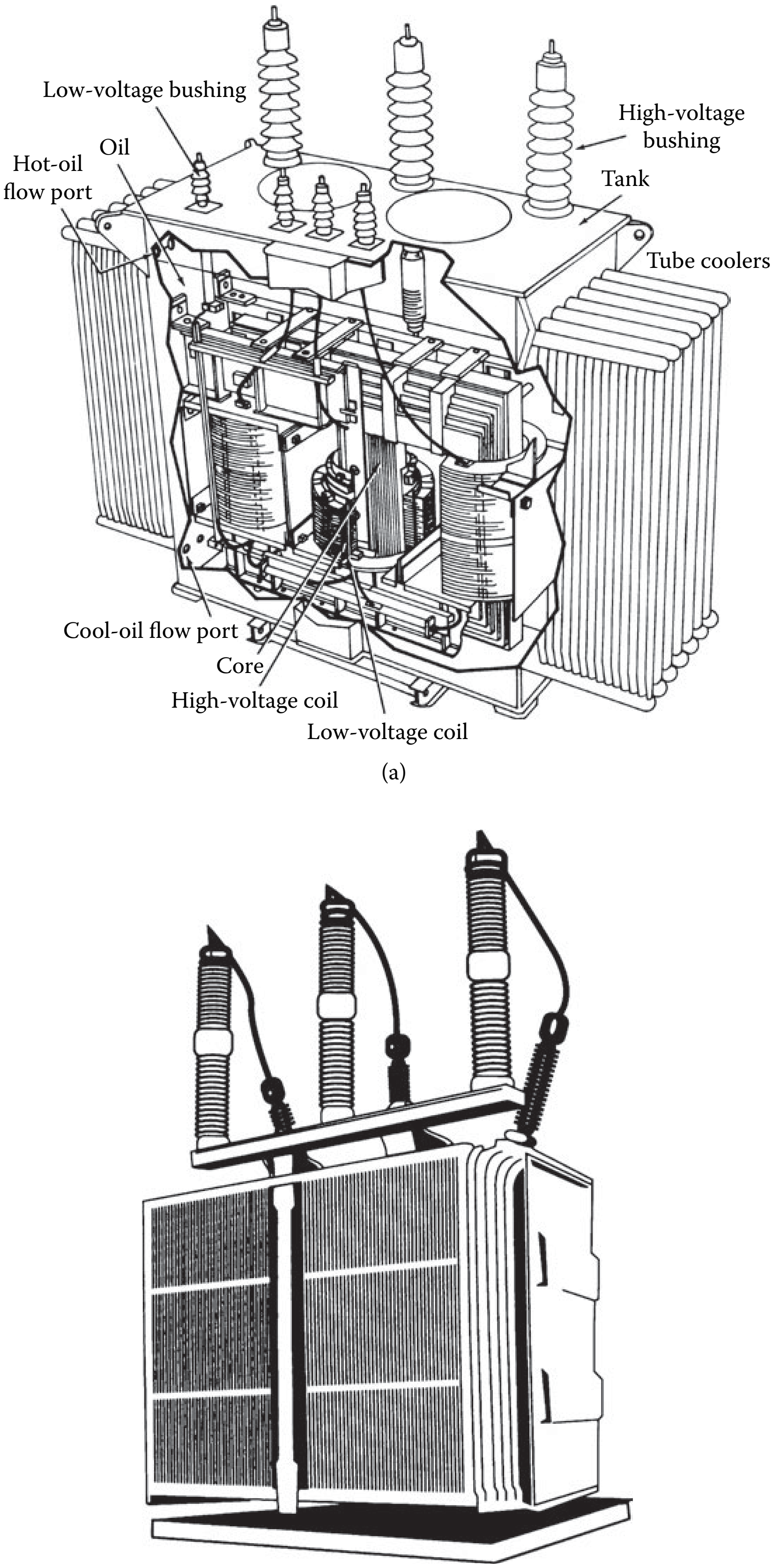

Figure 4.10 Construction of an oil-filled three-phase power transformer used for commercial power distribution: (*a*) cutaway view; (*b*) exterior view. (*Drawing* b *from* [5]. *Used with permission*.)

4.3.1 Counter-Electromotive Force

All transformers, generators, and motors exhibit the property of inductance. This property is the result of a *counter-emf* that is produced when a magnetic field is developed around a coil of wire. Inductance presents an opposition to the change in current flow in a circuit. This opposition is evident in the diagram shown in Figure 4.11. In a purely inductive circuit (containing no resistance), the voltage will lead the current by 90°. However, because all practical circuits have resistance, the offset will vary from one circuit to the next. Figure 4.12 illustrates a circuit in which voltage leads current by 30°. The angular separation between voltage and current is referred to as the *phase angle*. The phase angle increases as the inductance of the circuit increases. Any inductive circuit exhibits the property of inductance, including electrical power-transmission and distribution lines. The henry is the unit of measurement for inductance. A circuit has a 1 H inductance if a current changing at a rate of 1 A/s produces an induced counter-emf of 1 V.

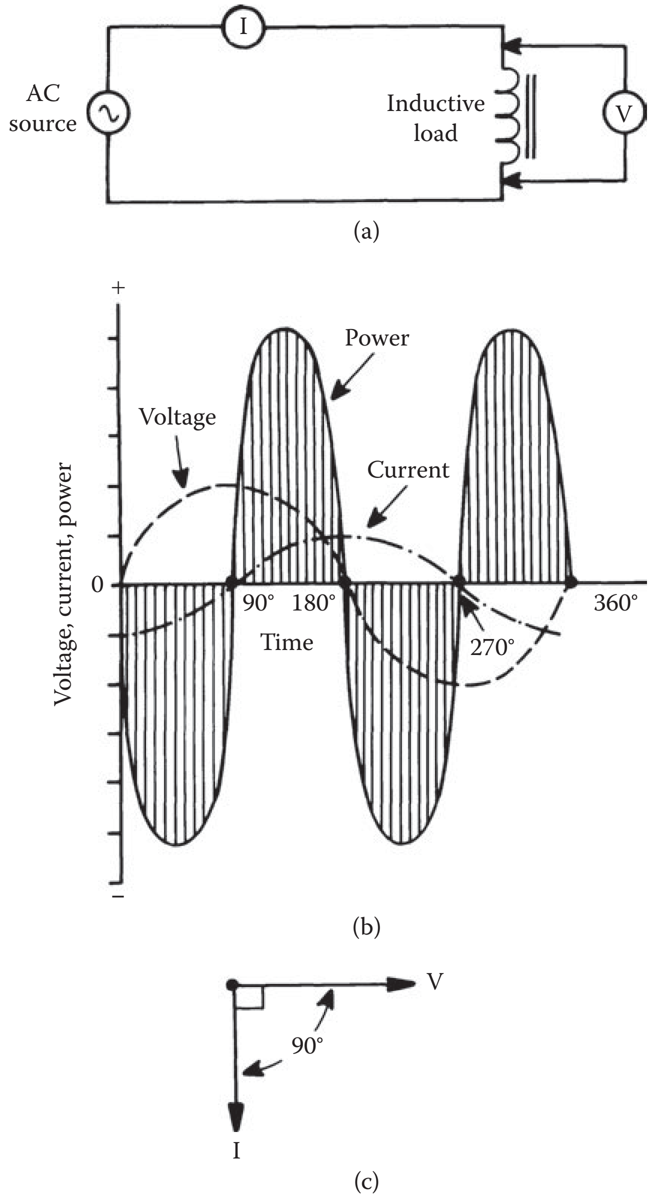

Figure 4.11 Purely inductive circuit: (*a*) circuit diagram; (*b*) representative waveforms; (*c*) vector representation.

In an inductive circuit with ac applied, an opposition to current flow is created by the inductance. This opposition is known as *inductive reactance* (X_l). The inductive reactance of a given ac circuit is determined by the inductance of the circuit and the rate of current change. Inductive reactance can be expressed as

$$X_l = 2\,\pi\,f\,L \qquad (4.19)$$

where

X_l = inductive reactance in ohms
2π = 6.28, the expression for one sine wave of alternating current (0° to 360°)
f = frequency of the ac source in hertz
L = inductance of the circuit in henrys

4.3.2 Full Load Percent Impedance

The *full load percent impedance* (FLPI) of a transformer is an important parameter in power-supply system design. FLPI is determined by the construction of the core and physical spacing between the primary and secondary windings. Typical FLPI values range from 1 to 5%. FLPI is a measure of the ability of a transformer to maintain its rated voltage with a varying load. The lower the FLPI, the better the regulation. FLPI also determines the maximum fault current that the transformer can deliver. For example, if a 5% FLPI transformer supplying 5 A nominal at the secondary is short-circuited, the device can,

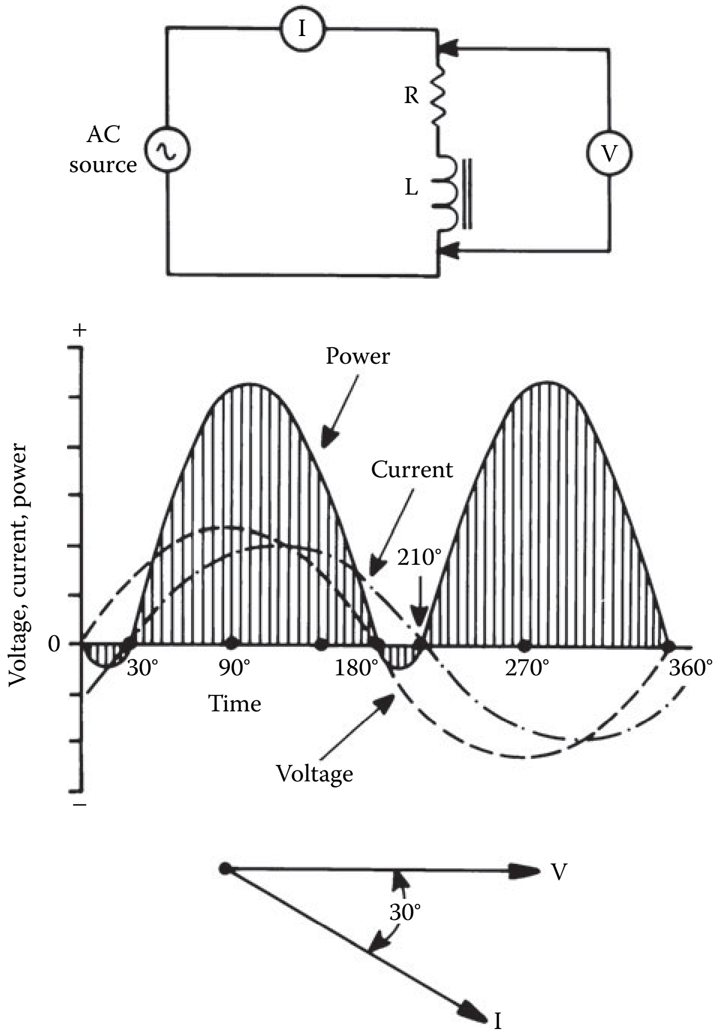

Figure 4.12 Resistive-inductive circuit: (*a*) circuit diagram; (*b*) representative waveforms; (*c*) vector representations.

theoretically, supply l00 A at full voltage. A similar transformer with a 10% FLPI can supply only 50 A when short-circuited. Typical short-circuit currents for a selection of small three-phase transformers are listed in Table 4.2.

4.3.3 Design Considerations

As touched upon previously, permeability μ describes the ease with which magnetic flux can be produced in a given material. More flux will be produced in a material with a high permeability than in one with a low permeability, given the same amount of current and the same number of turns in the coil. The ratio of a material's permeability to the permeability of free space, called *relative permeability*, is often used [6]. The actual permeability, which has units of webers per ampere-turn-meter, is found by multiplying the permeability of free space by the relative permeability.

The overall ability of a core to carry flux also depends on its size and shape, and its cross-sectional area. This is described by *permeance*. The basic relationship of permeance to permeability in a core is defined by

$$P = \frac{\mu A}{l} = \frac{l}{R} \quad \text{or} \quad R = \frac{l}{\mu A} \tag{4.20}$$

Table 4.2 Full Load Percent Impedance Short-Circuit Currents for a Selection of Three-Phase Transformers

DC Amps (kVa/kV)	Full Load Percent Impedance	Symmetrical Short-Circuit Current
1 A	1	57.7
1 A	2	28.8
1 A	3	19.3
1 A	4	14.4
1 A	5	11.5
2 A	1	115.5
2 A	2	57.7
2 A	3	38.5
2 A	4	28.8
2 A	5	23.1
3 A	1	173.2
3 A	2	86.6
3 A	3	57.7
3 A	4	43.3
3 A	5	34.6
4 A	1	230.9
4 A	2	115.5
4 A	3	77.0
4 A	4	57.7
4 A	5	46.2
5 A	1	288.6
5 A	2	144.3
5 A	3	96.2
5 A	4	72.2
5 A	5	57.7

where

P = Permeance
μ = Permeability of the material
A = The cross-sectional area of the core
l = The mean length of the flux path in the core

This equation assumes uniform flux distribution in the core and constant permeability inside the core. It does not take into account the variations in the length of the flux path from the inside of the core to the outside. The reciprocal of permeance is *reluctance*.

Figure 4.13 shows the magnetization curve for a typical ferromagnetic material. Note that the curve follows two different paths, depending on whether the magnetizing force H is increasing or decreasing. This is called a *hysteresis curve*. It is caused by the fact that the magnetic particles in the core need to be rotated and realigned each time the polarity of the magnetizing force changes. This is why the magnetic force must be reversed to reduce the flux density to zero.

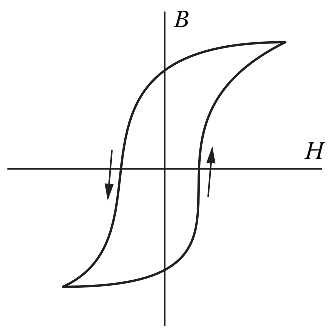

Figure 4.13 A typical magnetization curve. (*From* [6]. *Used with permission.*)

As the magnetizing force H increases, the flux density increases up to a point, and then the curve flattens out. In this flattened region, only a small increase in the flux density can be achieved, as illustrated in the figure. The core is said to be *saturated*. The flattening of the curve indicates that the permeability has decreased from the value it had when there was only a small amount of flux passing through the core.

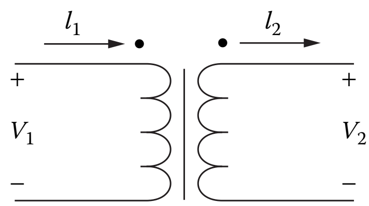

Figure 4.14 Dotted schematic symbol for a transformer. (*From* [6]. *Used with permission.*)

To eliminate ambiguity in the voltage and current polarity at the input and output of the transformer symbol, the *dot convention* is commonly used. In circuit diagrams, a small dot is placed near one end of each coil, as shown in Figure 4.14. The dot indicates a rise in voltage from the unmarked to the marked terminal on each coil. Under this convention, current into the dot on the primary side is labeled as having positive polarity, and current out of the dotted terminal on the other side is assigned positive polarity. This means that the power flow must be into the transformer on one side and out of the transformer on the other side.

4.3.4 The Ideal Transformer

Although no transformer is ideal in its characteristics, transformers approach their ideal characteristics in the operating range for which they were designed. The ideal transformer has no coil resistance and no core losses, so that it has no power loss [6]. It also has no leakage inductance, because the permeability of the core is infinite, and the core material is able to carry an infinite amount of flux without saturating. Therefore, the mutual inductance is also infinite. The capacitance in an ideal transformer is negligible. The equations for an ideal transformer are given as

$$v_1 i_1 = v_2 i_2 \tag{4.21}$$

$$\frac{v_1}{v_2} = \frac{N_1}{N_2} \tag{4.22}$$

$$\frac{i_1}{i_2} = \frac{N_2}{N_1} \tag{4.23}$$

$$\frac{Z_1}{Z_2} = \left(\frac{N_1}{N_2}\right)^2 \tag{4.24}$$

where

v_1 = Voltage in the primary
v_2 = Voltage in the secondary
i_1 = Current in the primary
i_2 = Current in the secondary
N_1 = Turns in the primary
N_2 = Turns in the secondary
Z_1 = Impedance of the primary
Z_2 = Impedance of the secondary

Equation 4.8 describes the effect of the transformer on an impedance on the secondary side (multiplied by the square of the turns ratio). The magnitude of the impedance as seen on the secondary side is referred to as the *reflected impedance*.

Equivalent circuits are often used to model the performance of transformers with greater accuracy. Although equivalent circuits are not exact replicas of real transformers, they are close enough to realize accurate results for most situations. The complete transformer equivalent circuit is shown in Figure 4.15.

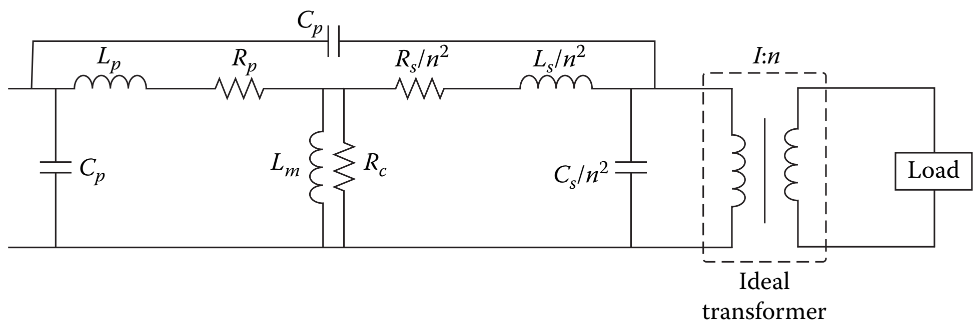

Figure 4.15 Transformer equivalent circuit. (*From* [6]. *Used with permission.*)

The leakage inductance of both coils has been modeled by an inductor in series with the load, because the current in the coils also produces the leakage flux. These inductances are labeled L_p and L_s, respectively. Notice that the leakage inductance for the secondary side has been divided by the turns ratio n^2 because it was reflected to the primary side. Resistors R_p and R_s are placed in series with the load to represent the resistance of the conductors used to wind the coils. Again, the secondary resistance is divided by the square of the turns ratio because it was reflected.

The mutual inductance is represented by shunt inductor L_m, because the magnetizing current is not coupled to the load. Resistor R_c is also placed in shunt to represent the core loss resulting from hysteresis and eddy currents in the core. The stray capacitances between turns of the coils are represented by a capacitor connected across each pair of terminals. This capacitance is larger for coils with more turns. Although the capacitance is actually distributed, it is lumped for the equivalent circuit, in order to simplify the analysis. The capacitance from one coil to the other is represented by another capacitor placed in parallel with the leakage inductance and resistance.

The transfer function of the complete equivalent circuit is quite complex. For this reason, the equivalent circuit is often broken up into several equivalent circuits, each of which is valid only for a certain set of operating conditions. In the low-frequency range, the transformer acts like a highpass filter. (See Figure 4.16.) Above the *corner frequency*, the output voltage is nearly equal to the input voltage. Below the corner frequency, the output voltage is substantially smaller than the input voltage because of the presence of shunt inductor L_m. The distributed capacitances and leakage inductances can be largely neglected.

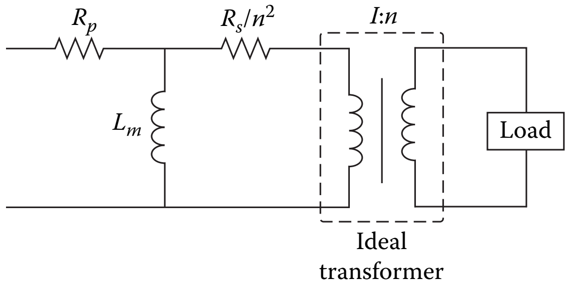

Figure 4.16 Transformer equivalent circuit for low-frequencies. (*From* [6]. *Used with permission*.)

4.3.5 Application Considerations

Transformers are the most common pieces of equipment found in utility substations and distribution systems. Different types of transformers are used for varied purposes, from voltage level changes to phase angle regulation [7]. Because the primary circuits of distribution systems are designed for high voltages (in order to increase their load-carrying capability), the voltage must be stepped down at the consumer service entrance.

Transformers can be classified as *distribution transformers* and *power transformers*. The former type normally steps down voltages from primary voltage levels, such as 2,400, 4,160, or 13,800 V, to 120 or 240 V. These devices are almost always located outdoors where they are hung from crossarms, mounted on poles directly, or placed on platforms or in underground vaults. Power transformers are larger in size than distribution transformers and usually have auxiliary means for cooling. These transformers are typically installed at distribution substations for stepping down voltages from the subtransmission levels of 34.5 and 69 kV to primary distribution levels of up to 13.8 kV.

Single-phase distribution transformers typically have one high-voltage primary winding and two low-voltage secondary windings, which are rated at a nominal 120 V. The secondary coils may be connected in parallel to supply a two-wire 120 V circuit, shown in Figure 4.17*a*, or in series to supply a three-wire 120/240 V single circuit, shown in Figure 4.17*b*. As seen in the figures, one leg of the 120 V two-wire system and the middle leg of the 120/240 V three-wire system are grounded to limit the voltage to ground on the secondary side. In general, the 120/240 V three-wire connection is preferred because it has twice the load capacity of the 120 V system with only a 1.5 times increase in conductor size. Each 120 V winding has one half the total kilovoltampere rating of the transformer. The loads on the secondary side of the transformers are kept as balanced as possible, such that maximum transformer capacity can be utilized, and the neutral current kept to a minimum.

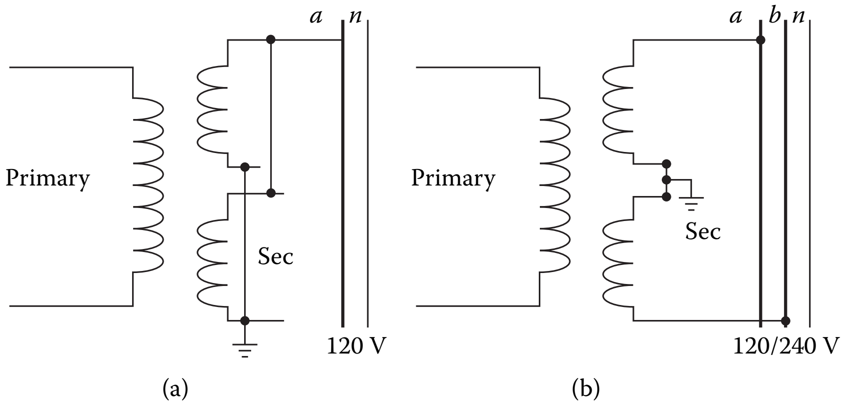

Figure 4.17 Connections for a single-phase distribution transformer: (*a*) parallel connection, (*b*) series connection. (*From* [7]. *Used with permission.*)

A three-phase transformer bank can be easily created by using three single-phase transformers. The two sides of these three transformers can be either connected in a *wye* or a *delta* configuration, thus allowing four possible types of connections. These are

- **Wye-wye.** With the wye-wye (Y-Y) connection, the secondary side is in phase with the primary circuit, and the ratio of primary to secondary voltage is the same as the ratio of turns in each of the phases. A possible connection is shown in Figure 4.18. Power distribution circuits supplied from a wye-wye bank often create series disturbances in communication circuits (e.g., telephone interference) in their immediate vicinity. One of the advantages of this connection is that when a system is changed from a delta to a four-wire wye to increase system capacity, existing transformers can be used.
- **Wye-delta.** In the Y-Δ connection, there is a 30° phase angle shift between the primary and secondary sides. The phase angle difference can be made either lagging or leading, depending on the external connections of the transformer bank. The case with the primary side lagging is shown in Figure 4.19, and the case with the primary side leading is shown in Figure 4.20. The transformation ratio is $\sqrt{3}$ times the ratio of turns in each of the phases.

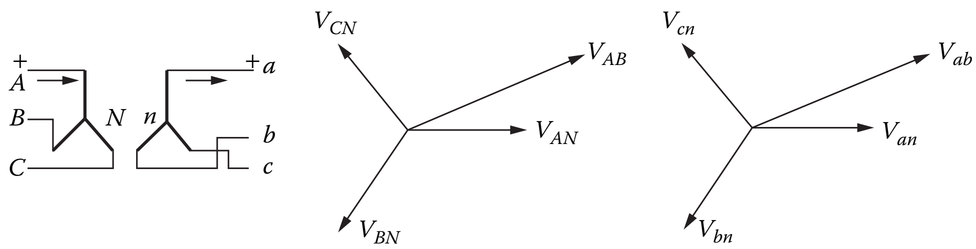

Figure 4.18 Y-Y transformer with 0° phase shift between the primary and the secondary sides. (*From* [7]. *Used with permission.)*

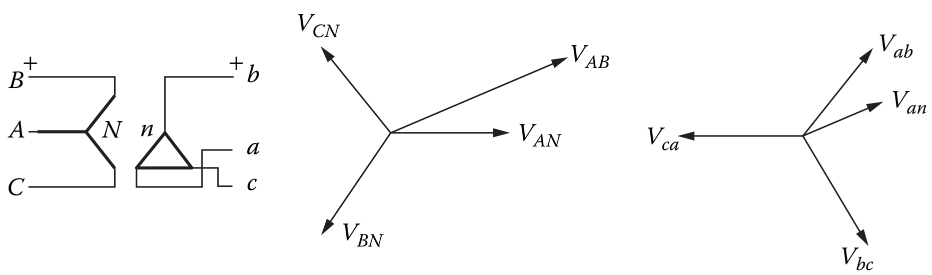

Figure 4.19 Y-Δ transformer with the primary side lagging the secondary side by 30°. (*From* [7]. *Used with permission.*)

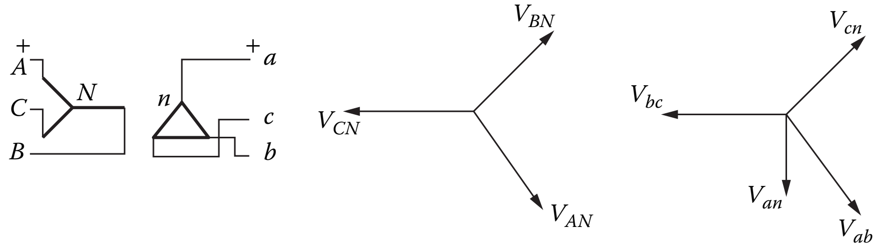

Figure 4.20 Y-Δ transformer with the primary side leading the secondary side by 30°. (*From* [7]. *Used with permission.*)

- **Delta-wye.** With the Δ-Y connection, the neutral of the secondary wye can be grounded and single-phase loads connected across the phase and the neutral conductor. Three-phase loads are connected across the phases. The phasor relationship between the primary and the secondary sides is shown in Figure 4.21. The transformation ratio is $1/\sqrt{3}$ times the ratio of turns in each of the phases.
- **Delta-delta.** The Δ-Δ connection does not cause a phase shift between the primary and the secondary sides. The phasor relationship of this transformer is shown in Figure 4.22. The transformation ratio is equal to the ratio of the turns in each of the phases. There is no problem from third-harmonic overvoltage or telephone interference because such disturbances get trapped in the delta and do not pass into the lines.

Although these four configurations are the most common ones used, other arrangements are possible, including:

- **Open-delta.** An advantage of the Δ-Δ connection is that if one of the single-phase transformers becomes damaged or is removed for maintenance, the remaining two can be operated in a so-called *open-delta* connection. Because the currents in each of the two remaining transformers are the same as the line current, each transformer carries $\sqrt{3}$ times the current it was carrying in the closed-delta connection. The open-delta bank continues to deliver three-phase currents and voltages in their correct phase relationship. To keep the transformers from being overloaded, however, it is necessary to reduce the line currents by approximately $1/\sqrt{3}$.

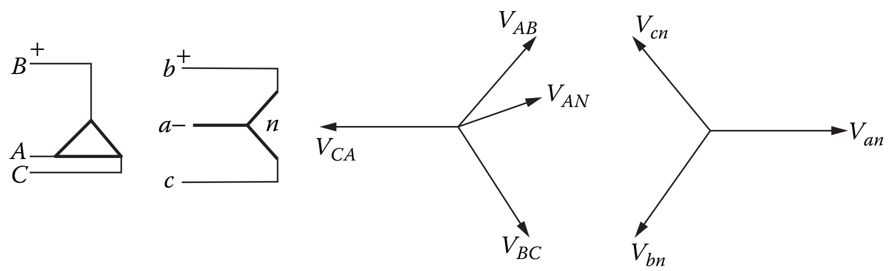

Figure 4.21 Δ-Y transformer with the primary side leading the secondary side by 30°. (*From* [7]. *Used with permission.*)

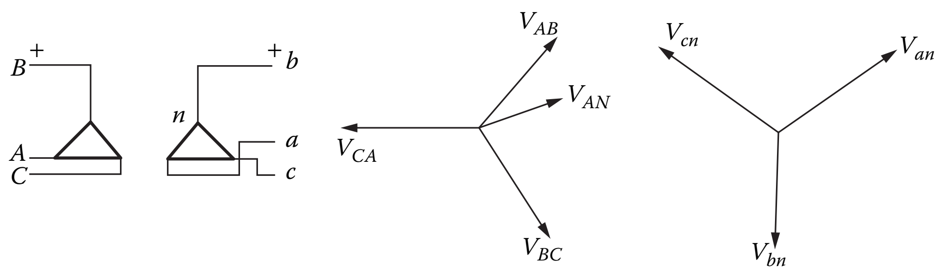

Figure 4.22 Δ-Δ transformer with 0° phase shift between the primary and the secondary sides. (*From* [7]. *Used with permission.*)

- **Scott or T-connection.** The Scott or T-connection is used when a two-phase (or a transformed three-phase) supply is needed from a three-phase system. In general, the T-connection is used for deriving a three-phase transformation, and the Scott connection is mainly used for obtaining a two-phase output. The two connections are similar in basic design. Either connection requires two specially wound single-phase transformers. The main transformer has a 50% tap on the primary winding, whereas the other transformer, called the *teaser transformer*, has an 86.6% tap. The main transformer is connected between two primary lines, whereas the teaser transformer is connected from the center tap of the main transformer to the third primary line. The secondary sides of the transformers provide two-phase service. A T-connection is shown in Figure 4.23.

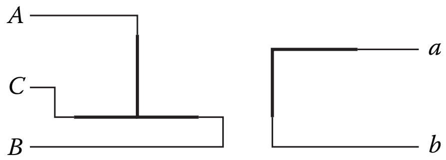

Figure 4.23 The T-connection for a three-phase to two-phase transformation. (*From* [7]. *Used with permission.*)

4.4 Transformer Failure Modes

The failure of a power transformer is almost always a catastrophic event that will cause the system to fail. The two primary enemies of power transformers are transient overvoltages and heat. Power input to a transformer is not all delivered to the secondary load. Some is expended as copper losses in the primary and secondary windings. These I^2R losses are practically independent of voltage; the controlling factor is current flow. To keep the losses as small as possible, the coils of a power transformer are wound with wire of the largest cross section that space will permit. A medium-power, three-phase power transformer is shown in Figure 4.24.

A practical transformer also will experience core-related losses, also known as *iron losses*. Repeated magnetizing and demagnetizing of the core (which occurs naturally in an ac waveform) results in power loss because of the repeated realignment of the magnetic domains. This factor (hysteresis loss) is proportional to frequency and flux density. Silicon steel alloy is used for the magnetic circuit to minimize hysteresis loss. The changing magnetic flux also induces circulating currents (eddy currents) in the core material. Eddy current loss is proportional to the square of the frequency and the square of the flux density. To minimize eddy currents, the core is constructed of laminations or layers of steel that are clamped or bonded together to form a single magnetic mass.

Figure 4.24 A medium-power, three-phase transformer.

4.4.1 Thermal Considerations

Temperature rise inside a transformer is the result of power losses in the windings and the core. The insulation within and between the windings tends to blanket these heat sources and prevents efficient dissipation of the waste energy, as illustrated in Figure 4.25. Each successive layer of windings (shown as *A*, *B*, and *C* in the figure) acts to prevent heat transfer from the hot core to the local environment (air).

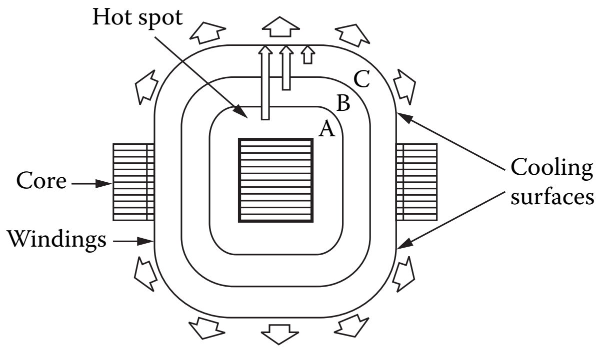

Figure 4.25 The dynamic forces of heat generation in a power transformer.

The hot spot shown in the figure can be dangerously high even though the outside transformer case and winding are relatively cool to the touch. Temperature rise is the primary limiting factor in determining the power-handling capability of a transformer. To ensure reliable operation, a large margin of safety must be designed into a transformer. Design criteria include winding wire size, insulation material, and core size.

4.4.1.1 Life Expectancy and Temperature

The nameplate kVA rating of a transformer represents the kVA that will result in the rated average winding temperature rise when the unit is operated at 100% of rated kVA under normal service conditions [8]. When operating under these conditions, the result should be a normal life expectancy for the transformer.

A general rule of thumb says that a 30-year life can be expected for a transformer with a 220°C insulating system that has a winding hot-spot temperature allowance of 30°C. Operating such a transformer at rated kVA on a continuous basis with a 30°C, 24-hr average ambient (40°C maximum ambient) should equate to a normal useful life.

It should be recognized that the life expectancy of transformers operating at varying temperatures is not accurately known. Fluctuating load conditions and changes in ambient temperatures make it difficult, if not impossible, to arrive at such definitive information. However, if a transformer is operated under normal conditions, it could easily last longer. A 40-year life span is not unusual, and some transformers have exceeded that.

4.4.2 Voltage Considerations

Transformer failures resulting from transient overvoltages typically occur between layers of windings within a transformer. (See Figure 4.26.) At the end of each layer, where the wire rises from one layer to the next, zero potential voltage exists. However, as the windings move toward the opposite end of the coil in a typical layer-wound device, a potential difference of up to twice the voltage across one complete layer exists. The greatest potential difference, therefore, is found at the far opposite end of the layers.

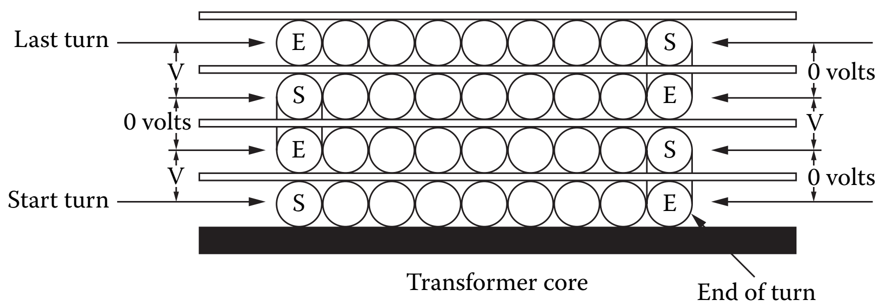

Figure 4.26 Voltage distribution between the layers of a typical layer-wound power transformer.

This voltage distribution applies to continuous 60 Hz signals. When the transformer is first switched on or when a transient overvoltage is impressed upon the device, the voltage distribution from one hot layer to the next can increase dramatically, raising the possibility of arc-over. This effect is caused by the inductive nature of the transformer windings and the inherent distributed capacitance of the coil. Insulation breakdown can result from one or more of the following:

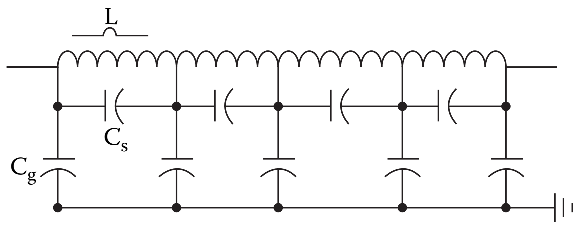

Figure 4.27 Capacitive distribution along the windings of a power transformer.

- Puncture through the insulating material of the device
- Tracking across the surface of the windings
- Flashing through the air

Any of these modes can result in catastrophic failure. Figure 4.27 illustrates the mechanisms involved. A transformer winding can be modeled as a series of inductances and shunt capacitances. The interturn and turn-to-ground capacitances are shown by C_s and C_g, respectively. During normal operation, the applied voltage is distributed evenly across the full winding. However, if a steep front wave is impressed upon the device, the voltage distribution radically changes. For the voltage wave to start distributing itself along the winding, the line-to-ground capacitance (C_g) must be charged. This charging is dependent upon the transformer winding-to-ground capacitance and the impedance of the supply line.

4.4.3 Mechanical Considerations

Current flow through the windings of a transformer applies stress to the coils. The individual turns in any one coil tend to be crushed together when current flows through them. There also may be large repulsion forces between the primary and secondary windings. These mechanical forces are proportional to the square of the instantaneous current; they are, therefore, vibratory in nature under normal operating conditions. These forces, if not controlled, can lead to failure of the transformer through insulation breakdown. Vibration over a sufficient period of time can wear the insulation off adjacent conductors and create a short circuit. To prevent this failure mode, power transformers routinely are coated or dipped into an insulating varnish to solidify the windings and the core into one element.

4.4.3.1 Dry-Type and Liquid-Filled Transformers

The advantages and disadvantages of dry-type transformers vs. liquid-filled units depend upon the application [9]. Dry-type transformers can usually be located closer to the load, resulting in cost savings because of shorter cable runs and lower electrical losses. A liquid-filled transformer, on the other hand, may require special construction features for the room in which it will be placed because of fire-safety considerations. This may dictate a location some distance from the load. In addition, periodic testing must be conducted on the fluid to determine its dielectric strength, water content, dissolved gases, and other parameters.

In some applications, there is no option to the use of liquid-filled transformers; dry-types are limited in size and voltage handling capability. Liquid-filled types are available in almost limitless kVA and voltage ratings. Also, if requirements call for a transformer to be located outdoors, it may be less expensive to purchase a liquid-filled unit. With oil as the liquid, the cost would be lower than for a dry-type of equivalent rating; with low-firepoint fluids, the cost would probably be comparable to a dry-type.

For liquid-filled transformers, the main cooling/insulating mediums used today are mineral oil, high-molecular-weight hydrocarbon, and silicone fluid. If a leak occurs in the transformer tank, fire safety becomes an important issue. Because of hazards associated with tank rupture and the possible ignition of the dielectric, a thorough analysis covering fire safety and the possible effects on the environment should be carried out well in advance of device installation.

Some materials are covered under the Federal Resource Conservation and Recovery Act and the Clean Water Act, including requirements for

- Special handling
- Spill reporting
- Disposal procedures
- Record-keeping

These considerations can have an effect on installation costs, long-term operating expenses, and maintenance procedures.

4.4.3.2 Insulation Materials

Liquid-filled transformers use an insulation system of kraft or aramid paper, pressboard or aramid spacers, and a fluid that serves as both an insulating and cooling medium for the transformer [9]. Paper is commonly used for insulation between layers of winding material. It typically has an diamond-patterned adhesive backing that, when cured, solidly contains the winding. Spacers serve as a form (which can be rectangular or cylindrical in shape) for the windings as well as a spacer between layers of the windings. The spacing is necessary to allow the insulating fluid to flow through and cool the windings and the core. Spacers are also used to insulate the windings from the core as well as to support the leads on their path to the bushings.

Any moisture that is present in the finished core and winding assembly is purged by vacuum and oven drying processes. After removal from the oven and while still hot, all connections are tightened and the entire assembly is immersed into its liquid-filled tank. This ensures that moisture will not again penetrate into the windings and also allows the insulation to absorb the maximum amount of dielectric fluid.

The particular type of insulation used is rarely specified by the customer for other than large utility substation transformers or for unusual applications. More often, it is the transformer manufacturer's or rebuilder's choice based upon the operating conditions the transformer must meet.

4.4.3.3 Insulating Liquids

Dielectric liquids of various types are used as an insulating medium as well as a means of cooling liquid-filled transformers [9]. Common insulating liquids include the following:

- **Mineral oil.** A mineral oil-filled transformer is generally the smallest, lightest, and most economical transformer available. Mineral oil has excellent properties for use in transformers, but it has the inherent weakness of being flammable. Its use, therefore, is restricted to outdoor installations or when the transformer is installed within a vault if used indoors.
- **Silicone.** A wide variety of synthetic polymer chemicals are referred to by the generic term *silicone*. Silicone transformer liquids are actually known chemically as *polydimethylsiloxane* (PDMS). PDMS is a water-clear, odorless, chemically stable, nontoxic liquid.
- **High-molecular-weight hydrocarbon (HMWH).** HMWH is another high-firepoint dielectric that is widely used as a transformer liquid. It has similar values for dielectric strength and dielectric constant, power factor, and thermal conductivity as mineral oil.

Fire properties of dielectric fluids are typically classified by the following characteristics:

- *Flash point*: The temperature at which vapors from a liquid surface will ignite in the presence of a flame.
- *Fire point*: The temperature at the surface of a liquid that will sustain a fire.
- *Flame spread*: A series of consecutive ignitions.
- *Ease of ignition*: How readily the liquid will generate and maintain a flammable fuel/vapor mixture at the surface.
- *Heat release rate*: The product of vaporization rate and the heat of combustion of the fluid. The higher this rate in a large-scale fire, the higher the degree of fire hazard.

Selection of the dielectric liquid depends on the transformer application. Normally, the choice is mineral oil if the device is to be located outdoors. The National Electrical Code (NEC) does, however, specify certain limitations regarding the use of oil-filled transformers in particular outdoor locations. The selection of less-flammable liquids (PDMS and HMWH) often depends upon personal preference, the liquid used in other transformers on the site, or the transformer manufacturer's recommendation.

4.4.3.4 Cooling

In cooling a liquid-filled transformer, the insulating fluid flows in the transformer through ducts and around the coil ends within a tank that contains the core and coils [9]. Removal of the heat from the fluid takes place in external tubes. These radiators consist of headers extending from the bottom and top of the transformer tank and rows of tubes connected between the two headers. When operating within its *self-cooled* (OA) rating, natural convection caused by temperature differences within the tank carries the oil up through the windings, down through the cooling tubes, and back into the tank. The transformer fluid, acting as a heat-transfer medium, picks up the heat from the core and coils and dissipates it to the air via the tubes.

Auxiliary cooling fans can be provided if the transformer is to be operated above its self-cooled ratings. This is advisable when the transformer is to operate under occasional heavy overloads or high ambient temperatures, or to accommodate new loads beyond its rating. Liquid-filled transformers, because of their double heat-transfer requirement (core/coil-to-liquid and liquid-to-air), have a lower forced air (FA) rating than dry-types. In liquid-filled types, the forced air rating of transformers up to 2500 kVA is raised to 115% of its self-cooled kVA rating, and those of larger units to 125% of their self-cooled VA rating.

Cooling fans can be controlled manually or automatically. Fans can be cycled on automatically based on the top oil temperature, winding temperature, or ambient temperature. Alarm contacts and remote indication are also available options.

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5 Capacitors

5.1 Introduction

A capacitor consists, basically, of two conductors separated by a dielectric. The operation of a capacitor in a circuit is dependent upon its ability to charge and discharge. When a capacitor charges, an excess of electrons is accumulated on one plate, and a deficiency of electrons is created on the other plate. Capacitance is determined by the size of the conductive material (the plates) and their separation (determined by the type and thickness of the dielectric material). Capacitance is directly proportional to plate size and inversely proportional to the distance between the plates. The unit of capacitance is the *farad* (F). A capacitance of 1 F results when a potential of 1 V causes an electric charge of 1 coulomb to accumulate on a capacitor.

5.2 Basic Principles

The value of a parallel-plate capacitor can be found from

$$C = \frac{x\varepsilon\left[\left(N-1\right)A\right]}{d} \times 10^{-13} \tag{5.1}$$

where

C = Capacitance (F)
ε = Dielectric constant of the insulation
d = Spacing between the plates
N = Number of plates
A = Area of the plates
x = 0.0885 when A and d are in centimeters

The work necessary to transport a unit charge from one plate to another is

$$e = k\ g \tag{5.2}$$

where

e = Volts expressing energy per unit charge
k = Proportionality factor between the work necessary to carry a unit charge between the two plates and the charge already transported
g = Coulombs of charge already transported

The latter quantity (k) is equal to $1/C$, where C is the capacitance in F.
The value of a capacitor can now be calculated from

$$C = \frac{q}{e} \tag{5.3}$$

where q = charge (C) and e is found from Equation 5.2.

The energy stored in a capacitor is

$$W = \frac{CV^2}{2} \tag{5.4}$$

where

W = Energy (J)
C = Capacitance (F)
V = Applied voltage (V)

If a direct current is applied to a capacitor, the device will charge to the value of the applied voltage. After the capacitor is fully charged, it will block the flow of direct current. However, if an ac voltage is applied, the changing value of current will cause the device to alternately charge and discharge. In a purely capacitive circuit, the situation shown in Figure 5.1 will exist. The greatest amount of current will flow when the voltage changes most rapidly; that point occurs at the 0 and 180° positions in the sine wave where the polarity reverses. At these positions, maximum current is developed in the circuit, as shown. It is evident by studying the waveform that, in a purely capacitive circuit, voltage will lag current by 90°. Because all practical circuits contain some resistance, a lag of 0 to 90° may be experienced in practice. Figure 5.2 illustrates a case in which voltage lags current by 30°.

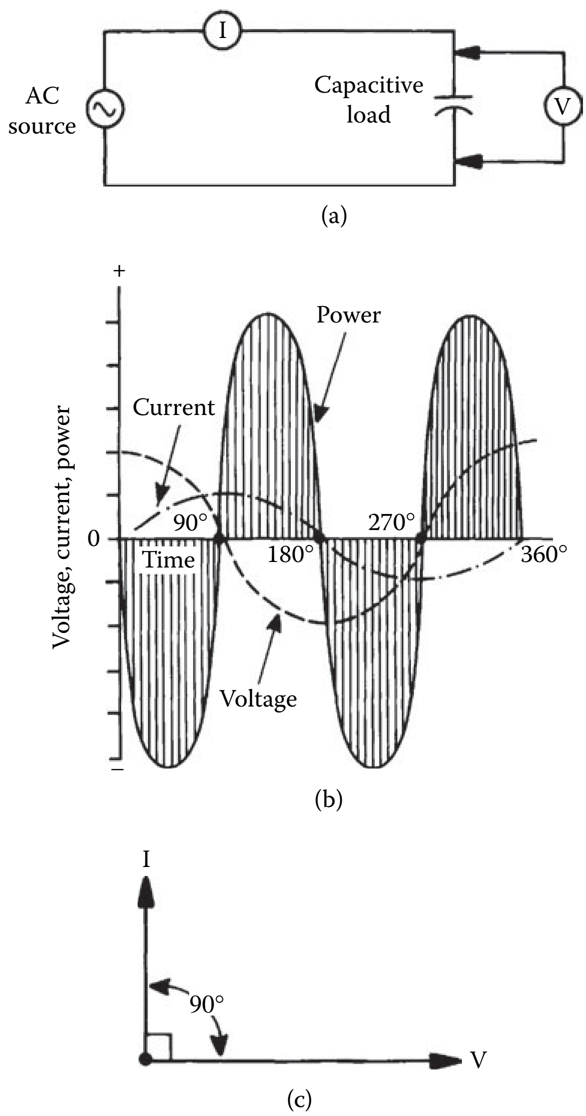

Figure 5.1 A purely capacitive circuit: (*a*) circuit diagram; (*b*) representative waveforms; (*c*) vector representation.

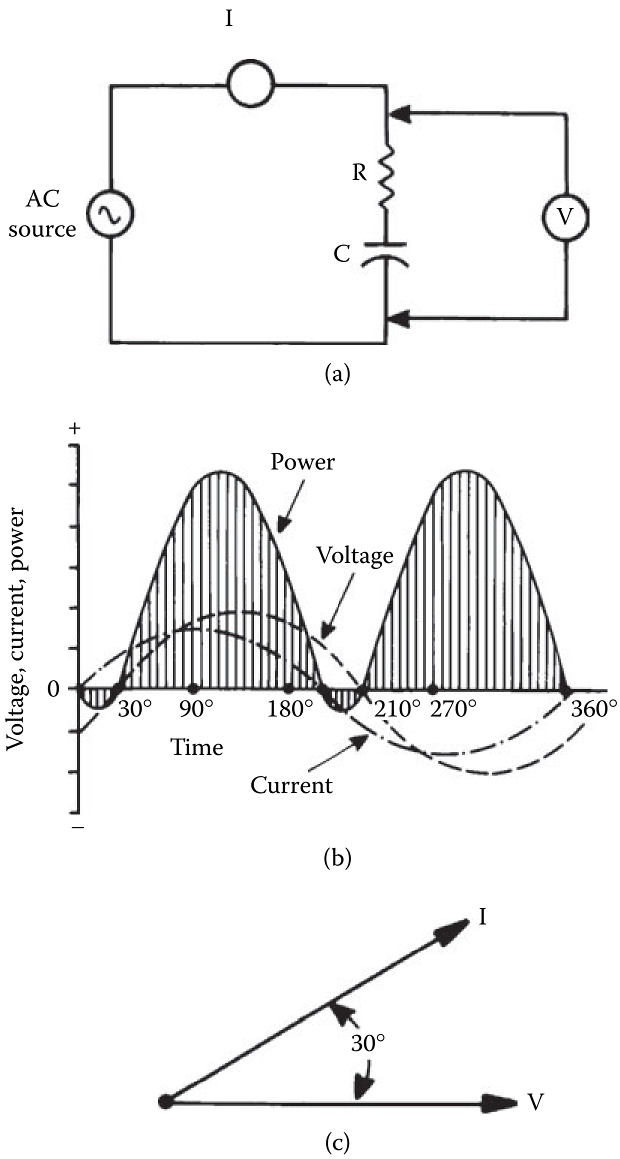

Figure 5.2 A resistive-capacitive circuit: (*a*) circuit diagram; (*b*) representative waveforms; (*c*) vector representation.

Because of the electrostatic field developed around a capacitor, an opposition to the flow of alternating current exists. This opposition is known as *capacitive reactance*, defined as

$$X_c = \frac{1}{2\pi fC} \tag{5.5}$$

where

X_c = Capacitive reactance (Ω)
$2\pi R$ = The mathematical expression of one sine wave
f = Frequency (Hz)
C = Capacitance (F)

The dielectric used for a given capacitor varies, depending upon the application. Common dielectrics include air, gas, mica, glass, and ceramic. Each has a different *dielectric constant,* temperature range, and thickness.

The dielectric constant of a material determines the electrostatic energy that may be stored in that material per unit volume for a given voltage. The value of the dielectric constant expresses the ratio of a capacitor whose dielectric is a vacuum to one using a given dielectric material. The dielectric constant of

Table 5.1 Comparison of Capacitor Dielectric Constants (*After* [1].)

Dielectric	K (Dielectric Constant)
Air or vacuum	1.0
Paper	2.0 – 6.0
Plastic	2.1 – 6.0
Mineral oil	2.2 – 2.3
Silicone oil	2.7 – 2.8
Quartz	3.8 – 4.4
Glass	4.8 – 8.0
Porcelain	5.1 – 5.9
Mica	5.4 – 8.7
Aluminum oxide	8.4
Tantalum pentoxide	26.0
Ceramic	12.0 – 400,000.0

air is 1, the reference unit employed for characterizing this parameter. As the dielectric constant is increased or decreased, the capacitance will increase or decrease, respectively. Table 5.1 lists the dielectric constants of various common materials.

The dielectric constant of most materials is affected by both temperature and frequency, except for quartz, Styrofoam, and Teflon, whose dielectric constants remain essentially constant.

In addition to capacitance, a practical capacitor has inductance and resistance components, as shown in Figure 5.3. The stray components are identified as follows:

- R_s = Series resistance of wire leads, contact terminations, and electrodes
- R_p = Shunt resistance resulting from the resistivity of the dielectric and case material, and dielectric losses
- L = Stray inductance resulting from the leads and the electrodes

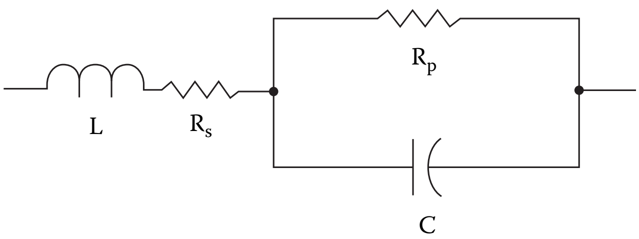

Figure 5.3 The equivalent circuit of a capacitor.

The *equivalent series resistance* (ESR) of a capacitor is the ac resistance of the device, reflecting both the series resistance (R_s) and the parallel resistance (R_p) at a given frequency. This parameter permits the loss resulting from the foregoing elements to be expressed as a loss in a single resistor in the equivalent circuit.

The *power factor* (PF) of a capacitor defines the electrical losses in the device operating under an ac voltage. In an ideal device, the current will lead the applied voltage by 90°. A practical capacitor, because of its dielectric, electrode, and contact termination losses, exhibits a phase angle of less than 90°. The power factor of a capacitor is defined as the ratio of the effective series resistance to the impedance of the capacitor. PF usually is expressed as a percentage.

The *quality factor* (Q) of a capacitor is the ratio of the capacitor reactance to the resistance of the device at a specified frequency. The Q is determined by the equations

$$Q = \frac{1}{2\pi f C R} \tag{5.6}$$

$$Q = \frac{1}{PF} \tag{5.7}$$

where

Q = Quality factor
f = Frequency (Hz)
C = Value of capacitance (F)
R = Internal resistance (Ω)
PF = Power factor

Other important specifications for capacitors include:

- *Dielectric absorption* (DA): The reluctance of the dielectric to give up stored electrons when the capacitor is discharged. This is often called *memory* because if a capacitor is discharged through a resistance and the resistance is removed, the electrons that remain in the dielectric will reconvene on the electrode, causing a voltage to appear across the capacitor. DA is usually measured by charging the capacitor for 5 min, discharging it for 5 s, then having an open circuit for 1 min, after which the recovery voltage is read. The percentage of DA is defined as the ratio of recovery voltage to charging voltage times 100.
- *Dissipation factor* (DF): The ratio of the effective series resistance to capacitive reactance. DF normally is expressed as a percentage.
- *Leakage current:* The current flowing through the capacitor when a dc voltage is applied.
- *Insulation resistance:* The ratio of the applied voltage to the leakage current. Insulation resistance is normally expressed in megohms.
- *Ripple current/voltage:* The rms value of the maximum allowable alternating current or voltage (superimposed on any dc level) at a specific frequency at which the capacitor may be operated continuously at a specified temperature.
- *Surge voltage:* The maximum operating voltage of the capacitor at any temperature.

5.2.1 Series and Parallel Connections

The formulas for series and parallel connection of capacitors can be obtained from the general consideration of series and parallel connection of impedances [2]. For series connection

$$\frac{1}{sC} = \frac{1}{sC_1} + \frac{1}{sC_2} + \ldots + \frac{1}{sC_n} \tag{5.8}$$

where $C_1, C_2, \ldots, C_n$ are the capacitances of the capacitors connected in series. Then, the equivalent capacitance C can be found as

$$C = \left(\frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_n}\right)^{-1} \tag{5.9}$$

and is always less than the value of the smallest capacitance. This result can be used when the conditions for using the impedance concept are valid, that is, the capacitors are discharged.

The series connection of two capacitors has the equivalent capacitance

$$C = \frac{C_1 C_2}{C_1 + C_2} \tag{5.10}$$

In a similar way one can obtain the equivalent capacitance of parallel connection as

$$C = C_1 + C_2 + \ldots + C_n \tag{5.11}$$

and is always larger than the largest capacitance.

Furthermore, the following two results are useful (for initially discharged capacitors):

- The voltage applied to two capacitors connected in series is divided between these two capacitors inversely proportionally to their capacitance (thus, the larger part of the voltage is on the smaller capacitance).

- The current applied to two capacitors connected in parallel is divided between these two capacitors proportionally to their capacitance (thus, the larger part of the current goes through the larger capacitance).

5.2.2 Practical Capacitors

Practical capacitors can be generally divided capacitors in four broad classes [2]:

- The first class includes low-loss capacitors with good capacitance stability. These are (in accordance with the dielectric) mica, glass, some ceramic, and low-loss plastic film (polypropylene, polystyrene) capacitors.
- The second class are capacitors of medium loss and medium stability designed to operate over a wide range of dc and ac voltages. These are paper (oil and wax impregnated), plastic film, and some ceramic capacitors. The dc applications include coupling, decoupling, bypass, smoothing and power separating filters, and energy storage. The ac applications include motor start, lightning, interference suppression, and power-line applications (switching and measurement equipment).
- The third class are aluminum and tantalum electrolytic capacitors providing high capacitance in a small size. For the same rated voltage tantalum capacitors have as much as three times larger capacitance per volume unit as aluminum, they are more reliable and have longer service life. The electrolytics are designed for dc and polarized voltage applications. Less-expensive aluminum capacitors are used in radio and television equipment; more expensive tantalum capacitors are destined for military and harsh environmental applications.
- The fourth class are fixed value capacitors (mica, glass, oil, gas, and vacuum) designed for high-voltage (up to 35 kV peak), high-current (up to 200 A) transmitter and power control applications.

The typical construction of common discrete capacitors is illustrated in Figure 5.4. Table 5.2 lists the characteristics of common capacitor types.

5.3 Capacitor Failure Modes

Experience has shown that capacitor failures are second only to semiconductors and vacuum tubes in components prone to malfunction in electronic equipment. Capacitors for ac applications range from high-voltage oil-filled devices, such as the one shown in Figure 5.5, to low voltage, high capacitance devices of the type typically found in power supplies (both linear and switching). Of all the various types of capacitors used today, it is estimated that electrolytics present the greatest potential for problems to equipment users.

5.3.1 Electrolytic Capacitors

Electrolytic capacitors are popular because they offer a large amount of capacitance in a small physical size. They are widely used as filters in low-voltage power supplies and as coupling devices in audio and RF stages. An aluminum electrolytic capacitor consists of two aluminum foil plates separated by a porous strip of paper (or other material) soaked with a conductive electrolyte solution. Construction of a typical device is illustrated in Figure 5.6. The separating material between the capacitor plates does not form the dielectric but, instead, serves as a spacer to prevent the plates from mechanically short-circuiting. The dielectric consists of a thin layer of aluminum oxide that is electrochemically formed on the positive foil plate. The electrolyte conducts the charge applied to the capacitor from the negative plate, through the paper spacer, and into direct contact with the dielectric. This sandwich arrangement of foil-spacer-foil is then rolled up and encapsulated.

Problems with electrolytic capacitors fall into two basic categories: mechanical failure and failure of electrolyte.

Table 5.2 Parameters and Characteristics of Discrete Capacitors (*After* [2].)

Capacitor Type	Range	Rated Voltage, V_R	TC ppm/°C	Tolerance, ±%	Insulation Resistance, MΩ μF	Dissipation Factor,%	Dielectric Absorption,%	Temperature Range, °C	Comments, Applications	Cost
Polycarbonate	100 pF – 30 μF	50 – 800	±50	10	5×10^5	0.200	0.10	–55/+125	High quality, small, low TC	High
Polyester/Mylar	1000 pF – 50 μF	50 – 600	+400	10	10^5	0.750	0.30	–55/+125	Good, popular	Medium
Polypropylene	100 pF – 50 μF	100 – 800	–200	10	10^5	0.200	0.10	–55/+105	High quality, low absorption	High
Polystyrene	10 pF – 2.7 μF	100 – 600	–100	10	10^6	0.050	0.04	–55/+85	High quality, large, low TC, signal filters	Medium
Polysulfone	1000 pF – 1 μF	—	+80	5	10^5	0.300	0.20	–55/+150	High temperature	High
Parylene	5000 pF – 1 μF	—	±100	10	10^5	0.100	0.10	–55/+125		High
Kapton	1000 pF – 1 μF	—	+I00	10	10^5	0.300	0.30	–55/+220	High temperature	High
Teflon	1000 pF – 2 μF	50 – 200	–200	10	5×10^6	0.040	0.04	–70/+250	High temperature, lowest absorption	High
Mica	5 pF – 0.01 μF	100 – 600	–50	5	2.5×10^4	0.001	0.75	–55/+125	Good at RF, low TC	High
Glass	5 pF – 1000 μF	100 – 600	+I40	5	10^6	0.001		–55/+125	Excellent long-term stability	High
Porcelain	100 pF – 0.1 μF	50 – 400	+I20	5	5×10^5	0.100	4.20	–55/+125	Good long-term stability	High
Ceramic (NPO)	100 pF – 1 μF	50 – 400	±30	10	5×10^3	0.020	0.75	–55/+125	Active filters, low TC	Medium
Ceramic	10 pF – 1 μF	50 – 30,000	—	—	—	—	—	–55/+125	Small, very popular, selectable TC	Low
Paper	0.01 – 10 μF	200 – 1,600	±800	10	5×10^3	1.000	2.50	–55/+125	Motor capacitors	Low
Aluminum	0.1 – 1.6 F	3 – 600	+2500	–10/+100	100	10.000	8.00	–40/+85	Power supply filters short life	High
Tantalum (Foil)	0.1 – 1000 μF	6 – 100	+800	–10/+100	20	4.000	8.50	–55/+85	High capacitance, small size, low inductance	High
Thin-film	10 – 200 pF	6 – 30	+I00	10	10^6	0.010	—	–55/+125		High
Oil	0.1 – 20 μF	200 – 10,000	—	—	—	0.500	—	—	High voltage filters, large, long life	—
Vacuum	1 – 1000 pF	2,000 – 3,600	—	—	—	—	—	—	Transmitters	—

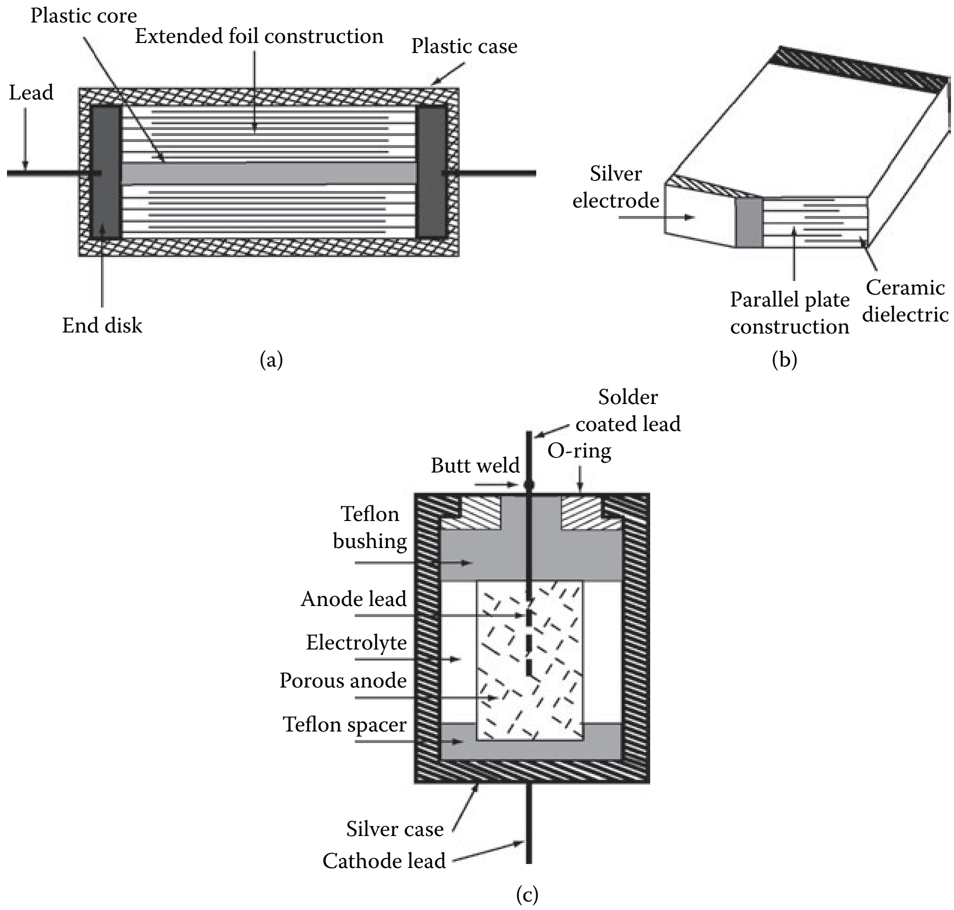

Figure 5.4 Construction of discrete capacitors. (*From* [2]. *Used with permission.*)

5.3.1.1 Mechanical Failure

Mechanical failures relate to poor bonding of the leads to the outside world, contamination during manufacture, and shock-induced short-circuiting of the aluminum foil plates. Typical failure modes include short circuits caused by foil impurities, manufacturing defects (such as burrs on the foil edges or tab connections), breaks or tears in the foil, and breaks or tears in the separator paper.

Short circuits are the most frequent failure mode during the useful life period of an electrolytic capacitor. Such failures are the result of random breakdown of the dielectric oxide film under normal stress. Proper capacitor design and processing will minimize such failures. Short circuits also can be caused by excessive stress, where voltage, temperature, or ripple conditions exceed specified maximum levels.

Open circuits, although infrequent during normal life, can be caused by failure of the internal connections joining the capacitor terminals to the aluminum foil. Mechanical connections can develop an oxide film at the contact interface, increasing contact resistance and eventually producing an open circuit. Defective weld connections also can cause open circuits. Excessive mechanical stress will accelerate weld-related failures.

Figure 5.5 An oil-filled, high-voltage capacitor.

5.3.1.2 Temperature Cycling

Capacitors are subject to failures induced by thermal cycling. Experience has shown that thermal stress is a major contributor to failure in aluminum electrolytic capacitors. Dimensional changes between plastic and metal materials can result in microscopic ruptures at termination joints, possible electrode oxidation, and unstable device termination (changing series resistance). The highest-quality capacitor will fail if its voltage or current ratings are exceeded. Appreciable heat rise (20°C during a 2-hour period of applied sinusoidal voltage) is considered abnormal and may be a sign of incorrect application of the component or impending failure of the device.

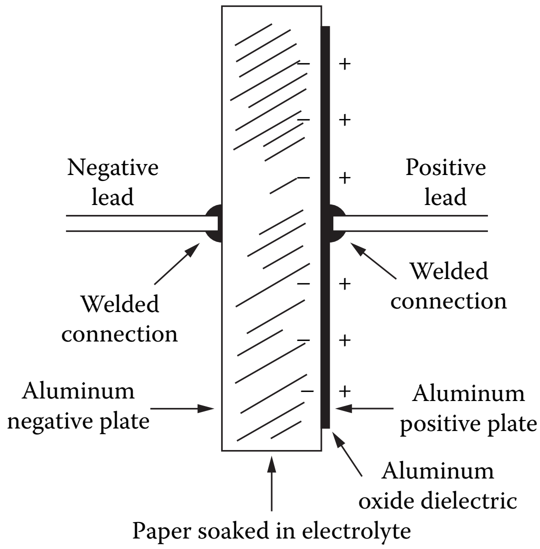

Figure 5.6 The basic design of an aluminum electrolytic capacitor.

Figure 5.7 illustrates the effects of high ambient temperature on capacitor life. Note that operation at 33% duty cycle is rated at 10 years when the ambient temperature is 35°C, but the life expectancy drops to just 4 years when the same device is operated at 55°C. A common rule of thumb is this: Within the range of + 75°C through the full-rated temperature, stress and failure rates double for each 10°C increase in operating temperature. Conversely, the failure rate is reduced by half for every 10°C decrease in operating temperature.

5.3.1.3 Electrolyte Failures

Failure of the electrolyte can be the result of application of a reverse bias to the component or of a drying of the electrolyte itself. Electrolyte vapor transmission through the end seals occurs on a continuous basis throughout the useful life of the capacitor. This loss has no appreciable effect on reliability during the useful life period of the product cycle. When the electrolyte loss approaches 40% of the initial electrolyte content of the capacitor, however, the electrical parameters deteriorate and the capacitor is considered to be worn out.

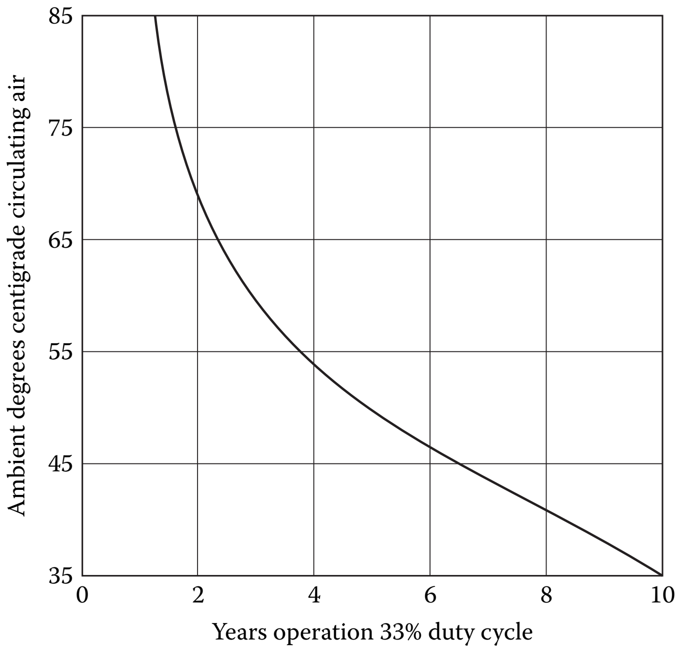

Figure 5.7 Life expectancy of an electrolytic capacitor as a function of operating temperature.

As a capacitor dries out, three failure modes may be experienced: leakage, a downward change in value, or *dielectric absorption*. Any one of these can cause a system to operate out of tolerance or fail altogether.

The most severe failure mode for an electrolytic is increased leakage, illustrated in Figure 5.8. Leakage can cause loading of the power supply or upset the dc bias of an amplifier. Loading of a supply line often causes additional current to flow through the capacitor, possibly resulting in dangerous overheating and catastrophic failure.

A change of device operating value has a less devastating effect on system performance. An aluminum electrolytic has a typical tolerance range of about ±20%. A capacitor suffering from drying of the electrolyte can experience a drastic drop in value (to just 50% of its rated value, or less). The reason for this phenomenon is that after the electrolyte has dried to an appreciable extent, the charge on the negative foil plate has no way of coming in contact with the aluminum-oxide dielectric. This failure mode is illustrated in Figure 5.9. Remember, it is the aluminum-oxide layer on the positive plate that gives the electrolytic capacitor its large rating. The dried-out paper spacer, in effect, becomes a second dielectric, which significantly reduces the capacitance of the device.

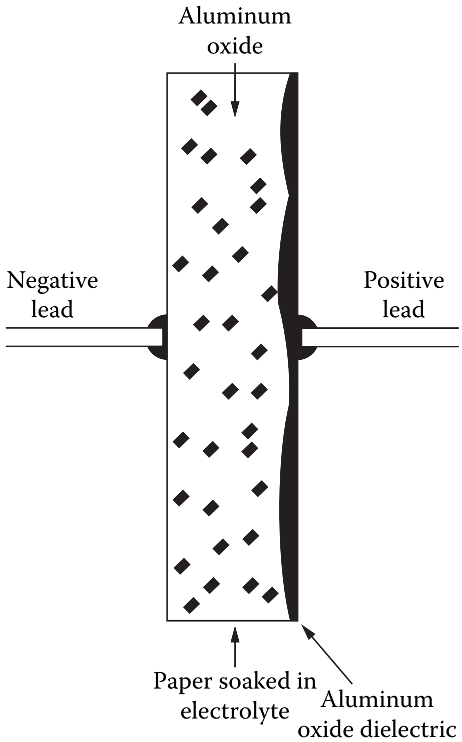

Figure 5.8 Failure mechanism of a leaky aluminum electrolytic capacitor. As the device ages, the aluminum oxide dissolves into the electrolyte, causing the capacitor to become leaky at high voltages

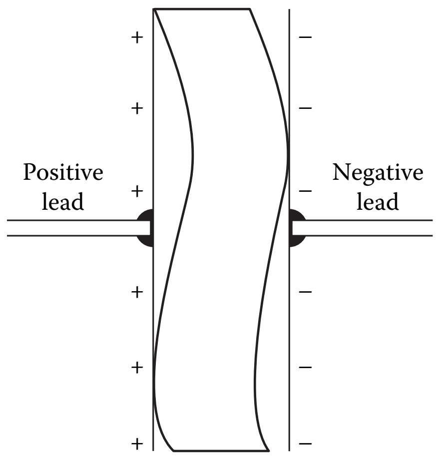

Figure 5.9 Failure mechanism of an electrolytic capacitor exhibiting a loss of capacitance. After the electrolyte dries, the plates can no longer come in contact with the aluminum oxide. The result is a decrease in capacitor value.

5.3.2 Capacitor Life Span

The life expectancy of a capacitor — operating in an ideal circuit and environment — will vary greatly, depending upon the grade of device selected. Typical operating life, according to capacitor manufacturer data sheets, range from a low of 3 to 5 years for inexpensive electrolytic devices, to a high of greater than 10 years for computer-grade products. Catastrophic failures aside, expected life is a function of the rate of electrolyte loss by means of vapor transmission through the end seals, and the operating or storage temperature. Properly matching the capacitor to the application is a key component in extending the life of an electrolytic capacitor. The primary operating parameters include:

- *Rated voltage* — the sum of the dc voltage and peak ac voltage that can be applied continuously to the capacitor. Derating of the applied voltage will decrease the failure rate of the device.
- *Ripple current* — the rms value of the maximum allowable ac current, specified by product type at 120 Hz and +85°C (unless otherwise noted). The ripple current may be increased when the component is operated at higher frequencies or lower ambient temperatures.

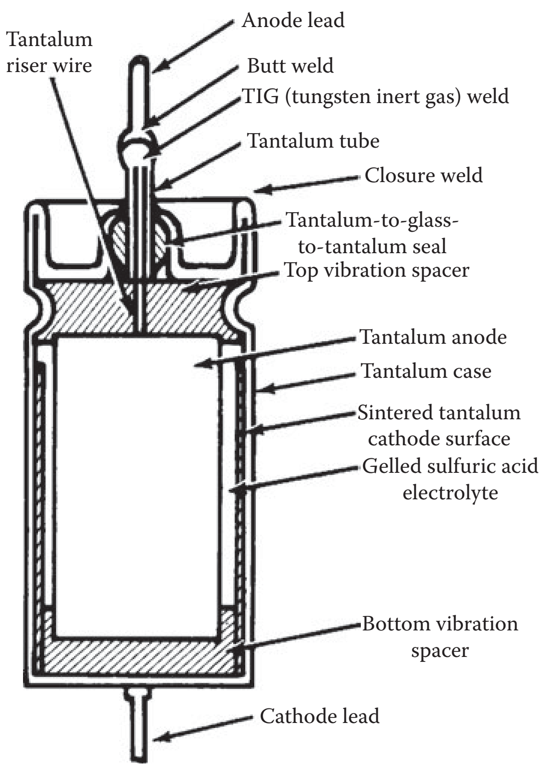

Figure 5.10 Basic construction of a tantalum capacitor.

- *Reverse voltage* — the maximum voltage that can be applied to an electrolytic capacitor without damage. Electrolytic capacitors are polarized and must be used accordingly.

5.3.3 Tantalum Capacitor

Tantalum electrolytic capacitors have become the preferred type of device where high reliability and long service life are primary considerations. The *tantalum pentoxide* compound possesses high dielectric strength and a high dielectric constant. As the components are being manufactured, a film of tantalum pentoxide is applied to the electrodes by means of an electrolytic process. The film is applied in various thicknesses. Figure 5.10 shows the internal construction of a typical tantalum capacitor. Because of the superior properties of tantalum pentoxide, tantalum capacitors tend to have as much as three times higher capacitance per volume efficiency as an aluminum electrolytic capacitor. This, coupled with the fact that extremely thin films can be deposited during the electrolytic process, makes tantalum capacitors efficient with respect to the number of microfarads per unit volume.

The capacitance of any device is determined by the surface area of the conducting plates, the distance between the plates, and the dielectric constant of the insulating material between the plates. In the tantalum capacitor, the distance between the plates is small; it is just the thickness of the tantalum pentoxide film. Tantalum capacitors contain either liquid or solid electrolytes.

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6 Semiconductors

6.1 Introduction

The first line of defense in the protection of electronic equipment from damaging transient overvoltages is the ac-to-dc power supply. Semiconductor power-supply components are particularly vulnerable to failure from ac line disturbances. Devices occasionally will fail from one large transient, but many more fail because of smaller, more frequent spikes that punch through the device junction. Such occurrences explain why otherwise reliable systems fail "without apparent reason."

6.2 Semiconductor Failure Modes

Semiconductor devices may be destroyed or damaged by transient disturbances in one of several ways. The primary failure mechanisms include:

- Avalanche-related failure
- Thermal runaway
- Thermal secondary breakdown
- Metallization failure
- Polarity reversals

When a semiconductor junction fails because of overstress, a low-resistance path is formed that shunts the junction. This path is not a true short, but it is a close approximation. The shunting resistance can be less than 10 Ω in a junction that has been heavily overstressed. By comparison, the shunting resistance of a junction that has been only mildly overstressed can be as high as 10 MΩ. The formation of low-resistance shunting paths is the result of the junction's electrothermal response to overstress.

6.2.1 Device Ruggedness

The best-constructed device will fail if exposed to stress exceeding its design limits. The *safe operating area* (SOA) of a power transistor is the single most important parameter in the design of high-power semiconductor-based systems. Fortunately, advances in diffusion technology, masking, and device geometry have enhanced the power-handling capabilities of semiconductor devices.

A bipolar transistor exhibits two regions of operation that must be avoided:

- *Dissipation region* — where the voltage-current product remains unchanged over any combination of voltage (V) and current (I). Gradually, as the collector-to-emitter voltage increases, the electric field through the base region causes hot spots to form. The carriers may punch a hole in the junction by melting silicon. The result is a dead (short-circuited) transistor.
- *Second breakdown* ($I_{s/b}$) *region* — where power transistor dissipation varies in a nonlinear inverse relationship with the applied collector-to-emitter voltage when the transistor is forward-biased.

To get SOA data into some type of useful format, a family of curves at various operating temperatures must be developed and plotted. This exercise gives a clear picture of what the data sheet indicates, compared with what happens in actual practice.

6.2.2 Forward Bias Safe Operating Area

The *forward bias safe operating area* (FBSOA) describes the ability of a transistor to handle stress when the base is forward-biased. Manufacturer FBSOA curves detail maximum limits for both steady-state dissipation and turn-on load lines. Because it is possible to have a positive base-emitter voltage and negative base current during the device storage time, forward bias is defined in terms of base current.

Bipolar transistors are particularly sensitive to voltage stress, more so than with stress induced by high currents. This situation is particularly true of switching transistors, and it shows up on the FBSOA curve. Figure 6.1 shows a typical curve for a common power transistor. In the case of the dc trace, the following observations can be made:

- The power limit established by the *bonding wire limit* portion of the curve permits 135 W maximum dissipation (15 A × 9 V).
- The power limit established by the *thermal limit* portion of the curve permits (at the maximum voltage point) 135 W maximum dissipation (2 A × 67.5 V). There is no change in maximum power dissipation.
- The power limit established by the *secondary breakdown* portion of the curve decreases dramatically from the previous two conditions. At 100 V, the maximum current is 0.42 A, for a maximum power dissipation of 42 W.

6.2.3 Reverse Bias Safe Operating Area

The *reverse bias safe operating area* (RBSOA) describes the ability of a transistor to handle stress with its base reverse-biased. As with FBSOA, RBSOA is defined in terms of current. In many respects, RBSOA and FBSOA are analogous. First among these is voltage sensitivity. Bipolar transistors exhibit the same sensitivity to voltage stress in the reverse bias mode as in the forward bias mode. A typical RBSOA curve is shown in Figure 6.2. Note that maximum allowable peak instantaneous power decreases significantly as voltage is increased.

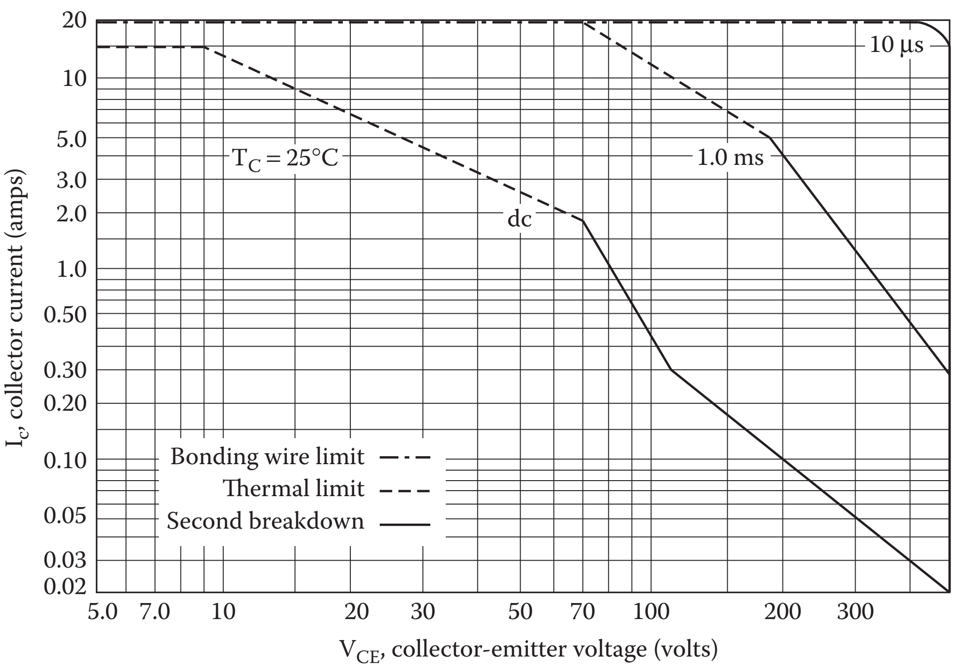


Figure 6.1 Forward bias safe operating area curve for a bipolar transistor (MJH16010A). (*Courtesy of Motorola*.)

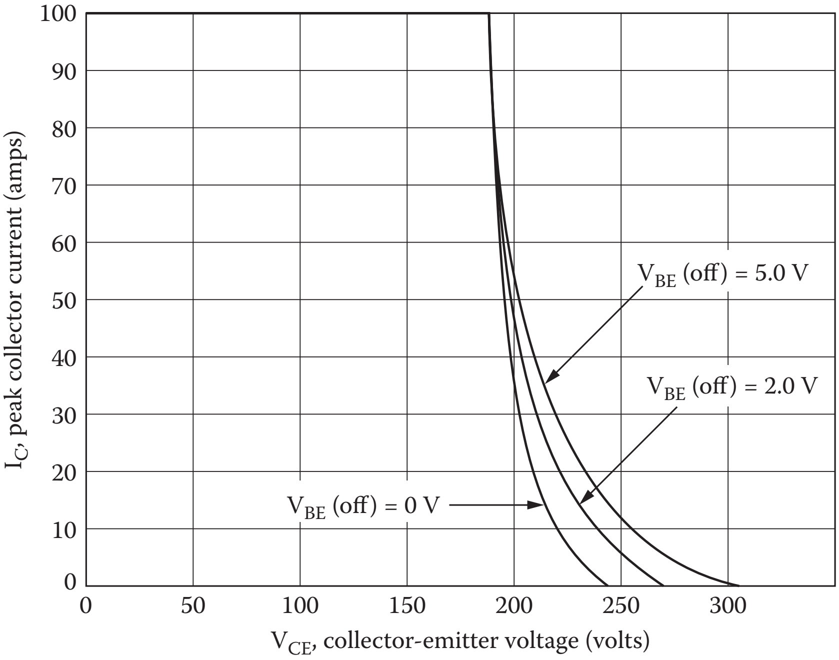


Figure 6.2 Reverse bias safe operating area curve for a bipolar transistor (MJH10610A). (*Courtesy of Motorola.*)

6.2.4 Power-Handling Capability

The primary factor in determining the amount of power a given device can handle is the size of the active junction(s) on the chip. The same power output from a device can be achieved through the use of several smaller chips in parallel. This approach, however, may result in unequal currents and uneven distribution of heat. At high power levels, heat management becomes a significant factor in chip design.

Specialized layout geometries have been developed to ensure even current distribution throughout the device. One approach involves the use of a matrix of emitter resistances constructed so that the overall distribution of power among the parallel emitter elements results in even thermal dissipation. Figure 6.3 illustrates this *interdigited* geometry technique.

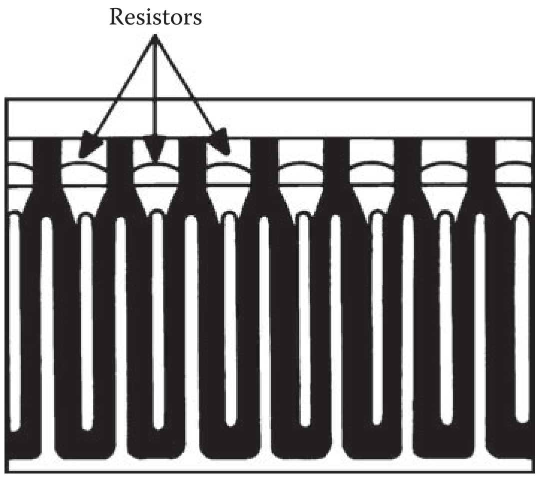


Figure 6.3 Interdigited geometry of emitter resistors used to balance currents throughout a power device chip.

With improvements in semiconductor fabrication processes, output device SOA is primarily a function of the size of the silicon slab inside the package. Package type, of course, determines the ultimate dissipation because of thermal saturation with temperature rise. A good TO-3 or a two-screw-mounted plastic package will dissipate approximately 350 to 375 W if properly mounted. Figure 6.4 demonstrates the relationships between case size and power dissipation for a TO-3 package.

6.2.5 Semiconductor Derating

Good engineering practice calls for a measure of caution in the selection and application of active devices. Unexpected operating conditions, or variations in the manufacturing process, can result in field failures unless a margin of safety is allowed. Derating is a common method of achieving such a margin. The primary derating considerations are:

- *Power derating* — designed to hold the worst-case junction temperature to a value below the normal permissible rating.
- *Junction-temperature derating* — an allowance for the worst-case ambient temperature or case temperature that the device is likely to experience in service.
- *Voltage derating* — an allowance intended to compensate for temperature-dependent voltage sensitivity and other threats to device reliability as a result of instantaneous peak-voltage excursions caused by transient disturbances.

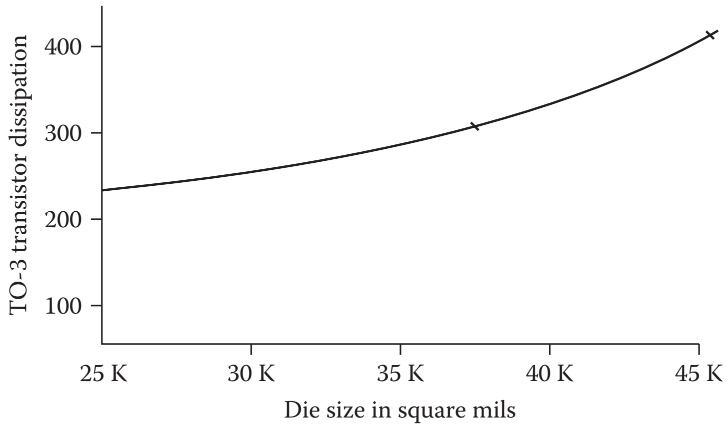


Figure 6.4 Relationship between case (die) size and transistor dissipation.

6.2.6 Failure Mechanisms

It is estimated that as much as 95% of all transistor failures in the field are directly or indirectly the result of excessive dissipation or applied voltages in excess of the maximum design limits of the device. There are at least four types of voltage breakdown that must be considered in a reliability analysis of discrete power transistors. Although they are not strictly independent, each type can be treated separately. Keep in mind, however, that each is related to the others.

6.2.6.1 Avalanche Breakdown

Avalanche is a voltage breakdown that occurs in the collector-base junction, similar to the *Townsend effect* in gas tubes. This effect is caused by the high dielectric field strength that occurs across the collector-base junction as the collector voltage is increased. This high-intensity field accelerates the free charge carriers so that they collide with other atoms, knocking loose additional free charge carriers that, in turn, are accelerated and have more collisions.

This multiplication process occurs at an increasing rate as the collector voltage increases, until at some voltage, V_a (avalanche voltage), the current suddenly tries to go to infinity. If enough heat is generated in this process, the junction will be damaged or destroyed. A damaged junction will result in higher-than-normal leakage currents, increasing the steady-state heat generation of the device, which ultimately can destroy the semiconductor junction.

6.2.6.2 Alpha Multiplication

Alpha multiplication is produced by the same physical phenomenon that produces avalanche breakdown, but differs in circuit configuration. This effect occurs at a lower potential than the avalanche voltage and generally is responsible for collector-emitter breakdown when base current is equal to zero.

6.2.6.3 Punch-Through

Punch-through is a voltage breakdown occurring at the collector-base junction because of high collector voltage. As collector voltage is increased, the *space charge region* (collector junction width) gradually increases until it penetrates completely through the base region, touching the emitter. At this point, the emitter and collector are effectively short-circuited together.

Although this type of breakdown occurs in some PNP junction transistors, alpha multiplication breakdown generally occurs at a lower voltage than punch-through. Because this breakdown occurs between the collector and emitter, punch-through is more serious in the common-emitter or common-collector configuration.

6.2.6.4 Thermal Runaway

Thermal runaway is a regenerative process by which a rise in temperature causes an increase in the leakage current; in turn, the resulting increased collector current causes higher power dissipation. This action raises the junction temperature, further increasing leakage current.

If the leakage current is sufficiently high (resulting from high temperature or high voltage), and the current is not adequately stabilized to counteract increased collector current because of increased leakage current, this process can regenerate to a point that the temperature of the transistor rapidly rises, destroying the device. This type of effect is more prominent in power transistors, where the junction normally is operated at elevated temperatures and where high leakage currents are present because of the large junction area. Thermal runaway is related to the avalanche effect and is dependent upon circuit stability, ambient temperature, and transistor power dissipation.

6.3 MOSFET Devices

Power MOSFETs (*metal-oxide semiconductor field-effect transistors*) have found numerous applications because of their unique performance attributes. A variety of specifications can be used to indicate the maximum operating voltages a specific device can withstand. The most common specifications include:

- Gate-to-source breakdown voltage
- Drain-to-gate breakdown voltage
- Drain-to-source breakdown voltage

These limits mark the maximum voltage excursions possible with a given device before failure. Excessive voltages cause carriers within the depletion region of the reverse-biased PN junction to acquire sufficient kinetic energy to result in ionization. Voltage breakdown also can occur when a *critical electric field* is reached. The magnitude of this voltage is determined primarily by the characteristics of the die itself.

6.3.1 Safe Operating Area

The safe dc operating area of a MOSFET is determined by the rated power dissipation of the device over the entire drain-to-source voltage range (up to the rated maximum voltage). The maximum drain-source voltage is a critical parameter. If exceeded even momentarily, the device can be damaged permanently.

Figure 6.5 shows a representative SOA curve for a MOSFET. Notice that limits are plotted for several parameters, including drain-source voltage, thermal dissipation (a time-dependent function), package capability, and drain-source on-resistance. The capability of the package to withstand high voltages is determined by the construction of the die, including bonding wire diameter, size of the bonding pad, and internal thermal resistances. The drain-source on-resistance limit is simply a manifestation of Ohm's law; with a given on-resistance, current is limited by the applied voltage.

To a large extent, the thermal limitations described in the SOA chart determine the boundaries for MOSFET use in linear applications. The maximum permissible junction temperature also affects the pulsed current rating when the device is used as a switch. MOSFETs are, in fact, more like rectifiers than bipolar transistors with respect to current ratings; their peak current ratings are not gain-limited, but thermally limited.

In switching applications, total power dissipation comprises both switching losses and on-state losses. At low frequencies, switching losses are small. As the operating frequency increases, however, switching losses become a significant factor in circuit design. The *switching safe operating area* (SSOA) defines the MOSFET voltage and current limitations during switching transitions. Although the SSOA chart outlines both turn-on and turn-off boundaries, it is used primarily as a source for turn-off SOA data. As such, it is the MOSFET equivalent of the reverse-biased SOA curve of bipolar transistors. As with the RBSOA rating, turn-off SOA curves are generated by observing device performance as it switches a clamped inductive load. Figure 6.6 shows a typical SSOA chart for a family of MOSFET devices.

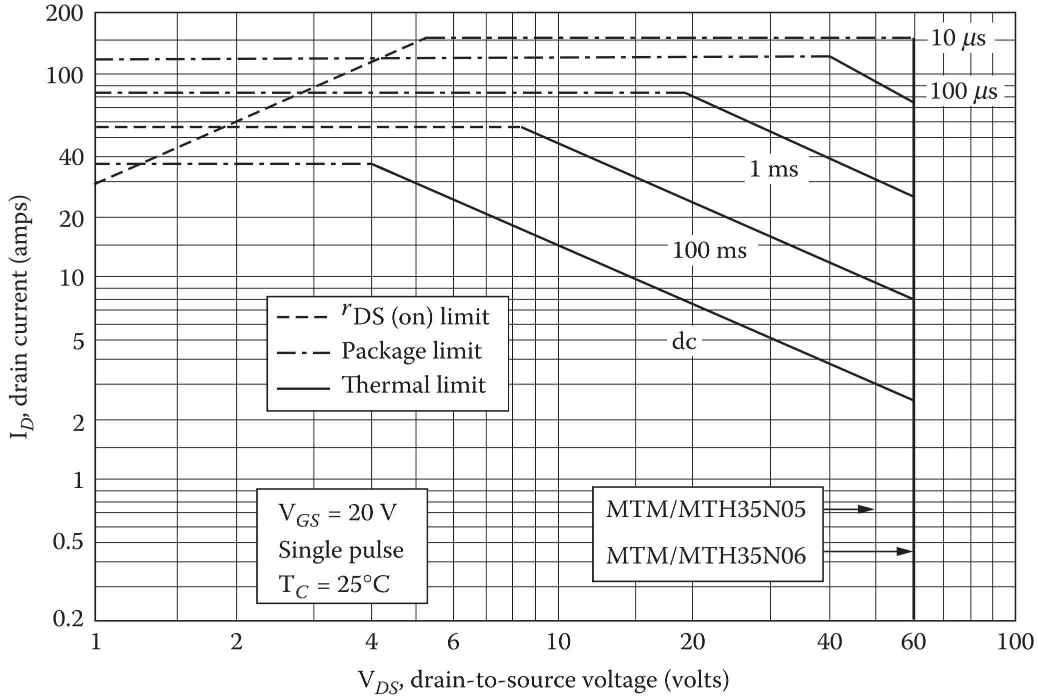


Figure 6.5 Safe operating area curve for a power FET device. (*Courtesy of Motorola.*)

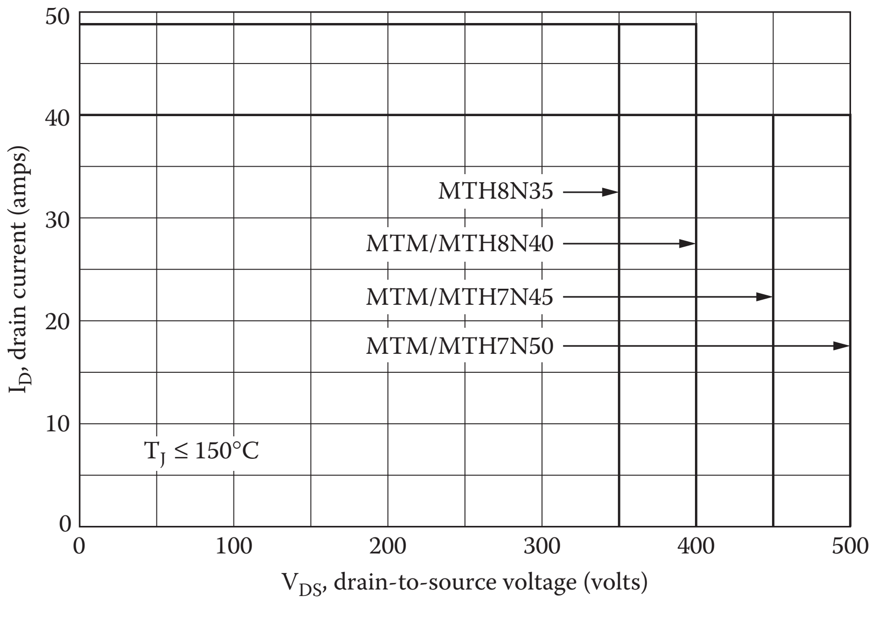


Figure 6.6 Maximum rated switching safe operating area of the MTM8N40 MOSFET. (*Courtesy of Motorola.*)

Figure 6.7 illustrates a FET device switching an inductive load in a circuit with no protection from *flyback* (back-emf) voltages. The waveform depicts the turn-off voltage transient resulting from the load and the parasitic lead and wiring inductance. The device experiences an avalanche condition for about 300 ns at its breakdown voltage of 122 V. Placing a clamping diode across the inductive load suppresses most (but not all) of the transient. (See Figure 6.8.) The drain-to-source (V_{ds}) voltage still will overshoot the supply rail by the sum of the effects of the diode's forward recovery characteristics, the diode lead inductance, and the parasitic series inductances. If the series resistance of the load is small in comparison with its inductance, a simple diode clamp may allow current to circulate through the load-diode loop for a significant period of time after the MOSFET is turned off. When this residual current is unacceptable, a resistance can be inserted in series with the diode at the expense of increasing the peak flyback voltage seen at the drain.

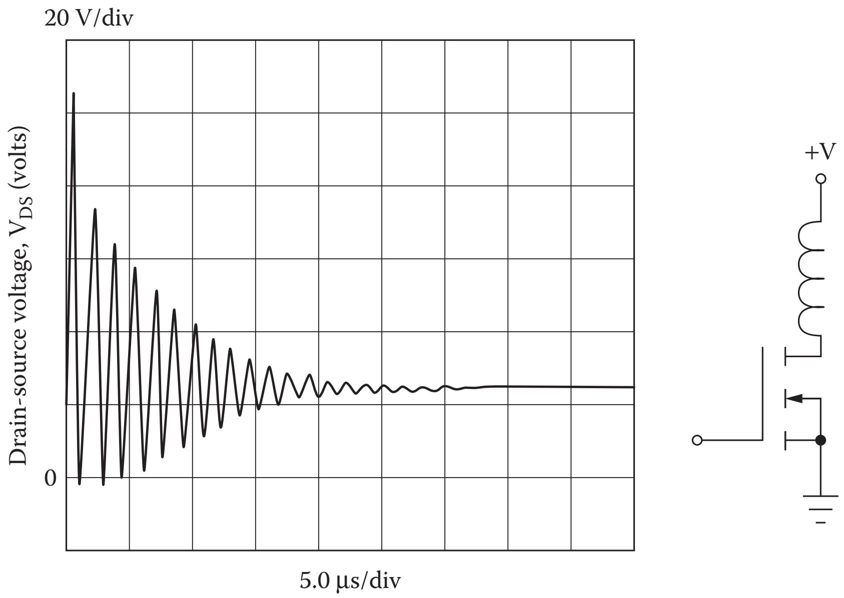


Figure 6.7 Drain-source transient resulting from switching off an unclamped inductive load. (*Courtesy of Motorola.*)

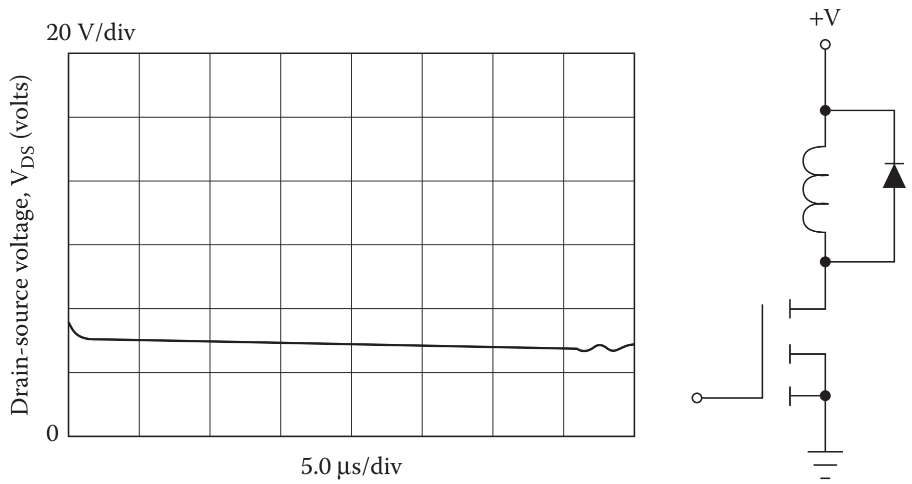


Figure 6.8 Drain-source transient with a clamping diode across the inductive load. (*Courtesy of Motorola.*)

Protecting the drain-source from voltage transients with a zener diode (a wideband device) is another simple and effective solution. Except for the effects of the lead and wiring inductances and the negligible time required to avalanche, the zener will clip the voltage transient at its breakdown voltage. A slow-rise-time transient will be clipped completely; a rapid-rise-time transient may momentarily exceed the zener breakdown. These effects are shown in Figure 6.9.

Figure 6.10 shows an *RC* clamp network that suppresses flyback voltages greater than the potential across the capacitor. Sized to sustain nearly constant voltage during the entire switch cycle, the capacitor absorbs energy only during transients and dumps that energy into the resistance during the remaining portion of the cycle.

A series *RC* snubber circuit is shown in Figure 6.11. Although the circuit effectively reduces the peak drain voltage, it is not as efficient as a true clamping scheme. Whereas a clamping network dissipates energy only during the transient, the *RC* snubber absorbs energy during portions of the switching cycle that are not overstressing the MOSFET. This configuration also slows turn-on times because of the additional drain-source capacitance that must be charged.

Historically, a MOSFET's maximum drain-to-source voltage specification prohibited even instantaneous excursions beyond stated limits; the first power MOSFET devices were never intended to be

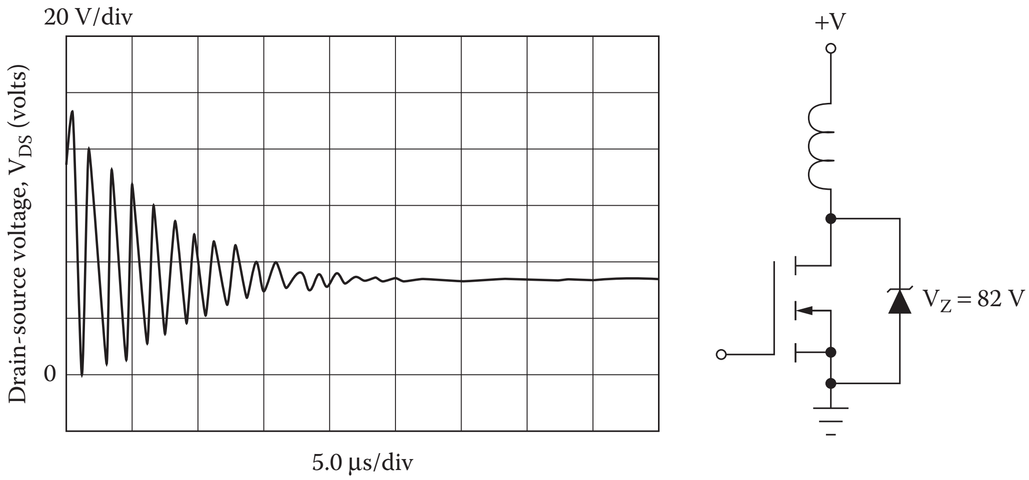


Figure 6.9 Drain-source transient with a clamping zener diode. (*Courtesy of Motorola.*)

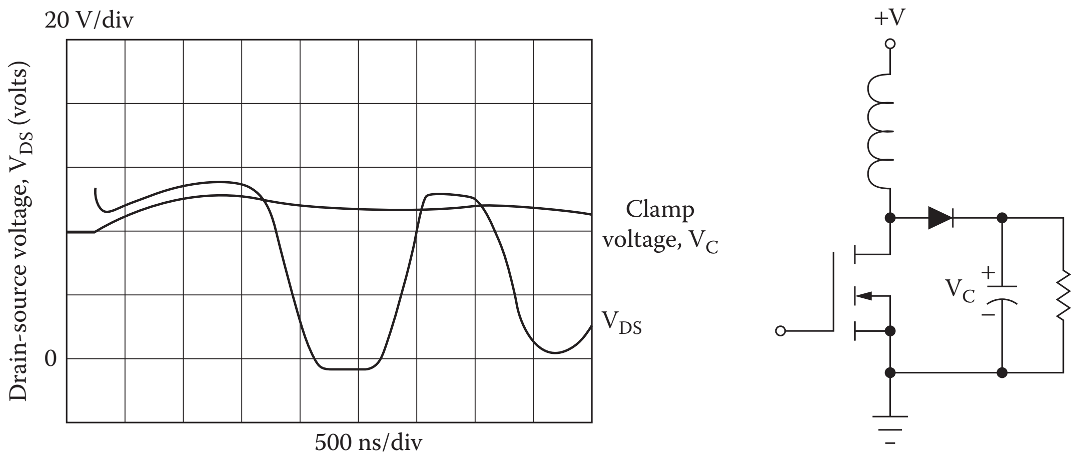


Figure 6.10 Transient waveforms for a gated *RC* clamp. (*Courtesy of Motorola.*)

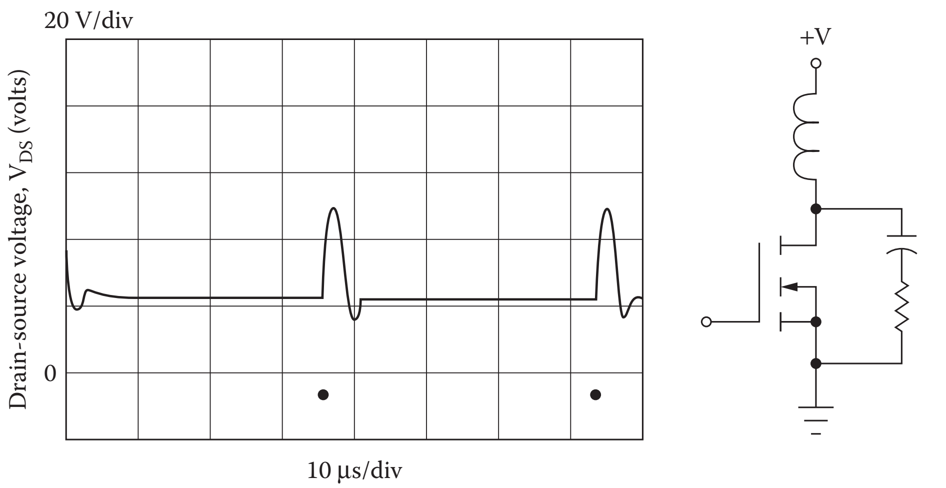


Figure 6.11 Drain-source transient with an *RC* snubber circuit. (*Courtesy of Motorola.*)

operated in avalanche. As is still the case with most bipolar transistors, avalanche limitations simply were not specified. Some devices happened to be rugged, whereas others were not. Manufacturers now have designed power MOSFET devices that are able to sustain substantial currents in avalanche at elevated junction temperatures. As a result, these “ruggedized” devices have replaced older MOSFETs in critical equipment.

6.3.2 MOSFET Failure Modes

The thermal and electrical stresses that a MOSFET device may experience during switching can be severe, particularly during turn-off when an inductive load is present. When power MOSFETs were introduced, it usually was stated that, because the MOSFET was a majority carrier device, it was immune to secondary breakdown as observed in bipolar transistors. It must be understood, however, that a parasitic bipolar transistor is inherent in the structure of a MOSFET. This phenomenon is illustrated in Figure 6.12. The parasitic bipolar transistor can allow a failure mechanism similar to secondary breakdown. Research has shown that if the parasitic transistor becomes active, the MOSFET may fail. This situation is particularly troublesome if the MOSFET drain-source breakdown voltage is approximately twice the collector-emitter sustaining voltage of the parasitic bipolar transistor. This failure mechanism results, apparently, when the drain voltage snaps back to the sustaining voltage of the parasitic device. This *negative resistance characteristic* can cause the total device current to constrict to a small number of cells in the MOSFET structure, leading to device failure. The precipitous voltage drop synonymous with secondary breakdown is a result of avalanche injection and any mechanism, electric or thermal, that can cause the current density to become sufficiently large for avalanche injection to occur.

6.3.3 Breakdown Effects

The effects of the breakdown modes outlined manifest themselves in various ways on the transistor:

- Avalanche breakdown usually results in destruction of the collector-base junction because of excessive currents. This, in turn, results in an open between the collector and base.
- Breakdown due to alpha multiplication and thermal runaway most often results in destruction of the transistor because of excessive heat dissipation that shows up electrically as a short circuit between the collector and the emitter. This condition, which is most common in transistors that have suffered catastrophic failure, is not always detected easily. In many cases, an ohmmeter check may indicate a normal condition. Only after operating voltages are applied will the failure mode be exhibited.

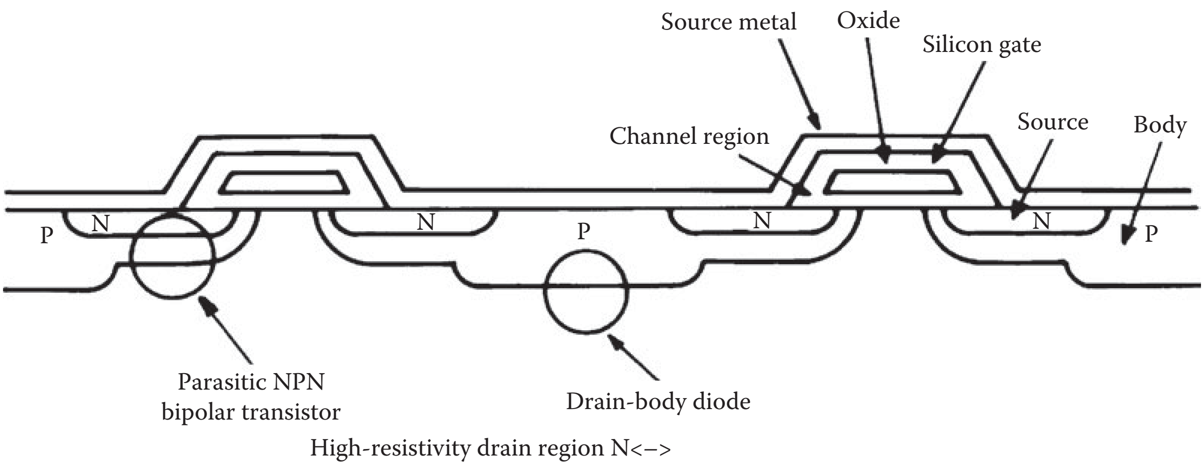


Figure 6.12 Cross section of a power MOSFET device showing the parasitic bipolar transistor and diode inherent in the structure.

- Punch-through breakdown generally does not cause permanent damage to the transistor; it can be a self-healing type of breakdown. After the overvoltage is removed, the transistor usually will operate satisfactorily.

6.3.3.1 Thermal Second Breakdown

Junction burnout is a significant failure mechanism for bipolar devices, particularly *junction field-effect transistor* (JFET) and Schottky devices. The junction between a P-type diffusion and an N-type diffusion normally has a positive temperature coefficient at low temperatures. Increased temperature will result in increased resistance. When a reverse-biased pulse is applied, the junction dissipates heat in a narrow *depletion region*, and the temperature in that area increases rapidly. If enough energy is applied in this process, the junction will reach a point at which the temperature coefficient of the silicon will turn negative. In other words, increased temperature will result in decreased resistance. A thermal runaway condition can then ensue, resulting in localized melting of the junction. If sustaining energy is available after the initial melt, the hot spot can grow into a *filament short*. The longer the energy pulse, the wider the resulting filament short. *Current filamentation* is a concentration of current flow in one or more narrow regions, which leads to localized heating.

After the transient has passed, the silicon will resolidify. The effect on the device can be catastrophic, or it can simply degrade the performance of the component. With a relatively short pulse, a hot spot can form, but not grow completely across the junction. As a result, the damage may not appear immediately as a short circuit, but manifest itself at a later time as a result of *electromigration* or another failure mechanism.

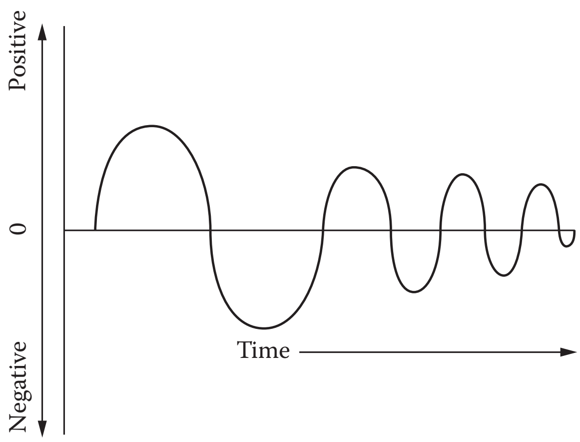
6.3.3.2 Metallization Failure

The smaller device geometry required by high-density integrated circuits has increased the possibility of metallization failure resulting from transient overvoltages. Metallization melt is a power-dependent failure mechanism. It is more likely to occur during a short-duration, high-current pulse. Heat generated by a long pulse tends to be dissipated in the surrounding chip die.

Metallization failure also can occur as a side effect of junction melt. The junction usually breaks down first, opening the way for high currents to flow. The metallization then heats until it reaches the melting point. Metallization failure results in an open circuit. A junction short circuit can, therefore, lead to an open-circuit failure.

6.3.3.3 Polarity Reversal

Transient disturbances typically build rapidly to a peak voltage and then decay slowly. If enough inductance or capacitance is present in the circuit, the tail will oscillate as it decays. This concept is illustrated in Figure 6.13. The oscillating tail can subject semiconductor devices to severe voltage polarity reversals, forcing the components into or out of a conducting state. This action can damage the semiconductor junction or result in catastrophic failure.



.**Figure 6.13** Waveshape of a typical transient disturbance. Note how the tail of the transient oscillates as it decays.

6.4 Thyristor Components

The term *thyristor* identifies a general class of solid-state *silicon controlled rectifiers* (SCRs). These devices are similar to normal rectifiers, but are designed to remain in a blocking state (in the forward direction) until a small signal is applied to a control electrode (the gate). After application of the control pulse, the device conducts in the forward direction and exhibits characteristics similar to those of a common silicon rectifier. Conduction continues after the control signal has been removed and until the current through the device drops below a predetermined threshold, or until the applied voltage reverses polarity.

The voltage and current ratings for thyristors are similar to the parameters used to classify standard silicon rectifiers. Some of the primary device parameters include:

- *Peak forward blocking voltage* — the maximum safe value that can be applied to the thyristor while it is in a blocking state.
- *Holding current* — the minimum anode-to-cathode current that will keep the thyristor conducting after it has been switched on by the application of a gate pulse.
- *Forward voltage drop* — the voltage loss across the anode-to-cathode current path for a specified load current. Because the ratio of rms-to-average forward current varies with the angle of conduction, power dissipation for any average current also varies with the device angle of conduction. The interaction of forward voltage drop, phase angle, and device case temperature generally are specified in the form of one or more graphs or charts.
- *Gate trigger sensitivity* — the minimum voltage or current that must be applied to the gate to trigger a specific type of thyristor into conduction. This value must take into consideration variations in production runs and operating temperature. The minimum trigger voltage is not normally temperature sensitive, but the minimum trigger current can vary considerably with thyristor case temperature.
- *Turn-on time* — the length of time required for a thyristor to change from a nonconducting state to a conducting state. When a gate signal is applied to the thyristor, anode-to-cathode current begins to flow after a finite delay. A second switching interval occurs between the point at which current begins to flow and the point at which full anode current (determined by the instantaneous applied voltage and the load) is reached. The sum of these two times is the turn-on time. The turn-on interval is illustrated in Figure 6.14.

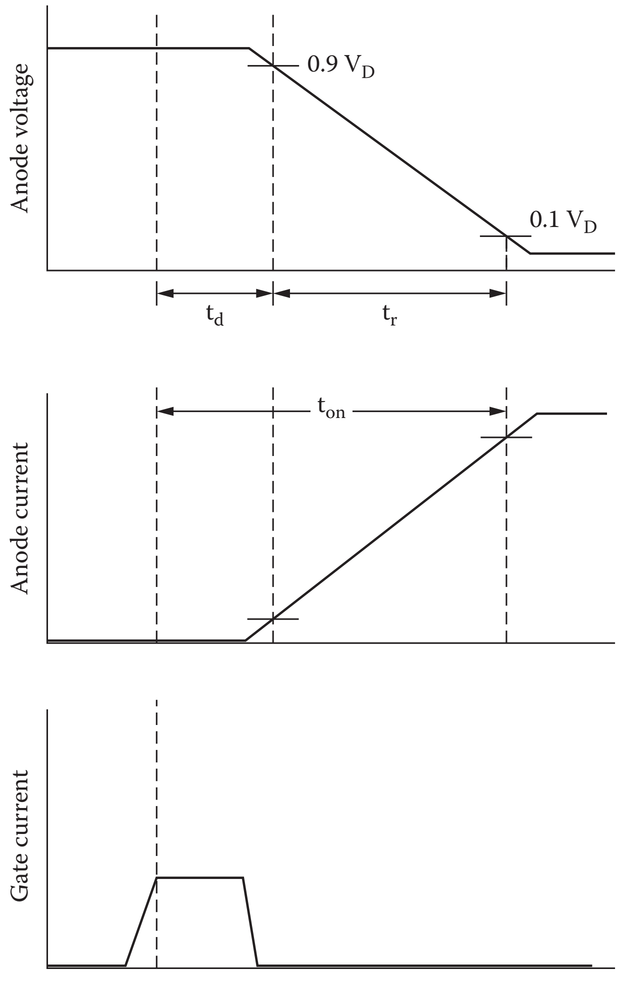


Figure 6.14 Turn-on waveforms for an SCR device. T_d = delay time interval between a specified point at the beginning of a gate pulse and the instant at which the principal voltage drops to a specified value. T_r = rise time between the principal voltage dropping from one value to a second lower value when the thyristor turns from off to on.

- *Turn-off time* — the length of time required for a thyristor to change from a conducting state to a nonconducting state. The turn-off time is composed of two individual periods: the *storage time* (similar to the storage interval of a saturated transistor) and the *recovery time*. If forward voltage is reapplied before the entire turn-off time has elapsed, the thyristor will conduct again.

6.4.1 Failure Modes

Thyristors, like diodes, are subject to damage from transient overvoltages because the peak inverse voltage or instantaneous forward voltage (or current) rating of the device may be exceeded. Thyristors face an added problem because of the possibility of device misfiring. A thyristor can break over into a conduction state, regardless of gate drive, if either of these conditions occur:

- Too high a positive voltage is applied between the anode and cathode.
- A positive anode-to-cathode voltage is applied too quickly, exceeding the dv/dt (delta voltage/delta time) rating.

If the leading edge is sufficiently steep, even a small voltage pulse can turn on a thyristor. This represents a threat not only to the device, but also to the load that it controls.

6.4.2 Application Considerations

Any application of a thyristor must take into account the device dv/dt rating and the electrical environment in which it will operate. A thyristor controlling an appreciable amount of energy should be protected against fast-rise-time transients that may cause the device to break over into a conduction state. The most basic method of softening the applied anode-to-cathode waveform is the resistor/capacitor snubber network shown in Figure 6.15. This standard technique of limiting the applied dv/dt relies on the integrating ability of the capacitor. In the figure, C_1 snubs the excess transient energy, while R_1 defines the applied dv/dt with L_t, the external system inductance.

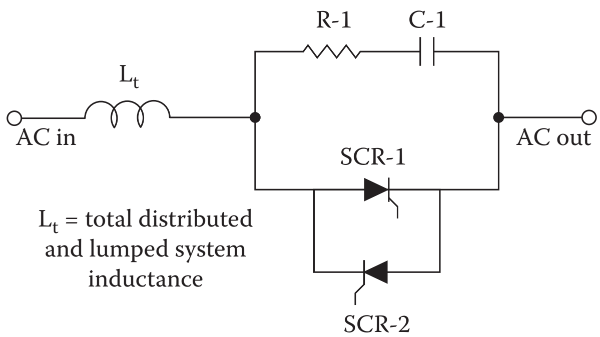


Figure 6.15 The basic *RC* snubber network commonly used to protect thyristors from fast-rise-time transients.

An applied transient waveform (assuming an infinitely sharp wavefront) will be impressed across the entire protection network of C_1, R_1, and L_t. The total distributed and lumped system inductance L_t plays a significant role in determining the ability of C_1 and R_1 to effectively snub a transient waveform. Power sources that are *stiff* (having little series inductance or resistance) will present special problems to engineers seeking to protect a thyristor from steep transient waveforms.

Exposure of semiconductors to a high-transient environment can cause a degrading of the device, which eventually may result in total failure. Figure 6.16 shows the energy-vs.-survival scale for several types of semiconductors.

6.5 ESD Failure Modes

Low-power semiconductors are particularly vulnerable to damage from electrostatic discharges (ESDs). MOS devices tend to be more vulnerable than other components. The gate of a MOS transistor is especially sensitive to electrical overstress. Application of excessive voltage can exceed the dielectric standoff voltage of the chip structure and punch through the oxide, forming a permanent path from the gate to the semiconductor below. An ESD pulse of 25 kV usually is sufficient to rupture the gate oxide. The scaling of device geometry that occurs with large-scale integrated (LSI) or very large-scale integrated (VLSI) components complicates this problem. The degree of damage caused by electrostatic discharge is a function of the following parameters:

- Size of the charge, determined by the capacitance of the charged object
- Rate at which the charge is dissipated, determined by the resistance into which it is discharged

Common techniques for controlling static problems include the following:

- Humidity control. Relative humidity (RH) of 50% or higher will greatly inhibit electrostatic problems. Too much humidity, however, can create corrosion problems and may make some paper products dimensionally unstable. Most data processing equipment manufacturers recommend 40 to 60% RH.
- Conductive floor coverings. Careful selection of floor surfaces will aid greatly in controlling ESD problems. Conductive synthetic rubber and other special-purpose floor coverings are ideal. Vinyl-asbestos is marginal. Nylon carpeting usually is unacceptable from an ESD standpoint.
- Static drain path. A static drain path from floor tiles or mats to the nearest grounded metal member is recommended in heavy traffic areas. The floor surface-to-ground resistance need not be particularly low; 500 kΩ to 20 MΩ is adequate for most applications.
- Ion generators. Localized, chronic static problems can be neutralized through the use of an ion generator. Such systems commonly are used in semiconductor assembly plants and in the printing industry to dissipate static charges.

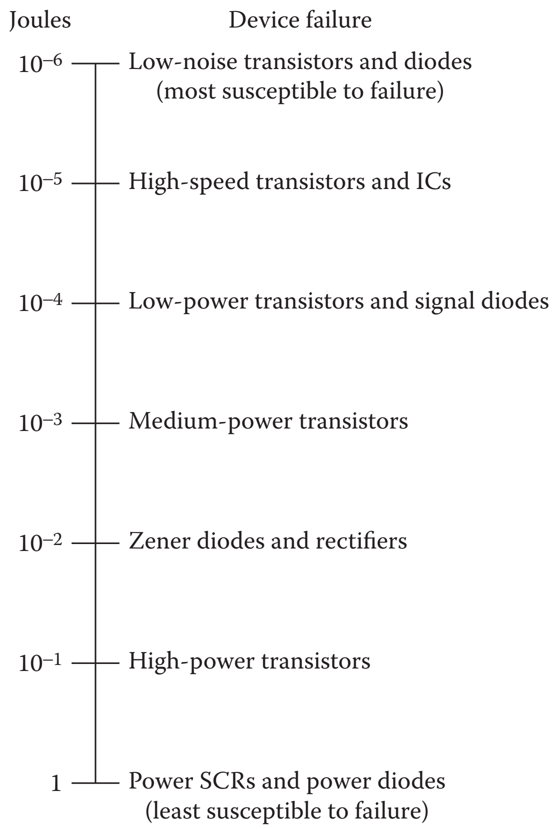


Figure 6.16 An estimate of the susceptibility of semiconductor devices to failure because of transient energy. The estimate assumes a transient duration of several microseconds.

6.5.1 Failure Mechanisms

Destructive voltages or currents from an ESD event can result in device failure because of thermal fatigue or dielectric breakdown. MOS transistors normally are constructed with an oxide layer between the gate conductor and the source-drain channel region, as illustrated in Figure 6.17 for a metal gate device and Figure 6.18 for a silicon gate device. Bipolar transistor construction, shown in Figure 6.19, is less susceptible to ESD damage because the oxide is used only for surface insulation.

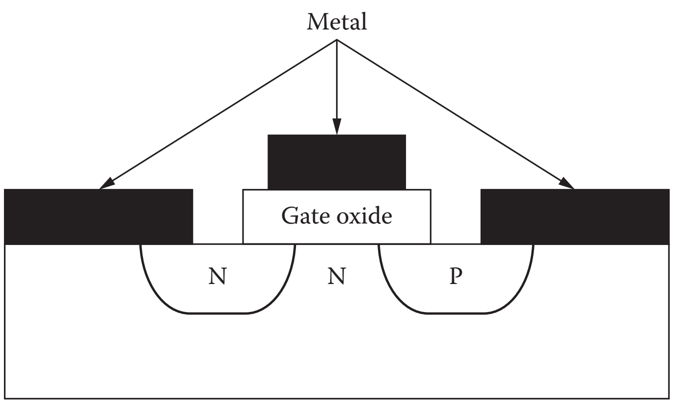


Figure 6.17 Construction of a metal gate NMOS transistor. (*After* [1].)

Oxide thickness is the primary factor in MOS ruggedness. A thin oxide is more susceptible to electrostatic punch-through, which results in a permanent low-resistance short-circuit through the oxide. Where pinholes or other weaknesses exist in the oxide, damage is possible at a lower charge level. Semiconductor manufacturers have reduced oxide thickness as they have reduced device size. This trend has resulted in a significant increase in sensitivity to ESD damage.

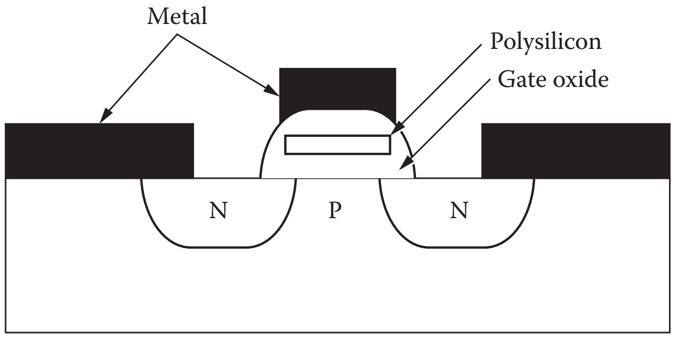


Figure 6.18 Construction of a silicon gate NMOS transistor. (*After* [1].)

Detecting an ESD failure in a complex device can present a significant challenge for quality control engineers. For example, erasable programmable read-only memory (EPROM) chips use oxide layers less than 100 angstroms, making them susceptible to single-cell defects that can remain undetected until the damaged cell itself is addressed. An electrostatic charge small enough that it does not result in oxide breakdown still can cause lattice damage in the oxide, lowering its ability to withstand subsequent ESD exposure. A weakened lattice will have a lower breakdown threshold voltage.

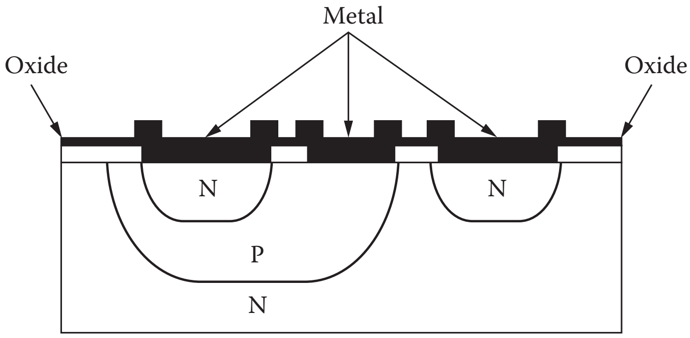


Figure 6.19 Construction of a bipolar transistor. (*After* [1].)

Table 6.1 lists the susceptibility of various semiconductor technologies to ESD-induced failure. Table 6.2 lists the ESD voltage levels that can result from common workbench operations.

Table 6.1 The Susceptibility of Various Technologies from ESD-Induced Damage (*Data courtesy of Motorola.*)

Device Type	Range of ESD Susceptibility (V)
Power MOSFET	100 to 2,000
Power Darlington	20,000 to 40,000
JFET	140 to 10,000
Zener diode	40,000
Schottky diode	300 to 2,500
Bipolar transistor	380 to 7,000
CMOS	250 to 2,000
ECL	500
TTL	300 to 2,500

Table 6.2 Electrostatic Voltages That Can Be Developed through Common Workbench Activities *(Data courtesy of Motorola.)*

Means of Static Generation	Electrostatic Voltages	
	10–20% RH	65–90% RH
Walking across carpet	35,000	1,500
Walking on vinyl floor	12,000	250
Worker at bench	6,000	100
Handling vinyl envelope	7,000	600
Handling common polybag	20,000	1,200

6.5.1.1 Latent Failures

Immediate failure resulting from ESD exposure is easily determined: the device no longer works. A failed component can be removed from the subassembly in which it is installed, representing no further reliability risk to the system. Not all devices exposed to ESD, however, fail immediately. Unfortunately, there is little data dealing with the long-term reliability of devices that have survived ESD exposure. Some experts, however, suggest that two to five devices are degraded for every one that fails. Available data indicates that latent failures can occur in both bipolar and MOS chips and that there is no direct relationship between the susceptibility of a device to catastrophic failure and its susceptibility to latent failure. Damage can manifest itself in one of two primary mechanisms:

- Shortened lifetime, a possible cause of many infant mortality failures seen during burn-in
- Electrical performance shifts, many of which can cause the device to fail electrical limit tests

6.5.1.2 Case in Point

Figure 6.20 shows an electron microscope photo of a chip that failed because of an overvoltage condition. An ESD to this MOSFET damaged one of the metallization connection points of the device, resulting in catastrophic failure. Note the spot where the damage occurred. The objects in the photo that look like bent nails are actually gold lead wires with a diameter of 1 mil. By contrast, a typical human hair is about 3 mils in diameter. The original photo was shot at ×200 magnification. Figure 6.21 offers another view of the MOSFET damage point, but at ×5000. The character of the damage can be observed. Some of the aluminum metallization has melted and can be seen along the bottom edge of the hole.

6.6 Semiconductor Development

Semiconductor failures caused by high-voltage stresses are becoming a serious concern for engineers, operators, and technical managers as new, high-density integrated circuits are placed into service. Internal IC connection lines that were 1.0 micron a few years ago have been reduced to well below 0.30 micron. Spacing between leads has been reduced by a factor of 4 or more. The most common microprocessors, and many other ICs, are manufactured using a planar process where a pure silicon wafer is selectively masked and diffused with chemicals to make multiple transistors. This combination is then selectively masked again, and metal is deposited on the wafer to interconnect the transistors [2]. A decade ago, most integrated circuits used only one layer of metal; today, however, advanced microprocessors use multiple layers of metal to increase the packing density. A cross section of a five-layer microprocessor is shown in Figure 6.22.

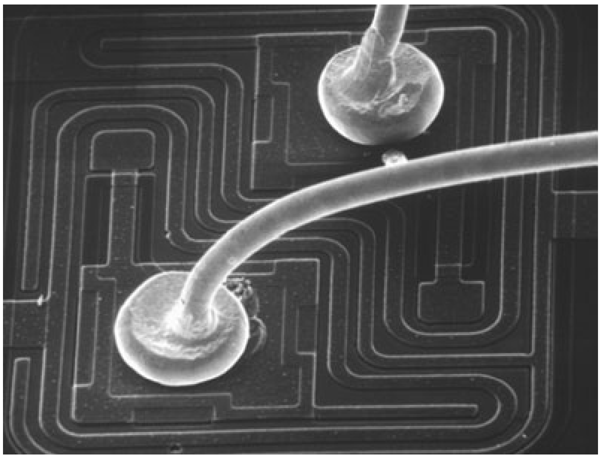


Figure 6.20 A scanning electron microscope photo illustrating ESD damage to the metallization of a MOSFET device.

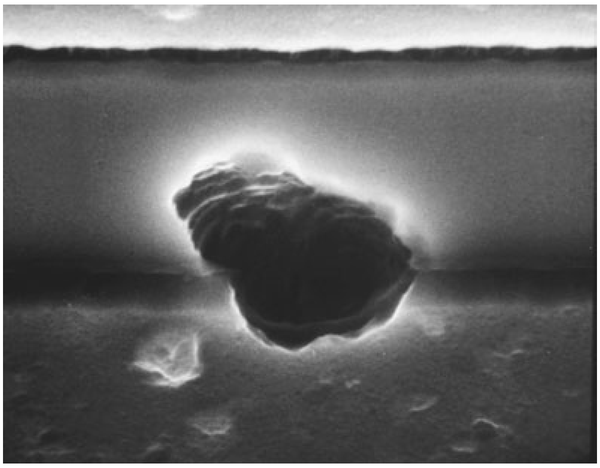


Figure 6.21 The device shown in the previous figure at ×5000 magnification. The character of the damage can be observed.

As the geometries of the individual transistors are reduced, the propagation delays through the devices also become smaller. Unfortunately, as the metalized interconnects get smaller, their resistance and capacitance increases and, therefore, the propagation delay through those interconnects increases. As the semiconductor industry moves to still smaller geometries, the delay through the metal will become greater than the delay through the transistor itself. There are several approaches to this challenge — the most obvious being to use a metal with higher conductivity than aluminum (currently used in chip production). Copper offers some attractive solutions but is more difficult to process. Alternative design techniques that use more transistors and fewer interconnects are also possible.

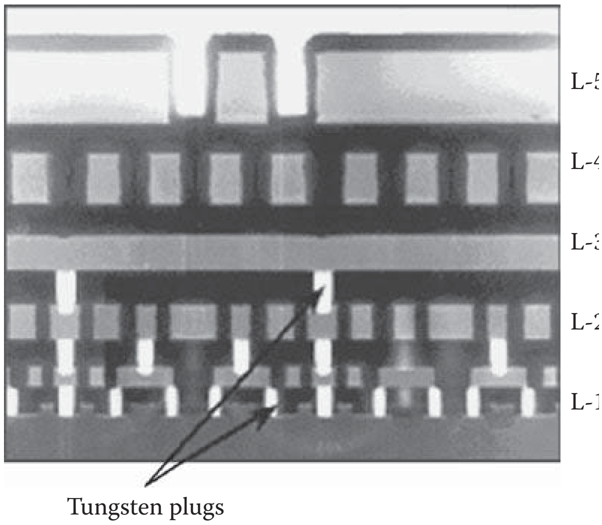


Figure 6.22 Cross section of a five-layer microprocessor device. (*From* [2]. *Courtesy of Intel.*)

As the transistor count goes up, then so does the power dissipation. More importantly, however, is the corresponding increase in frequency (power increases as the square of the frequency). The only variable that is changeable in the power equation is the supply voltage — power dissipation also is proportional to the square of the voltage. This operating limitation is the reason for movement to low-voltage microprocessors and other logic devices.

6.6.1 Failure Analysis

In the past, the IC overvoltage peril was primarily to semiconductor substrates. Now, however, the metallization itself—the points to which leads connect — is subject to damage. Failures are the result of three primary overvoltage sources:

- External human-made — overvoltages coupled into electronic hardware from utility company ac power feeds, or other ac or dc power sources
- External natural — overvoltages coupled into electronic hardware as a result of natural sources
- Electrostatic discharge — overvoltages coupled into electronic hardware as a result of static generation and subsequent discharge

Most semiconductor failures are of a random nature. That is, different devices respond differently to a specific stress. Figure 6.23 illustrates how built-in (latent) defects in a given device affect the time-to-failure point of the component. Slight imperfections require greater stress than gross imperfections to reach a quantifiable failure mode.

Integrated circuits intended for computer applications have been a driving force in the semiconductor industry. Figure 6.24 shows a simplified cutaway view of a DIP IC package. Connections between the die itself and the outside world are made with bonding wires. Figure 6.25 shows a cutaway view of a bonding pad.

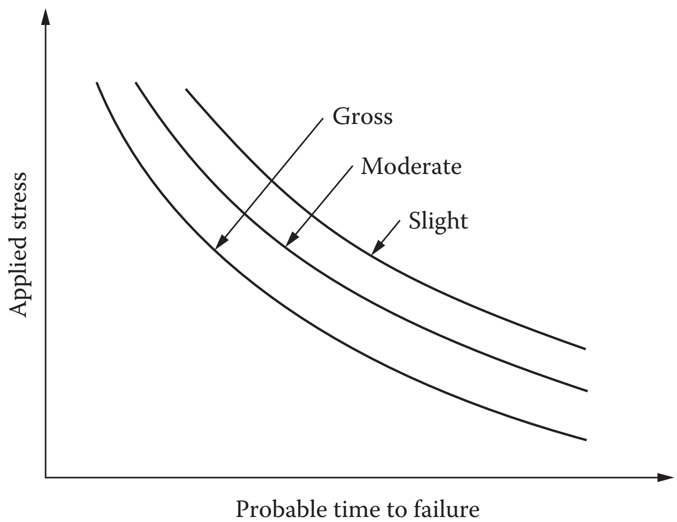


Figure 6.23 Illustration of the likelihood of component failure based on applied stress and degree of latent defects.

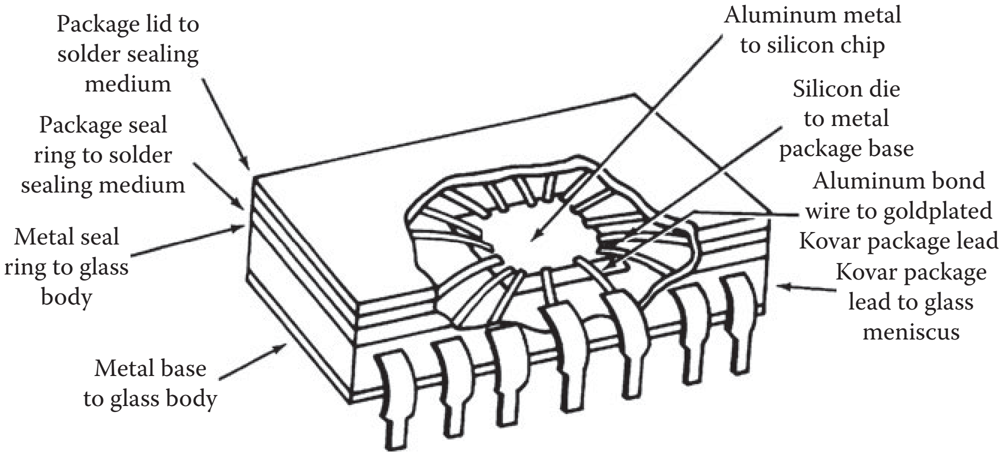


Figure 6.24 Cutaway view of a DIP integrated circuit package showing the internal-to-external interface. (*After* [1].)

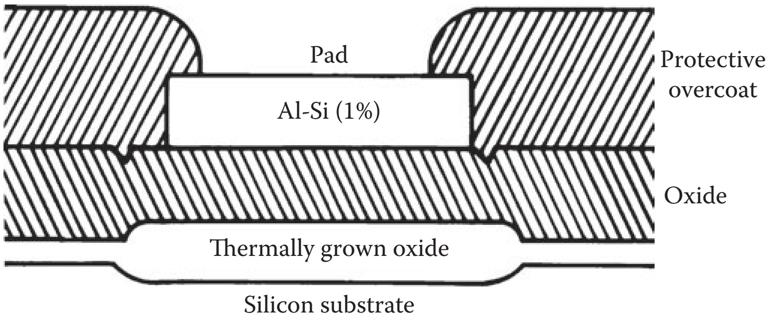


Figure 6.25 Cutaway structure of the bonding pad of a semiconductor device. (*After* [3].)

Hybrid microcircuits also have become common in consumer and industrial equipment. A hybrid typically utilizes a number of components from more than one technology to perform a function that could not be achieved in monolithic form with the same performance, efficiency, or cost. A simple multichip hybrid is shown in Figure 6.26.

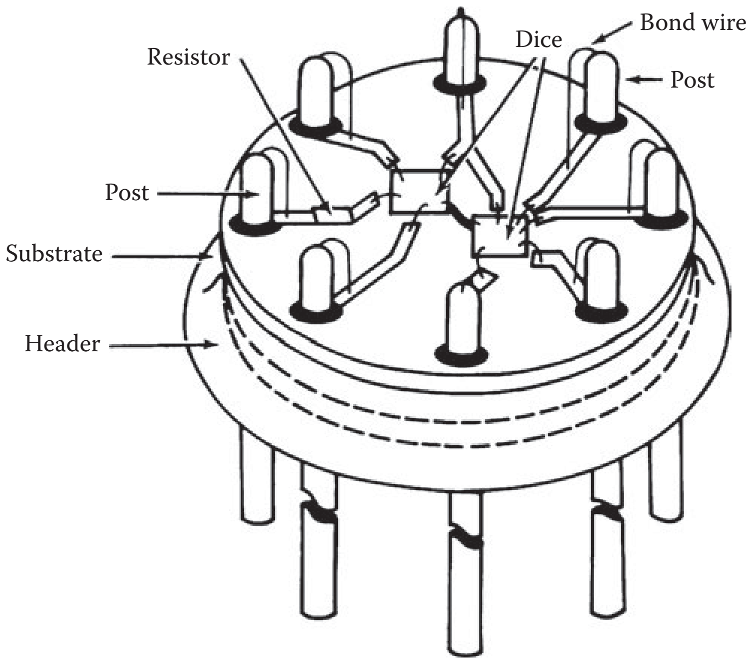


Figure 6.26 Basic construction of a multichip hybrid device. (*After* [1].)

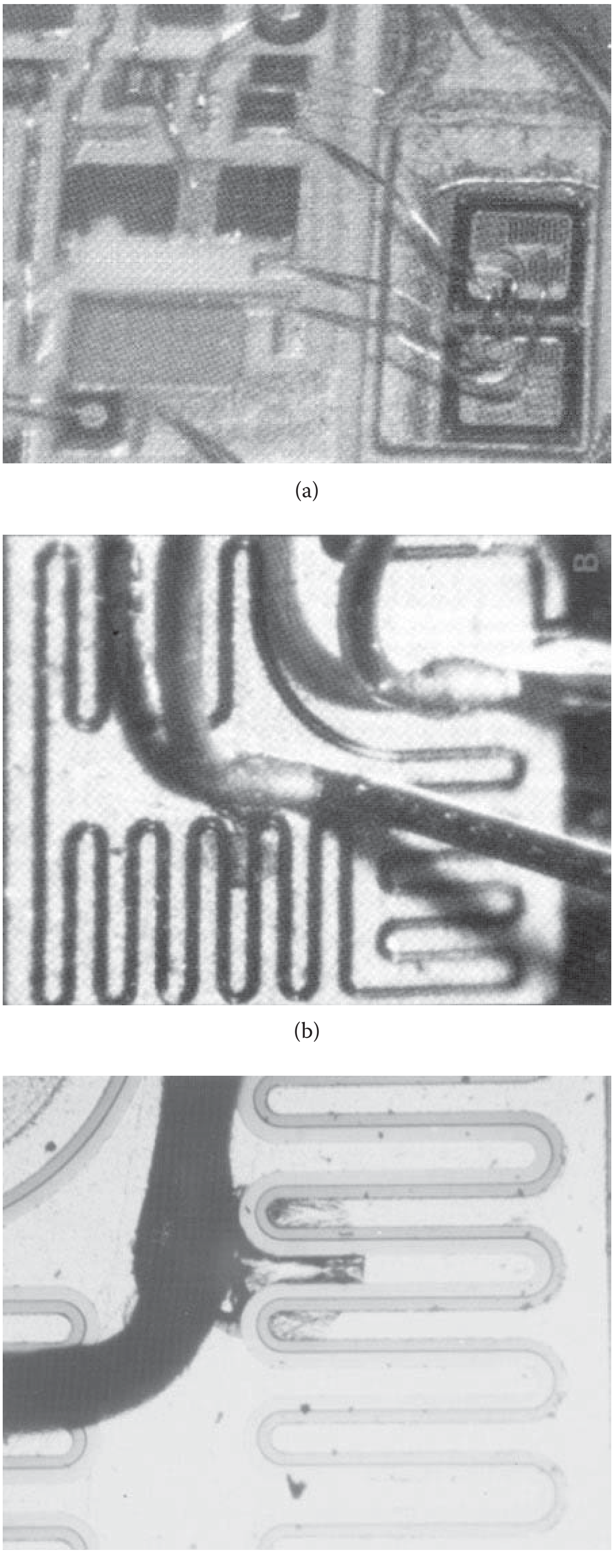


Figure 6.27 Three views of a hybrid voltage regulator that failed because of a damaged pass transistor: (*a*) the overall circuit geometry; (*b*) a closeup of the damaged pass transistor area; (*c*) an enlarged view of the damage point.

The effects of high-voltage breakdown in a hybrid semiconductor chip are illustrated graphically in Figure 6.27*a to c*. Failure analysis indicated that the pass transistor in this voltage regulator device was overstressed because of excessive input/output voltage differential.

6.6.2 Chip Protection

With the push for faster and more complex ICs, it is unlikely that semiconductor manufacturers will return to thicker oxide layers or larger junctions. Overvoltage protection must come, instead, from circuitry built into individual chips to shunt transient energy to ground.

Most MOS circuits incorporate protective networks. These circuits can be made quite efficient, but there is a tradeoff between the amount of protection provided and device speed and packing density. Protective elements, usually diodes, must be physically large if they are to clamp adequately. Such elements take up a significant amount of chip space. The *RC* time constants of protective circuits also can place limits on switching speeds.

Protective networks for NMOS devices typically use MOS transistors as shunting elements, rather than diodes. Although diodes are more effective, fewer diffusions are available in the NMOS process, so not as many forward-biased diodes can be constructed. Off-chip protective measures, including electromagnetic shielding, filters, and discrete diode clamping, are seldom used because they are bulky and expensive.

Figure 6.28 shows the protective circuitry used in a 54HC high-speed *complementary metal-oxide silicon* (CMOS) device. Polysilicon resistors are placed in series with each input pin, and relatively large-geometry diodes are added as clamps on the IC side of the resistors. Clamping diodes also are used at the output. The diodes restrict the magnitude of the voltages that can reach the internal circuitry. Protective features such as these have allowed CMOS devices to withstand ESD test voltages in excess of 2 kV.

6.7 Effects of Arcing

High voltages often are generated by breaking current to an inductor with a mechanical switch. They can, with time, cause pitting, corrosion, or material transfer of the switch contacts. In extreme cases, the contacts even can be welded together. The actual wear (or failure) of a mechanical switch is subject to many factors, including:

- Contact construction and the type of metal used
- Amount of contact bounce that typically occurs with the switching mechanism
- Atmosphere
- Temperature
- Steady-state and in-rush currents
- Whether ac or dc voltages are being switched by the mechanism

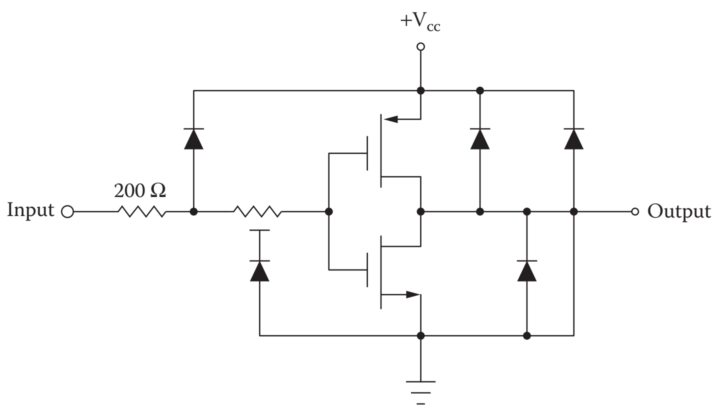


Figure 6.28 CMOS transistor with built-in ESD protection circuitry. (*After* [1].)

Effective transient suppression can significantly reduce the amount of energy dissipated during the operation of switch contacts. This reduction will result in a corresponding increase in switch life. In applications where relay contacts are acting as power-switching elements, the use of effective transient-suppression techniques will reduce the amount of maintenance (contact cleaning) required for the device.

6.7.1 Insulation Breakdown

The breakdown of a solid insulating material usually results in localized carbonization, which may be catastrophic, or may result in decreased dielectric strength at the arc-over point. The occurrence of additional transients often will cause a breakthrough at the weakened point in the insulating material, eventually resulting in catastrophic failure of the insulation. Similar problems can occur within the windings of a transformer or coil. Arcing between the windings of an inductor often is caused by self-induced voltages with steep wavefronts that are distributed unevenly across the turns of the coil. Repetitive arcing between windings can cause eventual failure of the device.

Printed wiring board (PWB) arcing can result in system failure modes in ways outlined for insulating materials and coils. A breakdown induced by high voltage along the surface of a PWB can create a conductive path of carbonized insulation and vaporized metal from the printed wiring traces or component leads.

The greatest damage to equipment from insulation breakdown caused by transient disturbances generally occurs *after* the spike has passed. The *follow-on* steady-state current that can flow through fault paths created by a transient often cause the actual component damage and system failure.

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7

Rectifier and Filter Circuits

7.1 Introduction

The circuit elements most vulnerable to failure in any given piece of electronic hardware are those exposed to the outside world. In most systems, the greatest threat generally involves the ac-to-dc power supply. The power supply is subject to high-energy surges from lightning and other sources. Because power-supply systems often are exposed to extreme voltage and environmental stresses, derating of individual components is a key factor in improving supply reliability. The goal of derating is to reduce the electrical, mechanical, thermal, and other environmental stresses on a component to decrease the degradation rate and to prolong useful life. Through derating, the margin of safety between the operating stress level and the maximum permissible stress level for a given part is increased. This consideration provides added protection from system overstress, unforeseen during design.

Experience has demonstrated that types of components tend to fail in predictable ways. Table 7.1 shows the statistical distribution of failures for a transient-suppression (EMP) protection circuit. Although the data presented applies only to a specific product, some basic conclusions can be drawn:

- The typical failure mode for a capacitor is a short circuit.
- The typical failure mode for a zener diode is a short circuit.
- The typical failure mode for a connector pin is an open circuit.
- The typical failure mode for a solder joint is an open circuit.

These conclusions present no great surprises, but they point out the predictability of equipment failure modes. The first step in solving a problem is knowing what is likely to fail and what the typical failure modes are.

Table 7.1 Statistical Distribution of Component Failures in an EMP Protection Circuit (*After* [1].)

Component	Mode of Failure	Distribution
Capacitor (all types)	Open	0.01
	Short	0.99
Coil	Open	0.75
	Short	0.25
Diode (zener)	Open	0.01
	Short	0.99
GE-MOV	Open	0.01
	Short	0.99
Transzorb	Open	0.01
	Short	0.99
Connector pin	Open	0.99
	Short to ground	0.01
Solder joint	Open	1.00
Lug connection	Open	1.00
Surge protector	Open	0.99
	Short	0.01

7.2 Power Rectifiers

Virtually all power supplies use silicon rectifiers as the primary ac-to-dc converting device. Rectifier parameters generally are expressed in terms of reverse-voltage ratings and mean-forward-current ratings in a ʃ-wave rectifier circuit operating from a 60 Hz supply and feeding a purely resistive load. The three primary reverse-voltage ratings are:

- *Peak transient reverse voltage* (V_{rm}) — the maximum value of any nonrecurrent surge voltage. This value must never be exceeded.
- *Maximum repetitive reverse voltage* [$V_{rm(rep)}$] — the maximum value of reverse voltage that can be applied recurrently (in every cycle of 60 Hz power). This includes oscillatory voltages that may appear on the sinusoidal supply.
- *Working peak reverse voltage* [$V_{rm(wkg)}$] — the crest value of the sinusoidal voltage of the ac supply at its maximum limit. Rectifier manufacturers generally recommend a value that has a significant safety margin, relative to the peak transient reverse voltage (V_{rm}), to allow for transient overvoltages on the supply lines.

There are three forward-current ratings of similar importance in the application of silicon rectifiers:

- *Nonrecurrent surge current* [$I_{fm(surge)}$] — the maximum device transient current that must not be exceeded at any time. $I_{fm(surge)}$ is sometimes given as a single value, but often is presented in the form of a graph of permissible surge-current values vs. time. Because silicon diodes have a relatively small thermal mass, the potential for short-term current overloads must be given careful consideration.
- *Repetitive peak forward current* [$I_{fm(rep)}$] — the maximum value of forward current reached in each cycle of the 60 Hz waveform. This value does not include random peaks caused by transient disturbances.
- *Average forward current* [$I_{fm(av)}$] — the upper limit for average load current through the device. This limit is always well below the repetitive peak forward-current rating to ensure an adequate margin of safety.

Rectifier manufacturers generally supply curves of the instantaneous forward voltage vs. instantaneous forward current at one or more specific operating temperatures. These curves establish the forward-mode upper operating parameters of the device.

Figure 7.1 shows a typical rectifier application in a bridge rectifier circuit.

7.2.1 Operating Rectifiers in Series

High-voltage power supplies (5 kV and greater) often require rectifier voltage ratings well beyond those typically available from the semiconductor industry. To meet the requirements of the application, manufacturers commonly use silicon diodes in a series configuration to yield the required working peak reverse voltage. For such a configuration to work properly, the voltage across any one diode must not exceed the

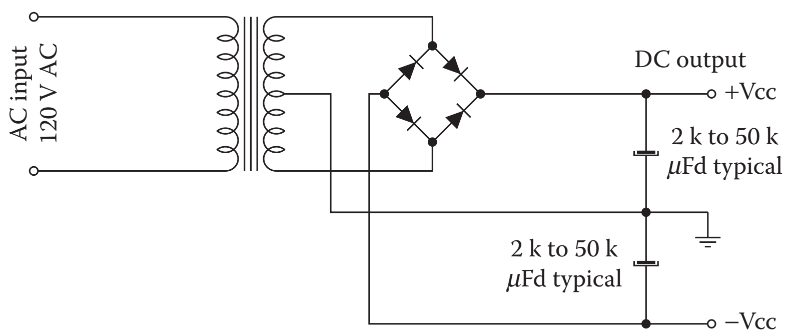

Figure 7.1 Conventional capacitor input filter full-wave bridge.

rated peak transient reverse voltage (V_{rm}) at any time. The dissimilarity commonly found between the reverse leakage current characteristics of different diodes of the same type number makes this objective difficult to achieve. The problem normally is overcome by connecting shunt resistors across each rectifier in the chain, as shown in Figure 7.2. The resistors are chosen so that the current through the shunt elements (when the diodes are reverse-biased) will be several times greater than the leakage current of the diodes themselves.

The *carrier storage* effect also must be considered in the use of a series-connected rectifier stack. If precautions are not taken, different diode recovery times (caused by the carrier storage phenomenon) will effectively force the full applied reverse voltage across a small number of diodes, or even a single diode. This problem can be prevented by connecting small-value capacitors across each diode in the rectifier stack. The capacitors equalize the transient reverse voltages during the carrier storage recovery periods of the individual diodes.

Figure 7.3 illustrates a common circuit configuration for a high-voltage, three-phase rectifier bank. A photograph of a high-voltage, series-connected, three-phase rectifier assembly is shown in Figure 7.4.

7.2.2 Operating Rectifiers in Parallel

Silicon rectifiers are used in a parallel configuration when a large amount of current is required from the power supply. Parallel assemblies normally are found in low-voltage, high-current supplies. *Current sharing* is the major design problem with a parallel rectifier assembly because diodes of the same type number do not necessarily exhibit the same forward characteristics.

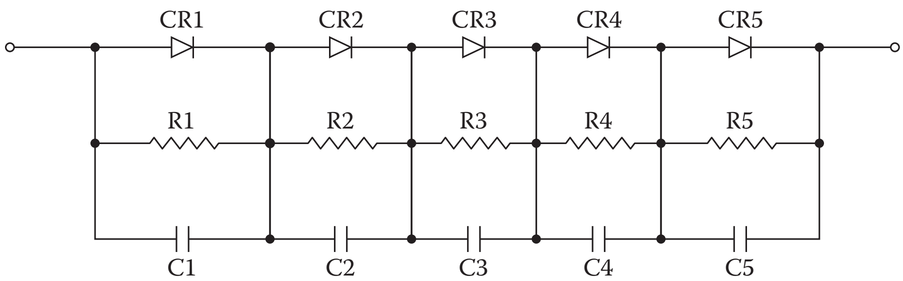

Figure 7.2 A portion of a high-voltage, series-connected rectifier stack.

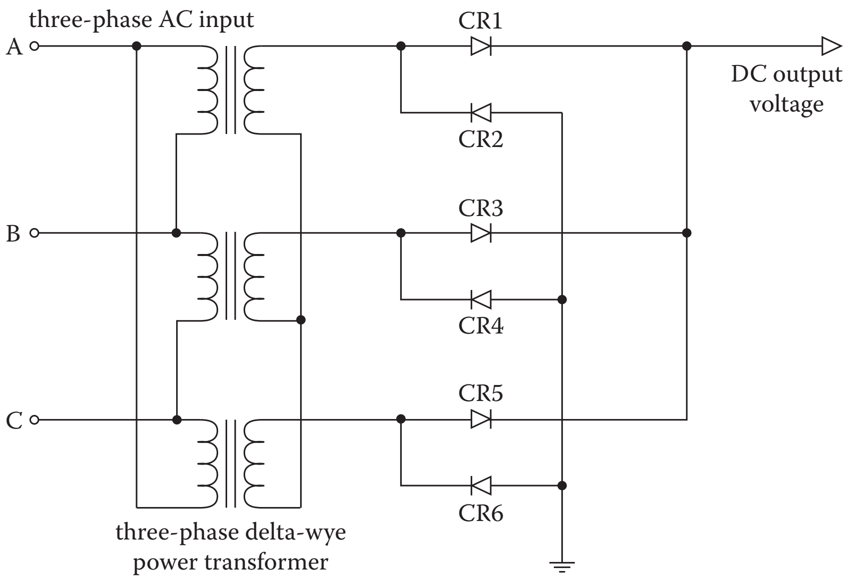

Figure 7.3 Three-phase, delta-connected high-voltage rectifier.

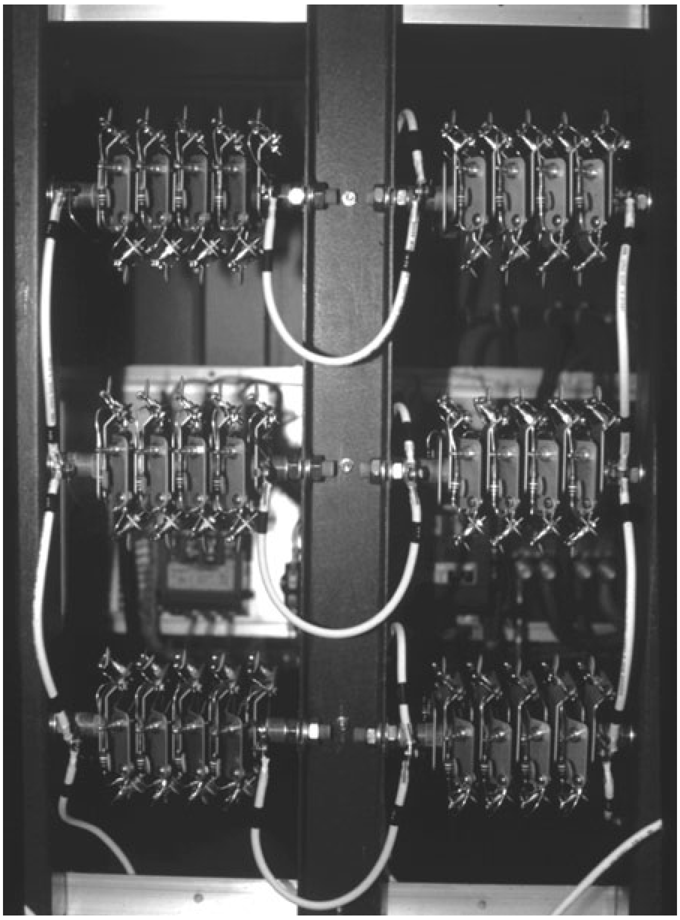

Figure 7.4 High-voltage rectifier assembly for a three-phase, delta-connected circuit.

Semiconductor manufacturers often divide production runs of rectifiers into tolerance groups, matching forward characteristics of the various devices. When parallel diodes are used, devices from the same tolerance group must be selected to avoid unequal sharing of the load current. As a margin of safety, designers allow a substantial derating factor for devices in a parallel assembly to ensure that the maximum operating limits of any one component are not exceeded.

The problems inherent in a parallel rectifier assembly can be reduced through the use of a resistance or reactance in series with each component, as shown in Figure 7.5. The build-out resistances (R_1 through R_4) force the diodes to share the load current equally. Such assemblies can, however, be difficult to construct and may be more expensive than simply adding diodes or going to higher-rated components. Power loss issues must also be considered with this approach.

7.2.3 Silicon Avalanche Rectifiers

The silicon avalanche diode is a special type of rectifier that can withstand high reverse power dissipation. For example, an avalanche diode with a normal forward rating of 10 A can dissipate a reverse transient of 8 kW for 10 ms without damage. This characteristic of the device allows elimination of the surge-absorption capacitor and voltage-dividing resistor networks needed when conventional silicon diodes are used in a series rectifier assembly. Because fewer diodes are needed for a given applied reverse voltage, significant underrating of the device (to allow for reverse voltage transient peaks) is not required.

When an extra-high-voltage rectifier stack is used, it is still advisable to install shunt capacitors — but not resistors — in an avalanche diode assembly. The capacitors are designed to compensate for the effects of carrier storage and stray capacitance in a long series assembly.

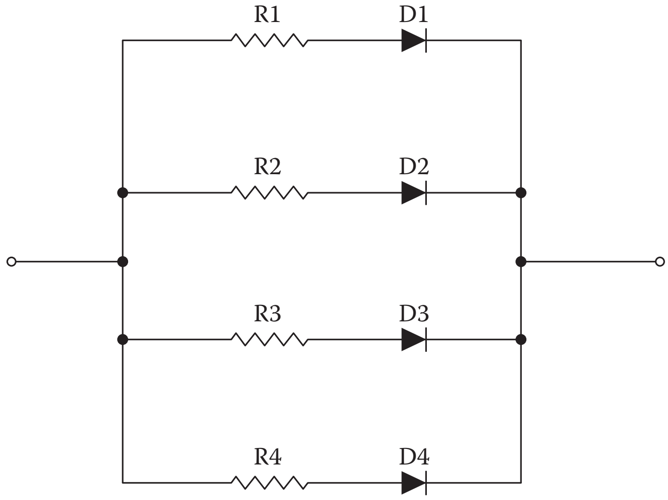

Figure 7.5 Using build-out resistances to force current sharing in a parallel rectifier assembly.

7.2.4 Single-Phase Rectifier Configurations

Rectifiers are one of the building blocks of ac power systems. Diodes are used to form rectifiers in electronic power supplies using one of four basic circuits:

- Half-wave
- Full-wave
- Bridge
- Voltage multiplier

7.2.4.1 Half-Wave Rectifier

The half-wave rectifier circuit is shown in Figure 7.6*a* [2]. When the input sinusoid voltage at *A* goes positive, the diode conducts, resulting in current in the load resistor *R*. When the input voltage goes negative, the diode becomes reverse-biased and, hence, does not conduct, resulting in negligible current across *R*. Therefore, the output voltage is given by

$$V_O = 0, \text{ if } V_i < \mathrm{V}_{DO} \tag{7.1}$$

$$V_O = R \,/\, (R + r_D)\; V_i - V_{DO}\, \mathrm{R} \,/\, (R + r_D) \tag{7.2}$$

where

V_i = The input voltage
V_{DO} = Diode forward voltage ≅ 0.7to 0.8 V
r_D = Diode resistance

Figure 7.6*b* shows the output voltage waveform for a sinusoidal input voltage. If $R >> r_D$, then Equation 7.2 simplifies to

$$V_O \cong V_i - V_{DO} \tag{7.3}$$

The following general aspects must be considered when designing a half-wave diode power supply:

- The current- or power-handling capability of the diode.
- The peak inverse voltage (PIV) that the diode must be able to withstand without breakdown. When the input voltage goes negative, the diode becomes reverse-biased and the input voltage V_S appears across the diode.

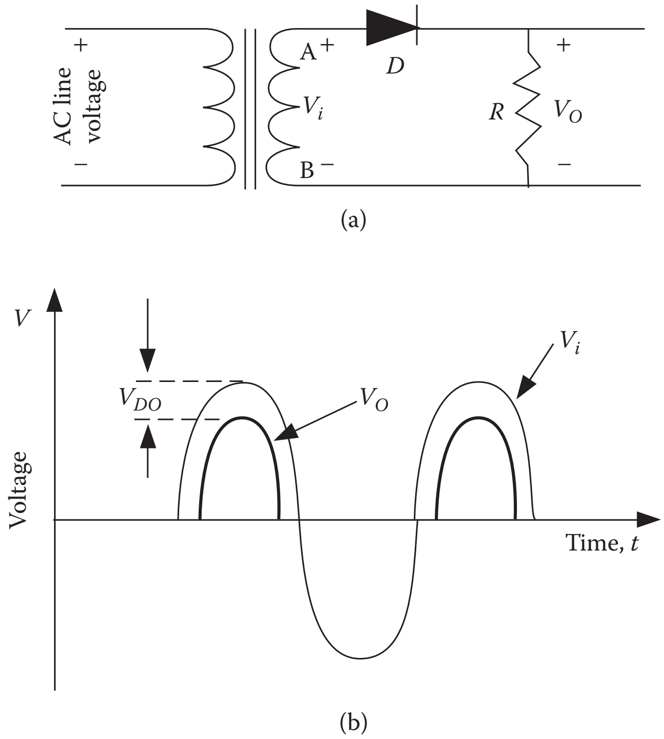

Figure 7.6 Half-wave rectifier circuit: (*a*) schematic diagram, (*b*) input and output waveforms. (*From* [2]. *Used with permission.*)

7.2.4.2 Full-Wave Rectifier

The full-wave rectifier utilizes both halves of the input sinusoid [2]. One common implementation is shown in Figure 7.7*a*. The full-wave rectifier consists of two half-wave rectifiers connected to a load *R*. The secondary transformer winding is center tapped to provide two equal voltages V_i for each half-wave rectifier. When the node *A* is at positive polarity, V_i with respect to node *B*, D_1 will be forward-biased and D_2 will be reverse-biased. Therefore, diode D_1 will conduct and the current will flow through *R* back to the center tap of the transformer. When the node *B* is at positive polarity V_i with respect to node *A*, D_2 will be forward-biased and diode D_1 will be reverse-biased. The current conducted by D_2 will flow through *R* and back to center tap. The current through *R* is always in the same direction, giving rise to unipolar voltage V_O across *R*. The input and output voltage waveforms of the full-wave rectifier are shown in Figure 7.7*b*.

The output voltage of the full-wave rectifier is given by

$$V_0 = \left[\frac{R}{R_t + r_D + R}\right]\left(V_S - V_{D0}\right) \tag{7.4}$$

where R_t = resistance associated with the transformer. The dc value of the output voltage V_{dc} is

$$V_{dc} \cong 2\left[\frac{R}{R_t + r_D + R}\right]\frac{V_m}{\pi} \tag{7.5}$$

$$V_{dc} = \frac{2V_m}{\pi} \text{ if R} >> R + r_D + r_i \tag{7.6}$$

where V_m = the peak output voltage.

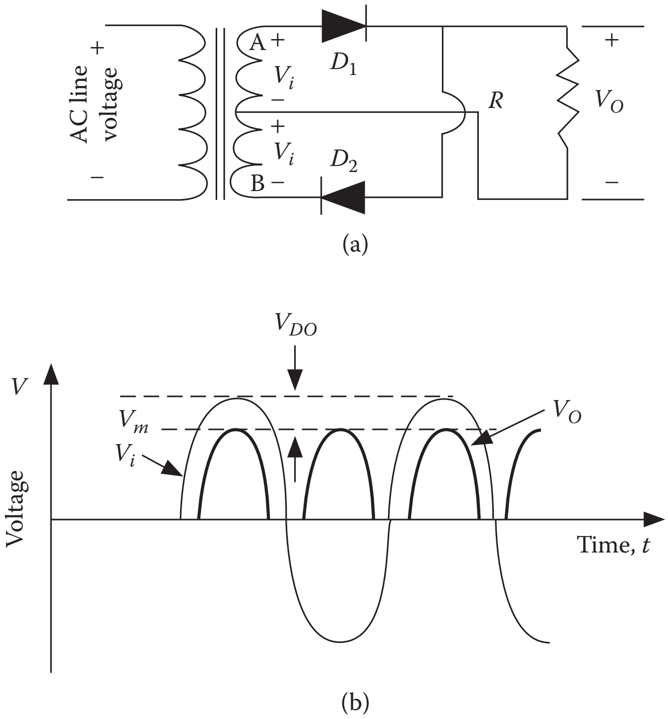

Figure 7.7 Full-wave rectifier circuit: (*a*) schematic diagram, (*b*) input and output waveforms. (*From* [2]. *Used with permission.*)

Thus, the full-wave rectifier produces double the output voltage of the half-wave rectifier. The ripple content r of the full-wave rectifier is given by

$$r = \left[\frac{\pi^2}{8} - 1\right]^{1/2} = 0.483 \tag{7.7}$$

The ripple factor for a full-wave rectifier is significantly less than that of a half-wave rectifier.

Another important element to be considered in the design of a full wave rectifier is the peak inverse voltage rating of the diodes. During the positive half-cycle, diode D_1 is conducting and D_2 is cut off. The voltage at the cathode of D_2 will be at its maximum when V_O is at its peak value of $(V_i - V_{DO})$ and V_i at its peak value. Therefore, the peak inverse voltage, $PIV = 2V_i - V_{DO}$, is approximately twice that of the half-wave rectifier.

7.2.4.3 Bridge Rectifier

The full-wave rectifier requires a center-tapped transformer. The bridge rectifier is an alternative implementation of the full-wave circuit [2]. (See Figure 7.8*a*.) This rectifier uses four diodes and does not require a center-tapped transformer. Figure 7.8*b* shows the input and output voltage waveforms for the bridge rectifier. During the positive half cycles of the input voltage, V_i is positive and the current is conducted through diode D_1, resistor R, and diode D_2. Meanwhile, diodes D_3 and D_4 will be reverse-biased. During the positive half-cycle, because two diodes are conducting, the output voltage will be $V_i - 2V_{DO}$. During the negative half-cycle, the voltage V_i will be negative, and diodes D_3 and D_4 are forward-biased; the current through R follows the same direction as in the case of the positive half-cycle.

During positive halfcycle, the reverse voltage across D_3 can be determined from the loop formed by D_3, R, and D_2 as

$$V_{D3}\ (\text{reverse}) = V_O + V_{D2}\ (\text{forward}) \tag{7.8}$$

The maximum value of V_{D3} occurs at the peak of V_O and is given by

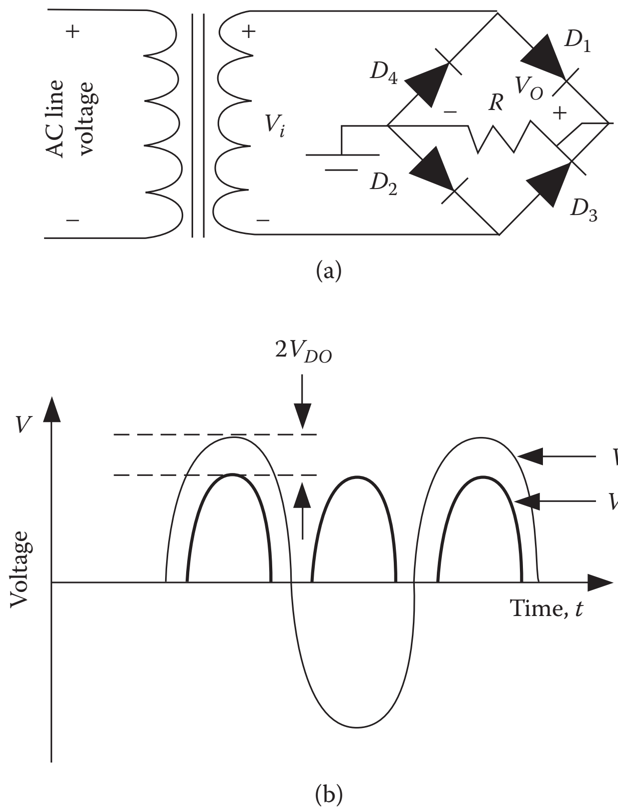

Figure 7.8 Bridge rectifier circuit: (*a*) schematic diagram, (*b*) input and output waveforms. (*From* [2]. *Used with permission*.)

$$PIV = V_i - 2V_{DO} + V_{DO} \tag{7.9}$$

$$PIV = V_i - V_{DO} \tag{7.10}$$

The PIV is about half the value for the full-wave rectifier with a center-tapped transformer, which is an advantage of the bridge rectifier.

7.2.4.4 Voltage Multiplier

The dc output voltage (V_{dc}) in a rectifier circuit is limited by the peak value of the ac voltage applied (V_I) [2]. Figure 7.9*a* shows the voltage doubler circuit composed of a *clamp* formed by C_1 and D_1 and a *peak rectifier* formed by D_2 and C_2. When excited by a sinusoid of amplitude V_p, the output of the clamping section reaches the negative peak value of $-2V_p$, as shown in Figure 7.9*b*. By connecting additional diode-capacitor circuits, it is possible to generate rectifier circuits that triple and quadruple the input voltage.

7.2.5 Polyphase Rectifier Circuits

High-voltage power supplies typically used in vacuum tube circuits incorporate multiphase rectification of the ac line voltage. Common configurations include 3-, 6-, and 12-phase. Three-phase rectification is the most common. Figure 7.10 illustrates four approaches to three-phase rectification:

- *Three-phase half-wave wye*, Figure 7.10*a*. Three half-wave rectifiers are used in each leg of the secondary Y, forming one phase. In such an arrangement, each diode carries current one third of each cycle, and the output wave pulses at three times the frequency of the ac supply. In order to avoid direct-current saturation in the transformer, it is necessary to employ a three-phase transformer rather than three single-phase transformers.

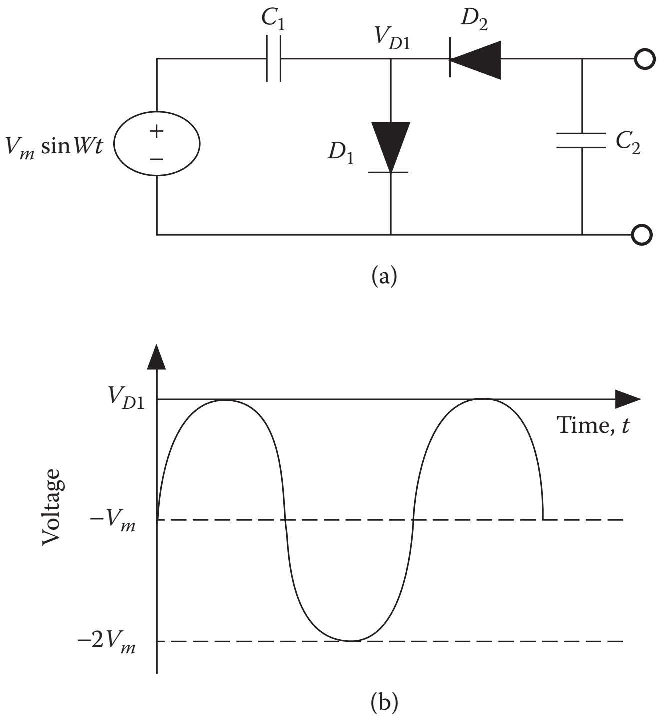

Figure 7.9 Voltage doubler circuit: (*a*) schematic diagram, (*b*) input and output waveforms. (*From* [2]. *Used with permission.*)

- *Three-phase full-wave bridge*, Figure 7.10*b*. Six diodes are used in this circuit to produce a low ripple output with a frequency of 6 times the input ac waveform. It is permissible in this configuration to use three single-phase transformers, if desired.
- *Six-phase star*, Figure 7.10*c*. This circuit, also known as a *three-phase diametric* configuration, uses six diodes with a transformer secondary configured as a star, as illustrated in the figure. The output ripple frequency is six times the input ac waveform.
- *Three-phase double-wye*, Figure 7.10*d*. This circuit uses six diodes and a complicated configuration of transformer windings. Note the balance coil (*interphase transformer*) in the circuit.

The relative merits of these rectifier configurations are listed in Table 7.2.

Polyphase rectifiers are used when the dc power required is on the order of 2 kW or more. The main advantages of a polyphase power supply over a single-phase supply include the following:

- Division of the load current between three or more lines to reduce line losses.
- Significantly reduced filtering requirements after rectification because of the low ripple output of a polyphase rectifier.
- Improved voltage regulation when using an inductive-input filter. Output voltage *soaring* is typically 6% or less from full load to no load conditions.
- Greater choice of output voltages from a given transformer by selection of either a delta or wye configuration.

The main disadvantage of a polyphase system is its susceptibility to phase imbalance. Resulting operational problems include increased ripple at the output of the supply and uneven sharing of the load current by the transformer windings.

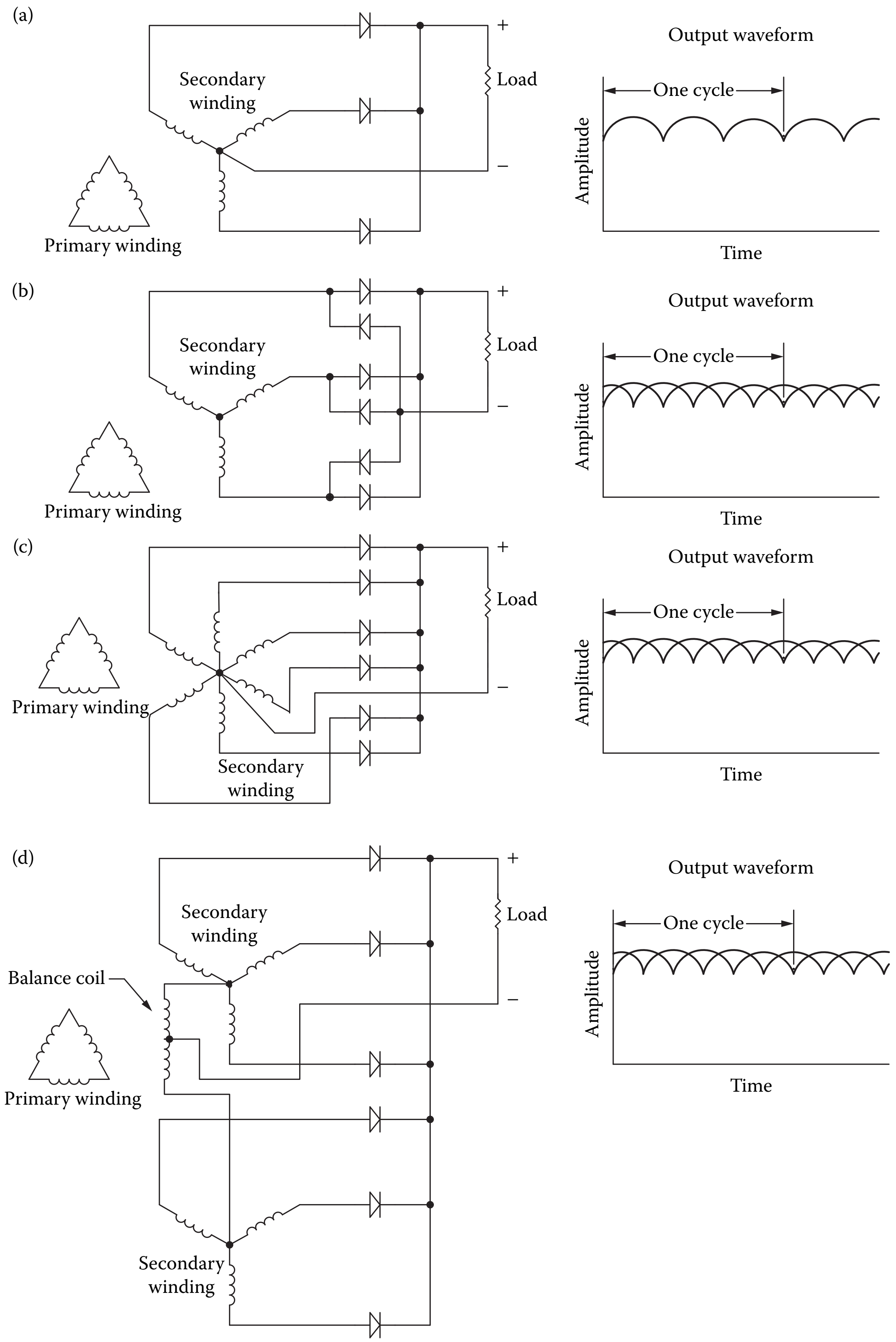

Figure 7.10 Basic three-phase rectifier circuits: (*a*) half-wave wye, (*b*) full-wave bridge, (*c*) six-phase star, (*d*) three-phase double-wye.

Table 7.2 Operating Parameters of Three-Phase Rectifier Configurations

Parameter	Three-Phase Star	Three-Phase Bridge	Six-Phase Star	Three-Phase Double-Wye	Multiplier[1]
Rectifier elements	3	6	6	6	
rms dc output	1.02	1.00	1.00	1.00	Average dc output
Peak dc output	1.21	1.05	1.05	1.05	Average dc output
Peak reverse volts per rectifier	2.09	1.05	2.09	2.42	Average dc output
output	2.45	2.45	2.83	2.83	rms secondary volts per transformer leg
	1.41	1.41	1.41	1.41	rms secondary volts line-to-line
Average dc output current per rectifier	0.333	0.333	0.167	0.167	Average dc output current
rms current per rectifier, resistive load	0.587	0.579	0.409	0.293	Average dc output current
rms current per rectifier, inductive load	0.578	0.578	0.408	0.289	Average dc output current
Percent ripple	18.3	4.2	4.2	4.2	—
Ripple frequency	3	6	6	6	Line frequency
ac line power factor	0.826	0.955	0.955	0.955	—
Transformer secondary rms volts per leg[2]	0.855	0.428	0.740	0.855	Average dc voltage output
Transformer secondary rms volts line-to-line	1.48	0.740	1.48 (max)	1.71 (max)	Average dc voltage output no load
Secondary line current	0.578	0.816	0.408	0.299	Average dc output current
Transformer secondary VA	1.48	1.05	1.81	1.48	dc watts output
Primary line current	0.817	1.41	0.817	0.707	(Avg. load I × secondary leg V) ÷ primary line V

[1] To determine the value of a parameter in any column, multiply the factor shown by the value given in this column.
[2] For inductive load or large choke input filter.

7.3 Power Supply Filter Circuits

A filter network for a high-voltage power supply typically consists of a series inductance and one or more shunt capacitances [3]. Bleeder resistors are also usually incorporated. Filter systems can be divided into two basic types:

- *Inductive input*, filter circuits that present a series inductance to the rectifier output.
- *Capacitive input*, filter circuits that present a shunt capacitance to the rectifier output.

7.3.1 Inductive Input Filter

An inductive input filter is shown in Figure 7.11, along with typical current waveforms [3]. When the input inductance is infinite, current through the inductance is constant and is carried at any moment by the rectifier anode that has the most positive voltage applied to it at that instant. As the alternating voltage being rectified passes through zero, the current suddenly transfers from one anode to another, producing square current waves through the individual rectifier devices.

When the input inductance is finite (but not too small), the situation changes to that shown by the solid lines of Figure 7.11. The current through the input inductance tends to increase when the output voltage of the rectifier exceeds the average or dc current value, and to decrease when the rectifier output voltage is less than the dc value. This causes the current through the individual anodes to be modified as shown. If the input inductance is too small, the current decreases to zero during a portion of the time between the peaks of the rectifier output voltage, and the conditions then correspond to a capacitor input filter system.

The output wave of the rectifier can be considered as consisting of a dc component upon which are superimposed ac voltages (*ripple voltages*). To a first approximation, the fluctuation in output current resulting from a finite input inductance can be considered as the current resulting from the lowest frequency component of the ripple voltage acting against the impedance of the input inductance. This assumption is permissible because the higher frequency components in the ripple voltage are smaller and at the same time encounter higher impedance. Furthermore, in practical filters, the shunting capacitor

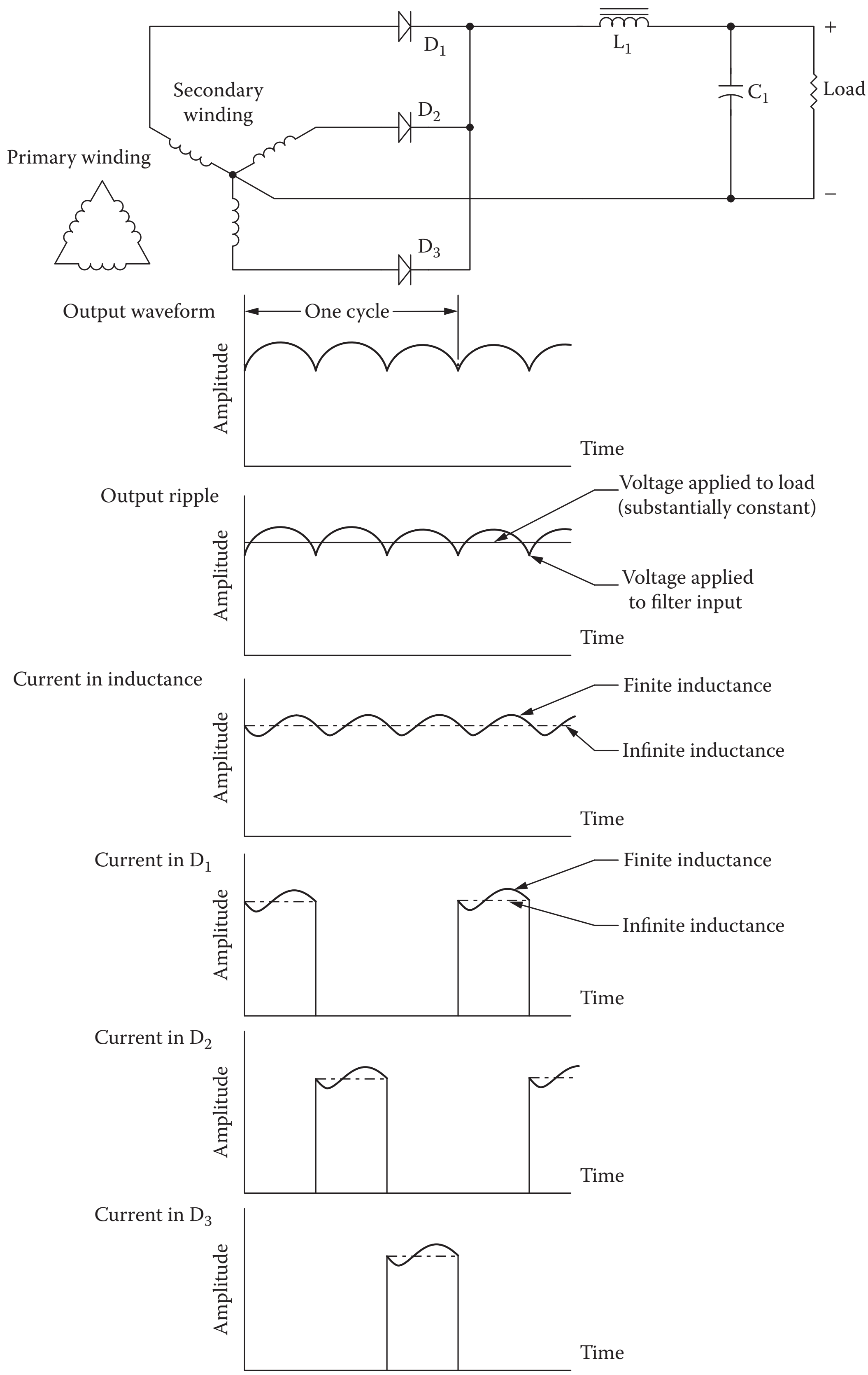

Figure 7.11 Voltage and current waveshapes for an inductive input filter driven by a three-phase supply.

following the input inductance has a small impedance at the ripple frequency compared with the reactance of the input inductance. The peak current resulting from a finite input inductance is, therefore, given approximately by the relation:

$$\frac{I_f}{I_i} = 1 + \frac{E_1 R_{eff}}{E_0 \omega L_1} \tag{7.11}$$

where

I_f = Peak current with finite input inductance
I_i = Peak current with infinite input inductance
E_1/E_0 = Ratio of lowest frequency ripple component to the dc voltage in the rectifier output
R_{eff} = Effective load resistance
ωL_1 = Reactance of the incremental value of the input inductance at the lowest ripple frequency

This equation is derived as follows:

- The peak alternating current through the input inductance is approximately $E_1/\omega L_1$.
- The average or dc current is E_0/R_{eff}.
- The peak current with finite inductance is, therefore, $(E_1/\omega L_1) + (E_0/R_{eff})$.
- The current with infinite inductance is E_0/R_{eff}.
- The effective load resistance value consists of the actual load resistance plus filter resistance plus equivalent diode and transformer resistances.

The normal operation of an inductive input filter requires that there be a continuous flow of current through the input inductance. The peak alternating current flowing through the input inductance must, therefore, be less than the dc output current of the rectifier. This condition is realized by satisfying the approximate relation

$$\omega L_1 = R_{eff} \frac{E_1}{E_0} \tag{7.12}$$

In the practical case of a 60 Hz single-phase, full-wave rectifier circuit, the foregoing equation becomes

$$L_1 = \frac{L_{eff}}{1130} \tag{7.13}$$

In a polyphase system, the required value of L_1 is significantly less. The higher the load resistance (the lower the dc load current), the more difficult it is to maintain a continuous flow of current, and with a given L_1, the previous equation will not be satisfied when the load resistance exceeds a critical value.

The minimum allowable input inductance (ωL_1) is termed the *critical inductance*. When the inductance is less than the critical value, the filter acts as a capacitor input circuit. When the dc drawn from the rectifiers varies, it is still necessary to satisfy the ωL_1 equation at all times, particularly if good voltage regulation is to be maintained. To accomplish this requirement at small load currents without excessive inductance, it is necessary to place a bleeder resistance across the output of the filter system in order to limit R_{eff} to a value corresponding to a reasonable value of L_1.

7.3.2 Capacitive Input Filter

When a shunt capacitance rather than a series inductance is presented to the output of a rectifier, the behavior of the circuit is greatly modified [3]. Each time the positive crest alternating voltage of the transformer is applied to one of the rectifier anodes, the input capacitor charges up to just slightly less than this peak voltage. The rectifier then ceases to deliver current to the filter until another anode approaches its peak positive potential, when the capacitor is charged again. During the interval when the voltage across the input capacitor is greater than the potential of any of the anodes, the voltage across the input capacitor drops off nearly linearly with time, because the first filter inductance draws a substantially constant current from the input capacitor. A typical set of voltage and current waves is illustrated in Figure 7.12.

The addition of a shunt capacitor to the input of a filter thus produces fundamental changes in behavior, including:

- The output voltage is appreciably higher than with an inductance input.
- The ripple voltage is lower with a capacitive input filter than an inductive input filter.
- The dc voltage across the filter input drops as the load current increases for the capacitive-input case, instead of being substantially constant, as for the inductive input case.
- The ratio of peak-to-average anode current at the rectifiers is higher in the capacitive case.
- The utilization factor of the transformer is lower with a capacitive input configuration.

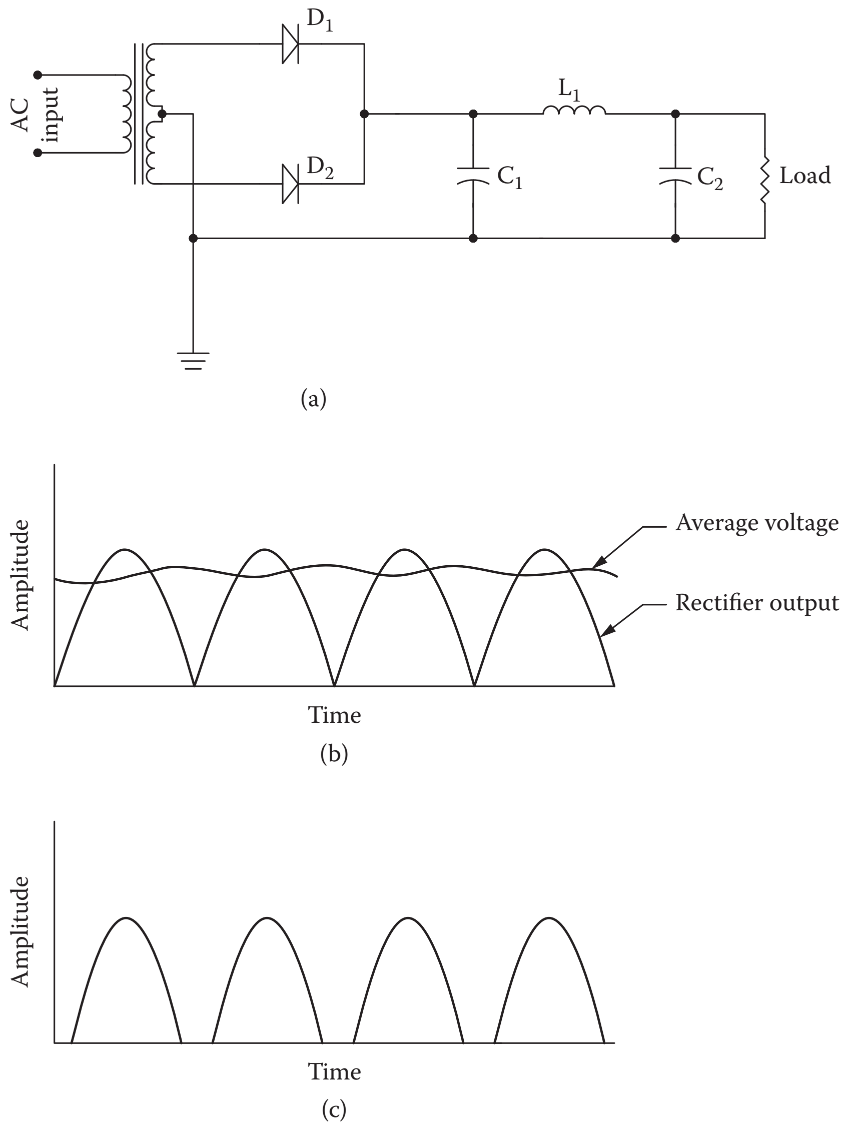

Figure 7.12 Characteristics of a capacitive input filter circuit: (*a*) schematic diagram, (*b*) voltage waveshape across input capacitor, (*c*) waveshape of current flowing through diode.

Filters incorporating shunt capacitor inputs are generally employed when the amount of dc power required is small. Inductance input filters are used when the amount of power involved is large; the higher utilization factor and lower peak current result in important savings in rectifier and transformer costs under these conditions. Inductance input systems are almost universally employed in polyphase rectifier applications.

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8

Power Electronics

8.1 Introduction

The modern age of power electronics began with the introduction of thyristors in the late 1950s [1]. There are now a number of power devices available for high-power and high-frequency applications. The most notable include:

- *Gate turn-off* (GTO) thyristor
- Power Darlington transistor
- Power MOSFET
- *Insulated-gate bipolar transistor* (IGBP)

These power devices are used primarily as switches to convert energy from one form to another. They are used in motor control systems, uninterruptible power supplies, high-voltage dc transmission, ac-to-dc power supplies, induction heating, and other power-conversion applications.

8.2 Thyristor Devices

The thyristor, also called a *silicon-controlled rectifier* (SCR), is basically a four-layer three-junction pnpn device [1]. It has three terminals: anode, cathode, and gate. The device is turned on by applying a short pulse across the gate and cathode. After the device turns on, the gate loses its control to turn off the device. The turn-off is achieved, instead, by applying a reverse voltage across the anode and cathode. The thyristor volt ampere characteristics are shown in Figure 8.1.

There are basically two classifications of thyristors: *converter grade* and *inverter grade*. The difference between a converter-grade and an inverter-grade thyristor is the low turn-off time (on the order of a few microseconds) for the latter. Converter-grade thyristors are slower and are used in *natural commutation* (or phase-controlled) applications. Inverter-grade thyristors are used in *forced commutation* applications such as dc-dc choppers and dc-ac inverters. Inverter-grade thyristors are turned off by forcing the current to zero using an external commutation circuit. This requires additional commutating components, thus resulting in additional losses in the inverter.

Thyristors are rugged devices in terms of transient currents (*di/dt* and dv/dt capability). The forward voltage drop in a thyristor typically is about 1.5 to 2 V; even at high currents on the order of 500 A, it seldom exceeds 3 V. Although the forward voltage determines the on-state power loss of the device at any given current, the switching power loss becomes a dominating factor affecting the device junction temperature at high operating frequencies. Thus, the maximum switching frequencies possible using thyristors are limited in comparison with many other power devices. Thyristors are commonly available at ratings of up to 6000 V, 3500 A.

A *triac* is functionally a pair of converter-grade thyristors connected in an antiparallel arrangement. The triac volt-ampere characteristics are shown in Figure 8.2. Because of the physical integration of the device, the triac has poor reapplied dv/dt capability, poor gate current sensitivity at turn-on, and a longer turn-off time, relative to a pair of equivalent-rating thyristors. Triacs are mainly used in phase control applications such as ac regulators for lighting and fan control, and in solid-state ac relays.

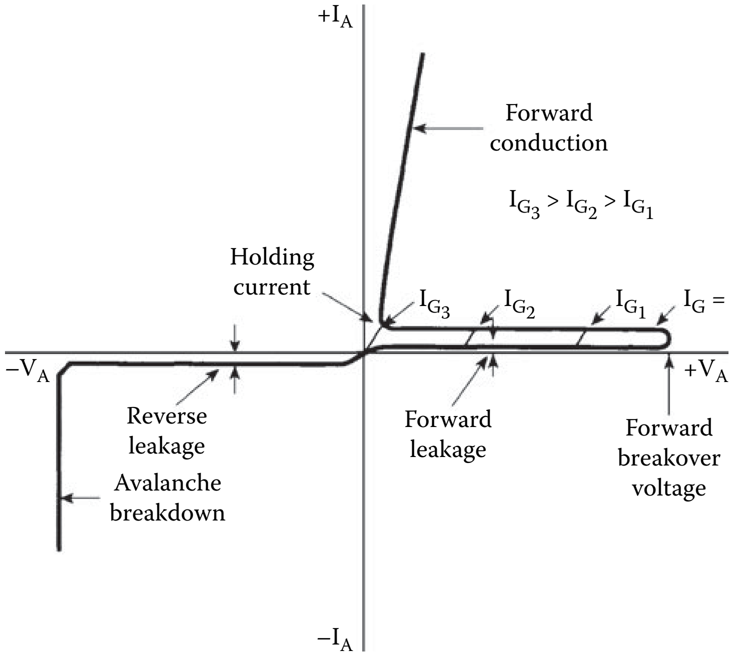

Figure 8.1 Voltampere characteristics of a thyristor. (*After* [1] *and* [2].)

8.2.1 Thyristor Servo Systems

Thyristor control of ac power has become a popular method of switching and regulating high-voltage or high-current power supplies. The type of servo system employed depends on the application. Figure 8.3 shows a basic single-phase ac control circuit using discrete thyristors. The rms load current (I_{rms}) at any specific phase delay angle (θ) is given in terms of the normal full-load rms current at a phase delay of zero ($I_{rms\text{-}0}$):

$$I_{rms} = I_{rms} - 0\left[1 - \frac{\alpha}{\pi} + (2\pi)^{-1}\sin 2\pi\right]\frac{1}{2} \qquad (8.1)$$

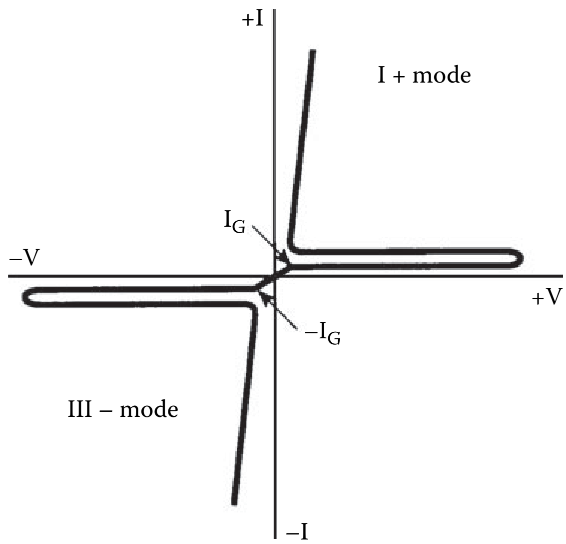

Figure 8.2 Voltampere characteristics of a triac. (*After* [1] *and* [2].)

The load rms voltage at any particular phase-delay angle bears the same relationship to the full-load rms voltage at zero phase delay as the previous equation illustrates for load current. An analysis of the mathematics shows that although the theoretical delay range for complete control of a resistive load is 0 to 180°, a practical span of 20 to 160° gives a power-control range of approximately 99% to 1% of maximum output to the load. Figure 8.4 illustrates typical phase-control waveforms.

The circuit shown in Figure 8.3 requires a source of gate trigger pulses that must be isolated from each other by at least the peak value of the applied ac voltage. The two gate pulse trains must also be phased 180° with respect to each other. Furthermore, the gate pulse trains must shift together with respect to the ac supply voltage phase when power throughput is adjusted.

Some power-control systems use two identical, but isolated, gate pulse trains operating at a frequency of twice the applied supply voltage (120 Hz for a 60 Hz system). Under such an arrangement, the forward-biased thyristor will fire when the gate pulses are applied to the SCR pair. The reverse-biased thyristor will not fire. Normally, it is considered unsafe to drive a thyristor gate positive while its

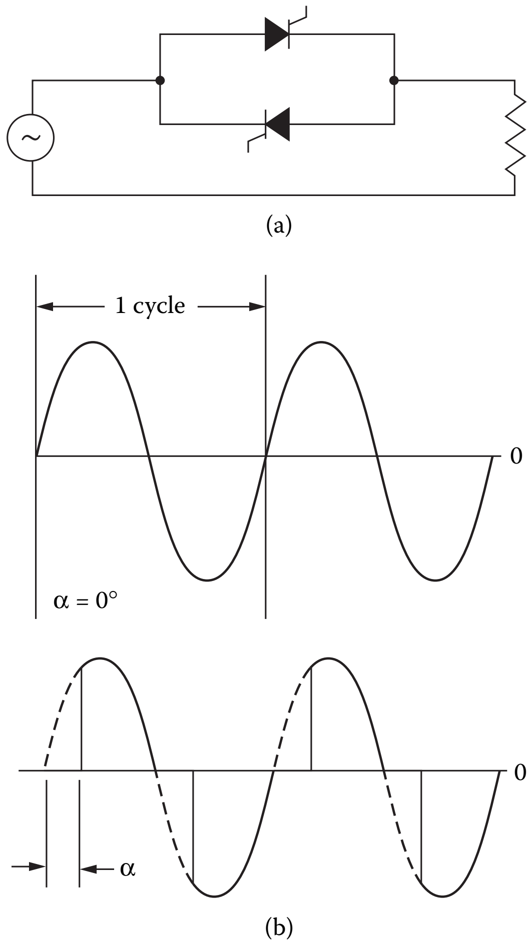

Figure 8.3 Inverse-parallel thyristor ac power control: (*a*) circuit diagram; (*b*) voltage and current waveforms for full and reduced thyristor control angles. The waveforms apply for a purely resistive load.

anode-cathode is reverse-biased. In this case, however, it may be permissible because the thyristor that is fired immediately conducts and removes the reverse voltage from the other device. The gate of the reverse-biased device is then being triggered on a thyristor that essentially has no applied voltage.

8.2.1.1 Inductive Loads

The waveforms shown in Figure 8.5 illustrate effects of phase control on an inductive load. When inductive loads are driven at a reduced conduction angle, a sharp transient change of load voltage occurs at the end of each current pulse (or loop). The transients generally have no effect on the load, but they can be dangerous to proper operation of the thyristors. When the conducting thyristor turns off, thereby disconnecting the load from the ac line supply, the voltage at the load rapidly drops to zero. This rapid voltage change, in effect, applies a sharply rising positive anode voltage to the thyristor opposing the device that has been conducting. If the thyristor dv/dt rating is exceeded, the opposing device will turn on and conduction will take place, independent of any gate drive pulse.

A common protective approach involves the addition of a resistor-capacitor (*RC*) snubber circuit to control the rate of voltage change seen across the terminals of the thyristor pair. (See Figure 8.6.) Whenever a thyristor pair is used to drive an inductive load, such as a power transformer, it is critically important that each device fires at a point in the applied waveform exactly 180° relative to the other. If proper timing is not achieved, the positive and negative current loops will differ in magnitude, causing a dc current to flow through the primary side of the transformer. A common trigger control circuit should, therefore, be used to determine gate timing for thyristor pairs.

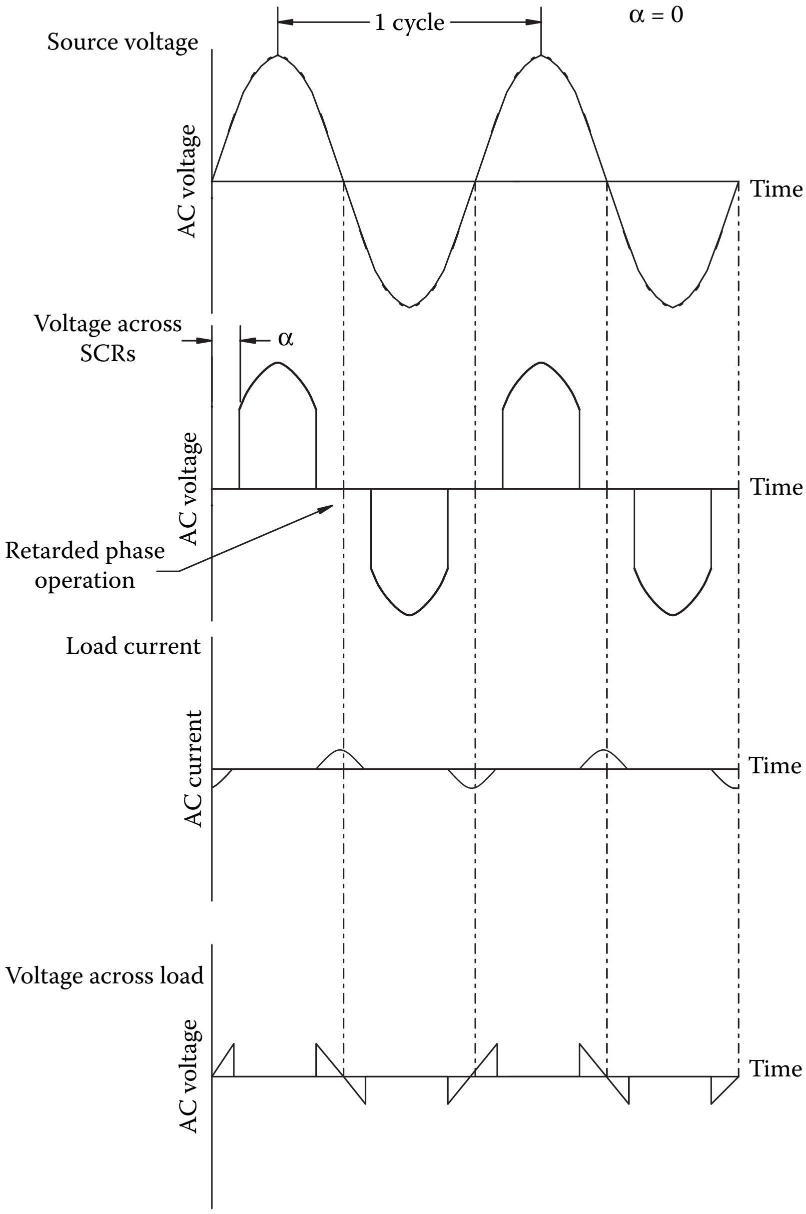

Figure 8.4 Waveforms in an ac circuit using thyristor power control.

8.2.1.2 Applications

Several approaches are possible for thyristor power control in a three-phase ac system. The circuit shown in Figure 8.7 consists of essentially three independent, but interlocked, single-phase thyristor controllers. This circuit is probably the most common configuration found in industrial equipment.

In a typical application, the thyristor pairs feed a power transformer with multitap primary windings, thereby giving the user an adjustment range to compensate for variations in utility company line voltages from one location to another. A common procedure specifies selection of transformer tap positions that yield a power output of 105% when nominal utility company line voltages are present. The thyristor power-control system then is used to reduce the angle of conduction of the SCR pairs as necessary to cause a reduction in line voltage to the power transformer to yield 100% rated power output from the power supply. A servo loop from a sample point at the load can be used to automatically compensate for line-voltage variations. With such an arrangement, the thyristors are kept within a reasonable degree of retarded-phase operation. Line voltages will be allowed to sag 5% or so without affecting the dc supply output. Utility supply voltage excursions above nominal value simply will result in delayed triggering of the SCR pairs.

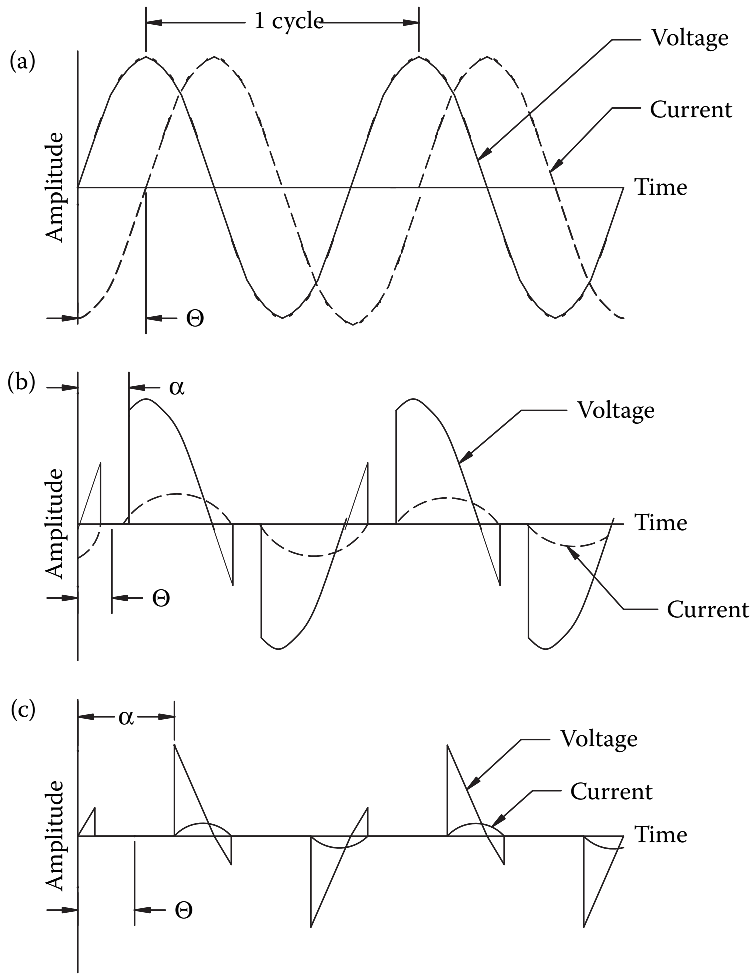

Figure 8.5 Voltage and current waveforms for inverse-parallel thyristor power control with an inductive load: (*a*) full conduction; (*b*) small-angle phase reduction; (*c*) large-angle phase reduction.

The effect of varying the conduction phase angle of a thyristor on the load current is illustrated in Figure 8.8. Note how the current I_{avg} decreases as the conduction angle is reduced from 180°.

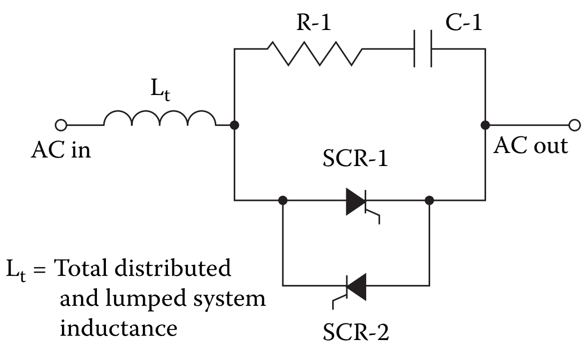

Figure 8.6 Protective RC snubber for a thyristor-based power controller.

Thyristor control of high-power loads (200 kW and above) typically uses special transformers that provide 6- or 12-phase outputs. Although they are more complicated and expensive, such designs allow additional operational control, and filtering requirements are reduced significantly. Figure 8.9 shows a six-phase *boost rectifier* circuit. The configuration consists basically of a full-wave, three-phase SCR bridge connected to a wye-configured transformer secondary. A second bridge, consisting of six diodes, is connected to low-voltage taps on the same transformer. When the SCRs are fully on, their output is at a higher voltage than the diode bridge. As a result, the diodes are reverse-biased and turned off. When the SCRs are partially on, the diodes are free to conduct. The diodes improve the quality of the output waveform during low-voltage (reduced conduction angle) conditions. The minimum output level of the supply is determined by the transformer taps to which the diodes are connected.

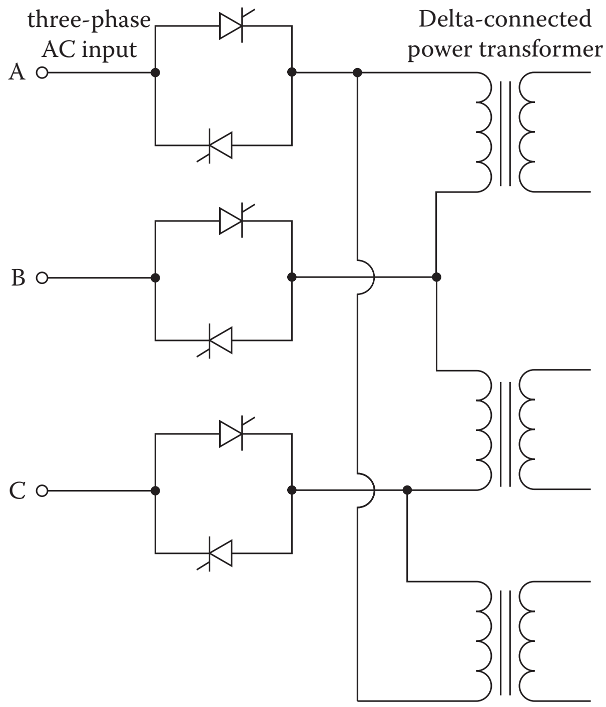

Figure 8.7 Modified full-thyristor three-phase ac control of an inductive delta load.

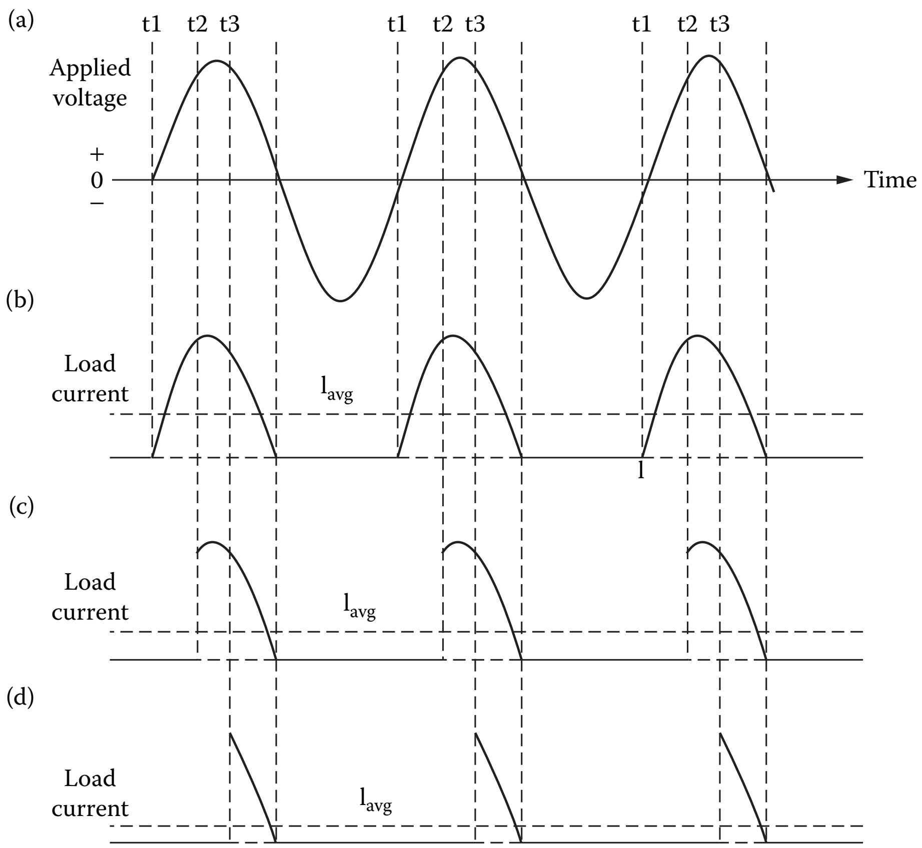

Figure 8.8 The effect of varying the phase angle of a thyristor on the load current I_{avg}: (*a*) applied voltage, (*b*) thyristor switched on at the zero crossing, (*c*) thyristor switched on at approximately 60° after the zero crossing, (*d*) thyristor switched on at approximately 90° after the zero crossing.

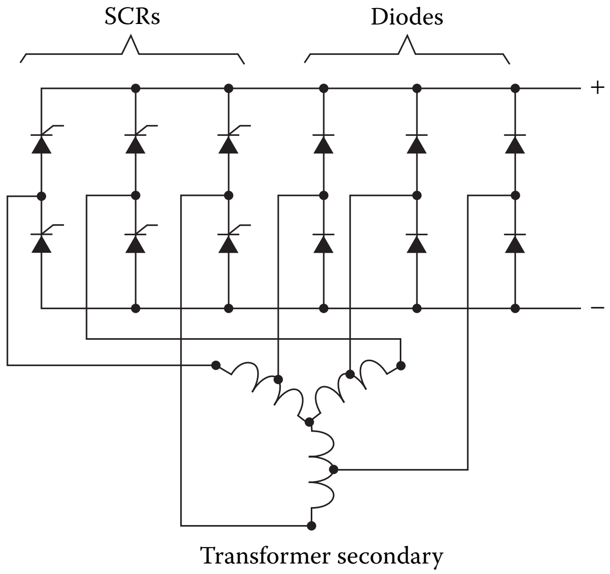

Figure 8.9 Six-phase boost rectifier circuit.

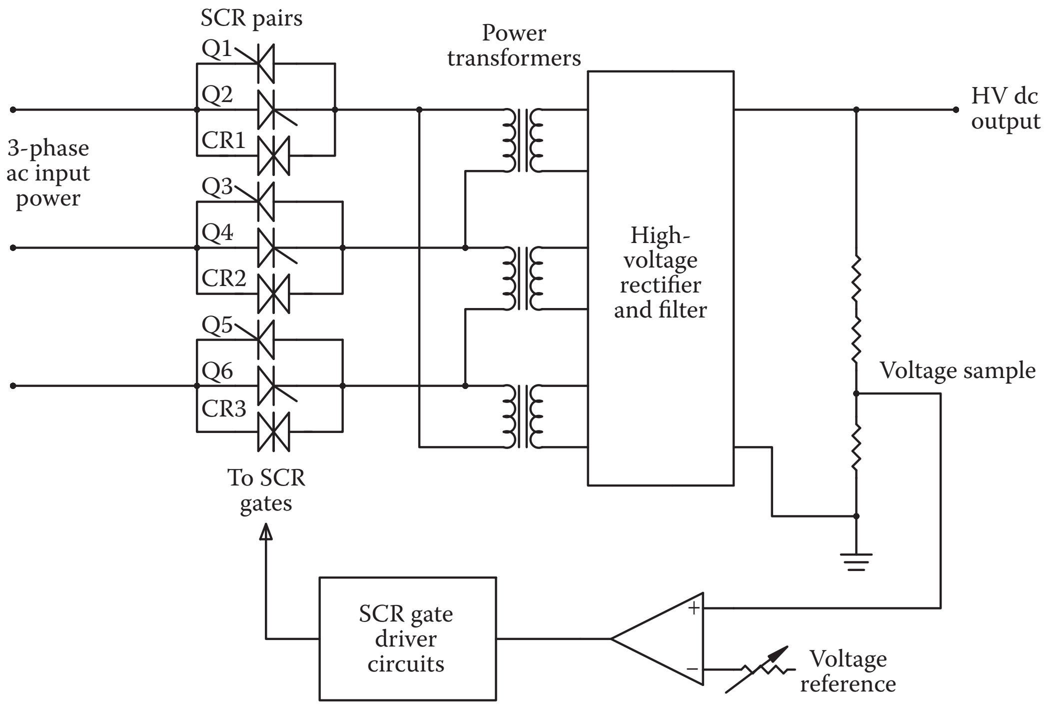

Figure 8.10 Thyristor-controlled high-voltage servo power supply.

A thyristor-driven, three-phase power-control circuit is shown in Figure 8.10. A single-phase power-control circuit is shown in Figure 8.11.

8.2.1.3 Triggering Circuits

Accurate, synchronized triggering of the gate pulses is a critical element in thyristor control of a three-phase power supply. The gate signal must be synchronized properly with the phase of the ac line that it is controlling. The pulse also must properly match the phase angle delay of the gates of other thyristors in the power-control system. Lack of proper synchronization of gate pulse signals between thyristor pairs can result in improper current sharing (current hogging) among individual legs of the three-phase supply.

The gate circuit must be protected against electrical disturbances that could make proper operation of the power-control system difficult or unreliable. Electrical isolation of the gate is a common approach.

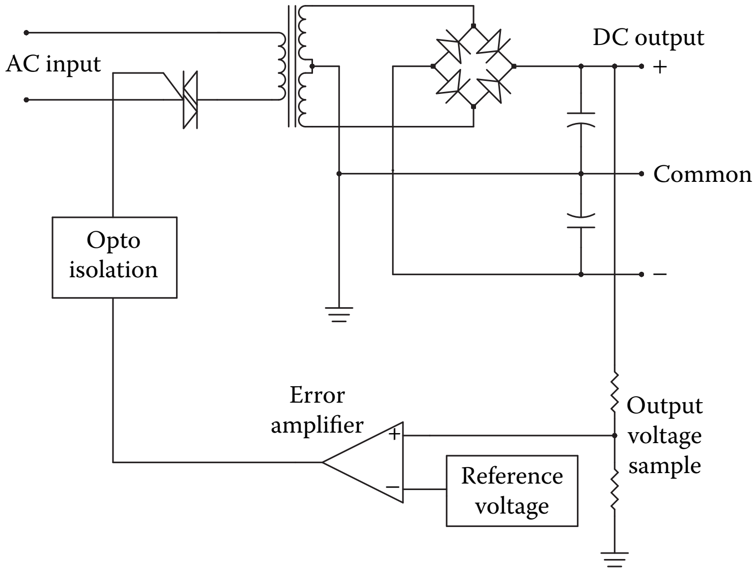

Figure 8.11 Phase-controlled power supply with primary regulation.

Standard practice calls for the use of gate pulse transformers in thyristor servo system gating cards. Pulse transformers are ferrite-cored devices with a single primary winding and (usually) multiple secondary windings that feed, or at least control, the individual gates of a back-to-back thyristor pair. This concept is illustrated in Figure 8.12. Newer thyristor designs may use optocouplers (primarily for low-power systems) to achieve the necessary electrical isolation between the trigger circuit and the gate.

It is common practice to tightly twist together the leads from the gate and cathode of a thyristor to the gating card assembly. This practice provides a degree of immunity to high-energy pulses that might inadvertently trigger the thyristor gate. The gate circuit must be designed and configured carefully to reduce inductive and capacitive coupling that might occur between power and control circuits. Because of the high di/dt conditions commonly found in thyristor-controlled power circuits, power wiring and control (gate) wiring must be separated physically as much as possible. Shielding of gating cards in metal card cages is advisable.

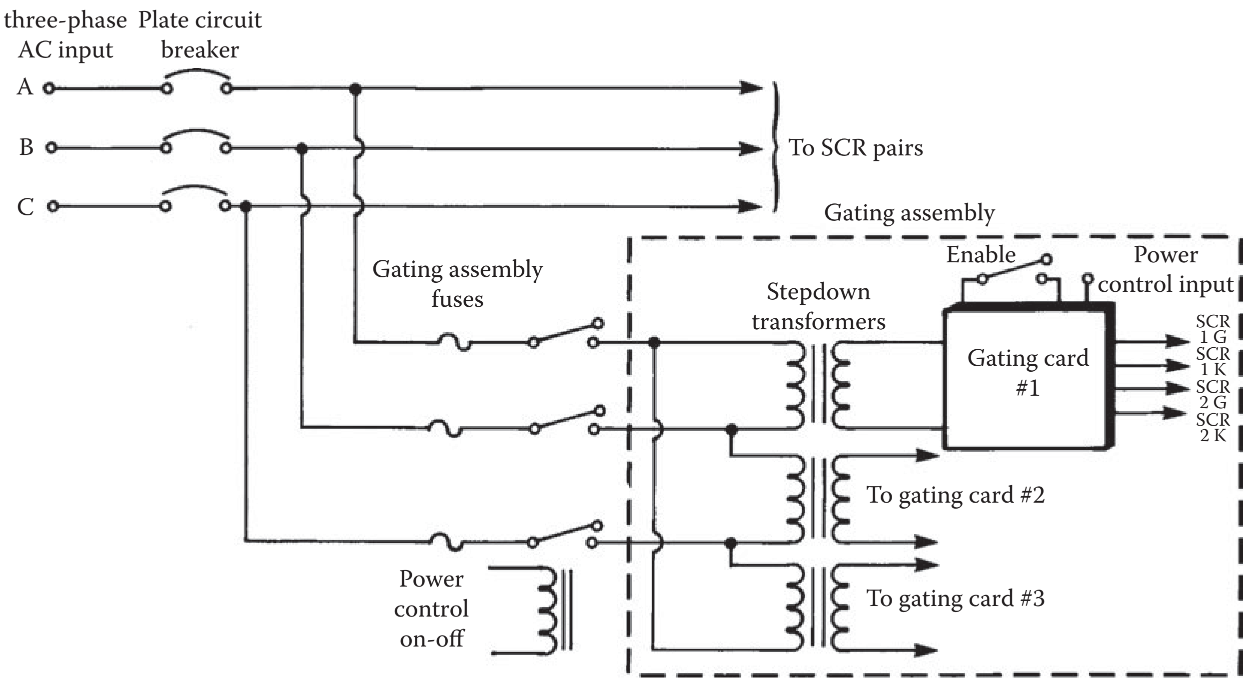

Figure 8.12 Simplified block diagram of the gating circuit for a phase-control system using back-to-back SCRs.

Equipment manufacturers use various means to decrease gate sensitivity to transient sources, including placement of a series resistor in the gate circuit or a shunting capacitor between the gate and cathode. A series resistor has the effect of decreasing gate sensitivity, increasing the allowable dv/dt of the thyristor, and reducing the turn-off time, which simultaneously increases the required holding and latching currents. The use of a shunt capacitor between the gate and cathode leads reduces high-frequency noise components that might be present on the gate lead and increases the dv/dt withstand capability of the thyristor. The application of these techniques is the exclusive domain of the design engineer. Users should not consider modifying a design without detailed consultation with the engineering department of the original equipment manufacturer.

8.2.1.4 Control Flexibility

Thyristor servo control of a high-voltage or high-current power supply is beneficial to the user for a number of reasons. First is the wide control over ac input voltages that such systems provide. A by-product of this feature is the capability to compensate automatically for line-voltage variations. Other benefits include the capability to soft-start the dc supply. Thyristor control circuits typically include a ramp generator that increases the ac line voltage to the power transformer from zero to full value within 2 to 5 s. This prevents high-surge currents through rectifier stacks and filter capacitors during system startup.

Although thyristor servo systems are preferred over other power-control approaches from an operational standpoint, they are not without their drawbacks. The control system is complex and can be damaged by transient activity on the ac power line. Conventional power contactors are simple and straightforward. They either make contact or they do not. For reliable operation of the thyristor servo system, attention must be given to transient suppression at the incoming power lines.

8.2.2 Gate Turn-Off Thyristor

The GTO is a power switching device that can be turned on by a short pulse of gate current and turned off by a reverse gate pulse [1]. The required reverse gate current amplitude is dependent on the anode current to be turned off. Hence, there is no need for an external commutation circuit to turn off the device. Because turn-off is provided by bypassing carriers directly to the gate circuit, the turn-off time is short, thus making the device well suited for high-frequency operation. The GTO turn-off characteristics are shown in Figure 8.13.

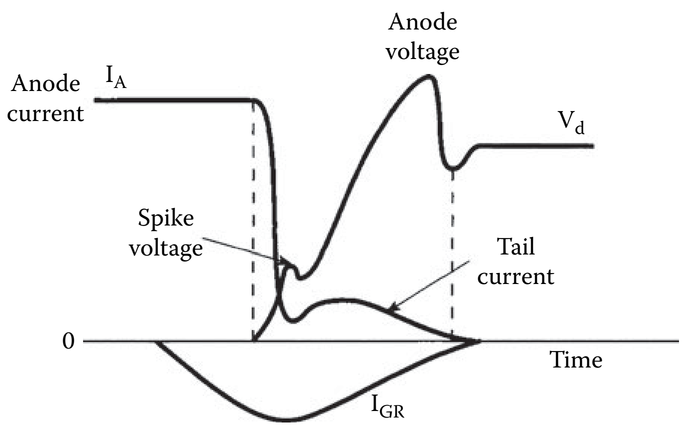

Figure 8.13 Turn-off characteristics of a GTO. (*After* [1] *and* [2].)

For reliable operation, the critical aspects are proper design of the gate turn-off circuit and the snubber circuit. The GTO has poor turn-off current gain, on the order of 4 to 5. For example, a 2000 A peak current GTO may require as high as 500 A of reverse gate current. Also, the GTO has a tendency to latch at high temperatures (above approximately 125°C). GTO devices are commonly available for operation up to 4500 V at 2500 A.

8.2.3 Reverse-Conducting Thyristor

In typical inverter applications, a diode in antiparallel is connected to the thyristor for commutation/freewheeling purposes. In a *reverse-conducting thyristor* (RCT), the diode is integrated with a fast switching thyristor in a single silicon chip [1]. Thus, the number of power devices in a given circuit can be reduced. This integration yields a substantial improvement in the static and dynamic characteristics of the device, as well as improved overall circuit performance.

The RCT is designed mainly for specific applications such as traction drives. The antiparallel diode limits the reverse voltage across the thyristor to 1 to 2 V. Also, because of the reverse recovery behavior of the diodes, the thyristor may see very high reapplied dv/dt when the diode recovers from its reverse voltage. This necessitates use of large RC snubber networks to suppress the voltage transients. As the range of application of thyristors and diodes extends into higher frequencies, their reverse recovery charge becomes increasingly important. High reverse recovery charge results in high power dissipation during switching.

8.2.4 Asymmetrical Silicon-Controlled Rectifier

The *asymmetrical silicon-controlled rectifier* (ASCR) has a forward blocking capability similar to an inverter-grade thyristor, but a limited reverse blocking capability (about 20 to 30 V) [1]. The ASCR has an on-state voltage drop of about 25% less than an inverter-grade thyristor of a similar rating. The ASCR features a fast turn-off time, and so it can work at higher frequencies than typical SCRs. Because the turn-off time is reduced by a factor of nearly 2, the size of the commutating components can be halved. The switching losses, therefore, also are reduced.

Gate-assisted turn-off techniques can be used to further reduce the turn-off time of an ASCR. The application of a negative voltage to the gate during turn-off helps to evacuate stored charges in the device and aids the recovery mechanism. This will — in effect — reduce the turn-off time by a factor of up to 2 over the conventional device.

8.2.5 Fusing

Current-limiting is a basic method of protection for thyristors operated from the utility ac line. The device typically used for breaking fault currents is either a fuse or a circuit breaker. Some designs incorporate both components. *Semiconductor fuses* often are used in conjunction with a circuit breaker to provide added protection. Semiconductor fuses operate more rapidly (typically within 8 ms) and more predictably than common fuses or circuit breakers. Surge currents caused by a fault can destroy a semiconductor device, such as a power thyristor, before the ac line circuit breaker has time to act. Manufacturers of semiconductor fuses and thyristors usually specify in their data sheets the I^2t ratings of each device. Because the thyristor rating normally assumes that the device is operating at maximum rated current and maximum junction temperature (conditions that do not represent normal operation), a safety factor is ensured.

8.3 Power Transistors

Power transistors are used in ac applications ranging up to several hundred kilowatts and switching frequencies up to approximately 10 kHz [1]. Devices for power conversion applications are generally npn type. The power transistor is turned on by supplying sufficient base current, which must be maintained throughout the conduction period. The device is turned off by removing the base drive and making the base voltage slightly negative. The *saturation voltage* of the device is normally 0.5 to 2.5 V and increases as the current increases. The transistor off-state losses are much lower than the on-state losses because the leakage current of the device is of the order of a few milliamperes. Because of relatively long switching times, switching losses significantly increase with switching frequency.

Power transistors do not have I^2t withstand capability. In other words, they can absorb very little energy before breakdown. Therefore, they cannot be protected by semiconductor fuses (like thyristors can), and thus an electronic protection method usually must be provided.

To reduce high base current requirements, Darlington configurations are commonly used. They are available in monolithic or in isolated package designs. The basic Darlington configuration is shown schematically in Figure 8.14. The Darlington arrangement offers a specific advantage in that it can considerably increase the current switched by the transistor for a given base drive.

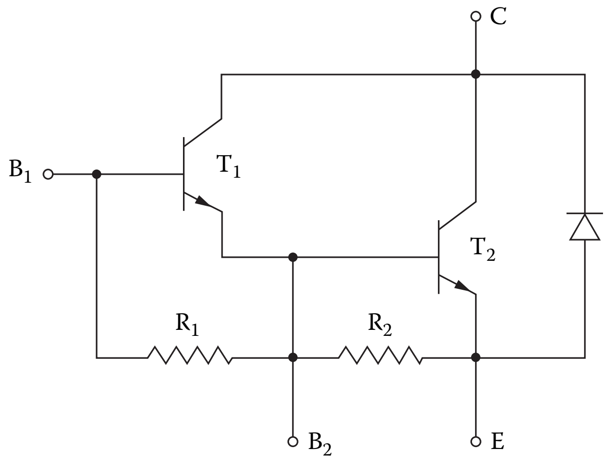

Figure 8.14 A two-stage Darlington transistor with bypass diode. (*After* [1] *and* [2].)

8.3.1 Power MOSFET

Power MOSFETs are a class of devices marketed under a variety of names by different manufacturers [1]. They have unique features that make them particularly attractive for switching applications. Power MOSFETs are essentially voltage-driven rather than current-driven devices (unlike bipolar transistors).

The gate of a MOSFET is isolated electrically from the source by a layer of silicon oxide. The gate draws only a minute leakage current on the order of nanoamperes. Hence, the gate drive circuit is simple, and power loss in the gate control circuit is practically negligible. Although in steady-state, the gate draws virtually no current, this is not so under transient conditions. The gate-to-source and gate-to-drain capacitances have to be charged and discharged appropriately to obtain the desired switching speed, and the drive circuit must have a sufficiently low output impedance to supply the required charging and discharging currents.

Power MOSFETs are majority carrier devices, and there is no minority carrier storage time. This attribute provides for exceptionally fast rise and fall times. Power MOSFETs are essentially resistive devices when turned on, whereas bipolar transistors present a more or less constant saturation voltage $V_{CE(sat)}$ over the normal operating range. At low currents, therefore, a power MOSFET may have a lower conduction loss than a comparable bipolar device, but at higher currents, the conduction loss will exceed that of the bipolar device.

8.3.1.1 Rugged MOSFET

With recent advancements in MOS technology, ruggedized MOSFETs are replacing conventional MOSFETs in numerous applications [1]. Theoretically, the secondary breakdown mechanism is absent in a power MOSFET. In the real world of *vertical conductive power* MOSFETs, however, secondary breakdown exists because of the presence of a parasitic npn transistor, thus forcing chip designers to develop the ruggedness concept to thwart such failures. The need to ruggedize power MOSFETs is related to device reliability. If a MOSFET is operated within its specification range at all times, its chances for failing catastrophically are minimal. However, if the absolute maximum ratings are exceeded, failure probability increases dramatically. Under actual operating conditions, a MOSFET may be subjected to transients either externally from the power bus supplying the circuit or from the circuit itself, caused, for example, by inductive kicks going beyond the absolute maximum ratings. Such conditions are likely in almost every application and, in many cases, are beyond the control of the designer.

The difference between a ruggedized MOSFET and a conventional device is that the ruggedized version is rated to withstand a specific amount of unclamped avalanche energy when operated at voltages above its maximum drain-to-source breakdown voltage (BV_{DSS}). In effect, the manufacturer guarantees that MOSFET will not fail catastrophically up to a specified amount of avalanche energy.

8.3.2 Insulated-Gate Bipolar Transistor

The IGBT combines the high input impedance and high-speed characteristics of a MOSFET with the conductivity characteristic (low saturation voltage) of a bipolar transistor [1]. The equivalent circuit of an IGBT is shown in Figure 8.15. The IGBT is turned on by applying a positive voltage between the gate and emitter, and as with the MOSFET, it is turned off by making the gate signal zero or slightly negative. The IGBT has a much lower on-state resistance than a MOSFET.

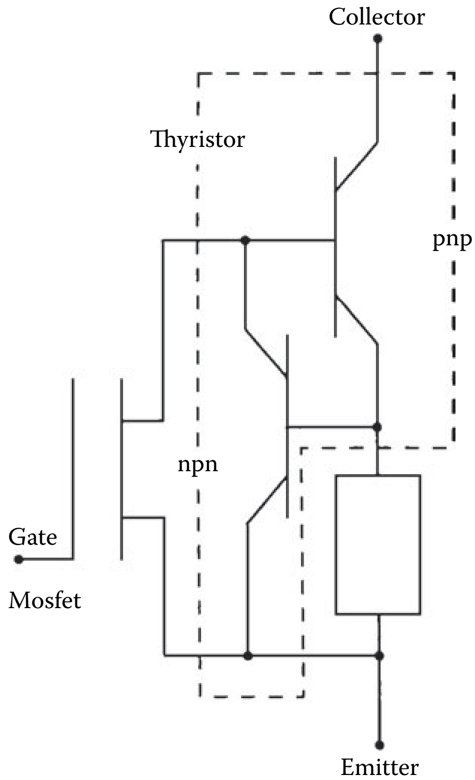

Figure 8.15 The equivalent circuit of the IGBT device. (*After* [1] *and* [2].)

In a sense, the device is similar to a thyristor and MOSFET. To illustrate: for a given IGBT, there is a critical value of drain current that will cause a large enough voltage drop to activate the thyristor element. Hence, device manufacturers specify the peak allowable drain current that can flow without latch-up occurring. There is also a corresponding gate source voltage that permits this current to flow, which should not be exceeded. After the IGBT is in latch-up, the gate no longer has any control of the drain current. The only way to turn off the IGBT in this situation is by forced commutation of the current, exactly the same as for a thyristor. If latch-up is not terminated quickly, the IGBT will be destroyed by the excessive power dissipation. Under dynamic conditions, when the IGBT is switching from on to off, it may latch up at drain current values less than the values described here (*static latch-up current* value). Various improvements to the basic IGBT design have increased the latching current to workable values.

Like the power MOSFET, the IGBT does not exhibit the secondary breakdown phenomenon common to bipolar transistors. However, care should be taken not to exceed the maximum power dissipation and specified maximum junction temperature of the device under all conditions for guaranteed reliable operation.

The on-state voltage of the IGBT is heavily dependent on the gate voltage. To obtain a low on-state voltage, a sufficiently high gate voltage must be applied. The on-state voltage also increases with temperature. Compared to a MOSFET structure, the IGBT is generally smaller for the same current rating. At voltages above 400 V, an IGBT can be one third the size of a MOSFET. The bipolar action in the IGBT, however, slows down the speed of the device so that it typically operates at a much lower frequency than the MOSFET. The switching frequency can be as high as 50 kHz for a standard device; higher frequencies are achievable at the expense of higher losses.

The IGBTs cannot be as easily paralleled as MOSFETs can. The factors that inhibit current sharing of parallel-connected IGBTs are:

- The on-state current unbalance, caused by $V_{CE(sat)}$ distribution and main circuit wiring resistance distribution
- Current unbalance at turn-on and turn-off, caused by the switching time difference of the parallel-connected devices and circuit wiring inductance distribution

If IGBT devices having different turn-on times are paralleled, the current is hogged by the device having the shorter turn-on time. If IGBTs having different turn-off times are paralleled, current is hogged by the device having the longer turn-off time. The time differences at turn-off must be controlled carefully because turn-off times are greater than those of turn-on.

8.3.3 MOS-Controlled Thyristor

The *MOS-controlled thyristor* (MCT) is basically a thyristor with built-in MOSFETs to turn on and turn off the circuit [1]. Device attributes include high-power, high-frequency, low-conduction-drop, and ruggedness. The MCT equivalent circuit is shown in Figure 8.16. The MCT has thyristor-type junctions and pnpn layers between the anode and cathode.

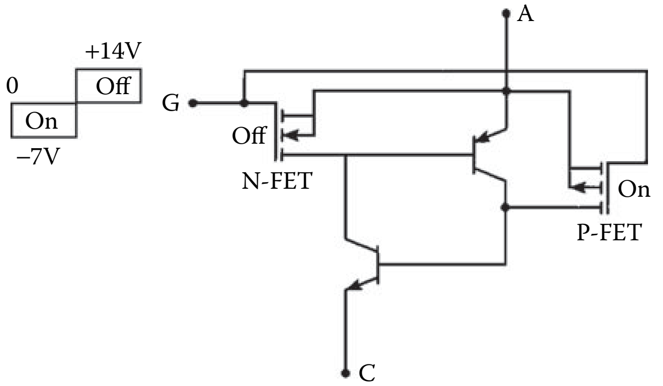

Figure 8.16 The equivalent circuit of the MCT device. (After [1] and [2].)

The MCT is turned on by a negative voltage pulse at the gate, with respect to the anode, and turned off by a positive voltage pulse. The MCT can operate at higher junction temperatures than the BJT, IGBT, and MOSFET. The MCT has relatively low switching times and storage time. The MCT is capable of high current densities and blocking voltages in both directions. Because the power gain of an MCT is extremely high, it can be driven directly from a logic gate.

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9 Origins of AC Line Disturbances

9.1 Introduction

Transient overvoltages come in a wide variety of forms, from a wide variety of sources. They can, however, be broken down into two basic categories: (1) those generated through natural occurrences, and (2) those generated through the use of equipment, either on-site or elsewhere.

9.2 Naturally Occurring Disturbances

Natural phenomena of interest to facility managers consist mainly of lightning and related disturbances. The *lightning effect* can be compared to that of a capacitor, as shown in Figure 9.1. A charged cloud above the Earth will create an oppositely charged area below it of about the same size and shape. When the voltage difference is sufficient to break down the dielectric (air), the two "plates" of the "capacitor" will arc over and neutralize their respective charges. If the dielectric spacing is reduced, as in the case of a conductive steel structure (such as a transmitting tower), the arc-over will occur at a lower-than-normal potential and will travel through the conductive structure.

The typical duration of a lightning flash is approximately 0.5 s. A single flash is made up of various discharge components, among which are typically three or four high-current pulses called *strokes*. Each stroke lasts about one 1 ms; the separation between strokes is typically several tens of milliseconds. Lightning often appears to flicker because the human eye can just resolve the individual light pulses that are produced by each stroke.

9.2.1 Sources of Atmospheric Energy

Lightning is one of the more visible effects of atmospheric electricity. Stellar events that occurred light-years ago spray the earth and its atmosphere with atoms that have been stripped of most or all of their electrons. In the process of entering the atmosphere, these particles collide with air molecules, which are knocked apart, creating billions more ion pairs each second. Even though these ions may exist for only about 100 s, they constantly are being replenished from deep space. The existence of ions in the atmosphere is the fundamental reason for atmospheric electricity. The primary sources of this energy are:

- *Cosmic rays*: Charged particles emitted by all radiating bodies in space. Most of these particles (ions) expend their energy in penetrating the envelope of air surrounding the earth. Through this process, they create more ions by colliding with air atoms and molecules. One high-energy particle may create up to a billion pairs of ions, many of which will become atmospheric electricity.
- *Solar wind*: Charged particles from the sun that continuously bombard the surface of the earth. Because about half of the earth's surface is always exposed to the sun, variations are experienced from day to night. Solar wind particles travel at only 200 to 500 miles per second, compared with cosmic particles that travel at near the speed of light. Because of their slower speed, solar wind particles have less of an effect on air atoms and molecules.

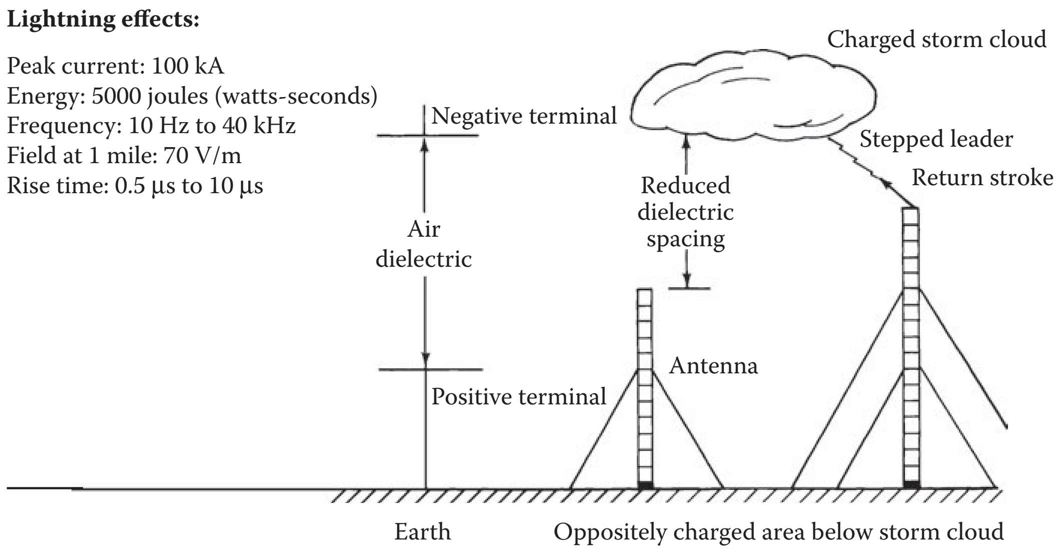

Figure 9.1 The lightning effect and how it can be compared to a more familiar mechanism, the capacitor principle. Also shown are the parameters of a typical lightning strike.

- *Natural radioactive decay*: The natural disintegration of radioactive elements. In the process of radioactive decay, air molecules are ionized near the surface of the earth. One of the results is radon gas.
- *Static electricity*: Energy generated by the interaction of moving air and the earth.
- *Electromagnetic generation*: Energy generated by the movement of air molecules through the magnetic field of the earth.

The combined effects of cosmic rays and solar wind account for most atmospheric electrical energy.

Atmospheric energy is present at all times, even during clear weather conditions. This energy takes the form of a voltage differential of 300 to 400 kV between the surface of the earth and the ionosphere. The voltage gradient is nonlinear; near the surface it may be 150 V/m of elevation, but it diminishes significantly at higher altitudes. Under normal conditions, the earth is negative with respect to the ionosphere, and ions flow between the two entities. Because there are fewer free ions near the Earth than the ionosphere, the volts/meter value is thought to be greater because of the lower effective conductivity of the air. This concept is illustrated in Figure 9.2.

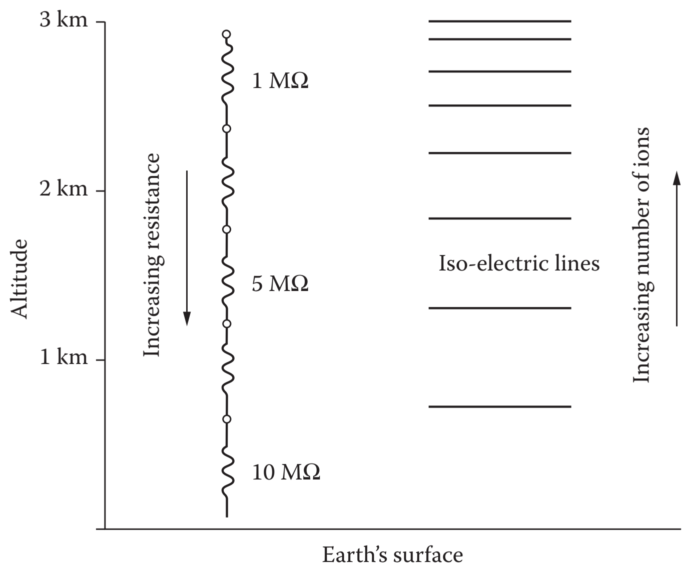

Figure 9.2 The effects of atmospheric conductivity.

Thermodynamic activity in a developing storm cloud causes it to become a powerfully charged cell, usually negatively charged on the bottom and positively charged on the top. (See Figure 9.3.) This voltage difference causes a distortion in the voltage gradient, and in fact, the polarity inverts, with the earth becoming positive with reference to the bottom of the cloud. This voltage gradient increases to a high value, sometimes exceeding 10 kV/m of elevation. The overall charge between the earth and the cloud may be on the order of 10 to 100 MV, or more. When sufficient potential difference exists, a lightning flash may occur.

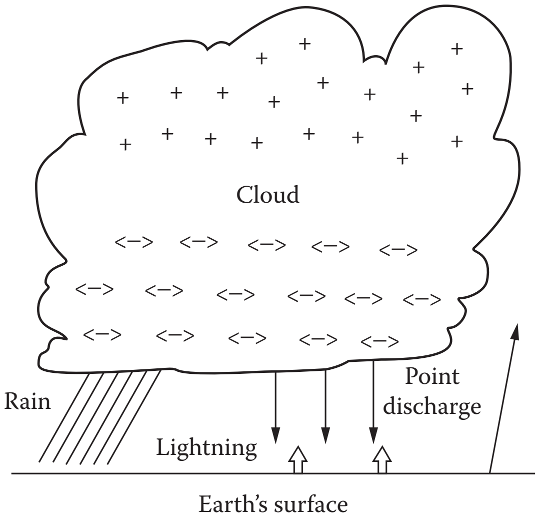

Figure 9.3 A developing thunderstorm cell.

Figure 9.4 shows the flash waveform for a typical lightning discharge. The rise time is very fast, in the microsecond range, as the lightning channel is established. The trailing edge exhibits a slow decay; the decay curve is known as a *reciprocal double exponential waveform*. The trailing edge is the result of the resistance of the ionized channel depleting energy from the cloud. The path length for a lightning discharge is measured in kilometers. The most common source of lightning is cumulonimbus cloud forms, although other types of clouds (such as nimbostratus) occasionally can produce activity.

Although most lightning strikes are negative (the bottom of the cloud is negative with respect to the earth), positive strikes also can occur. Such strikes have been estimated to carry as much as 10 times the current of a negative strike. A positive flash can carry 200 kiloamps (kA) or more of discharge current. Such hot strikes, as they are called, can cause considerable damage. Hot strikes can occur in the winter and are often the aftereffect of a particularly active storm. After a number of discharges, the lower negative portion of the cloud will become depleted. When charged, the lower portion may have functioned as a screen or shield between the earth and the upper, positively charged portion of the cloud. When depleted, the shield is removed, exposing the earth to the massive charge in the upper cloud containing potentials of perhaps 500 MV or more.

9.2.2 Characteristics of Lightning

A typical lightning flash consists of a stepped leader that progresses toward the ground at a velocity that can exceed 50 m/μs. When sufficient potential difference between the cloud and the ground exists, arcs

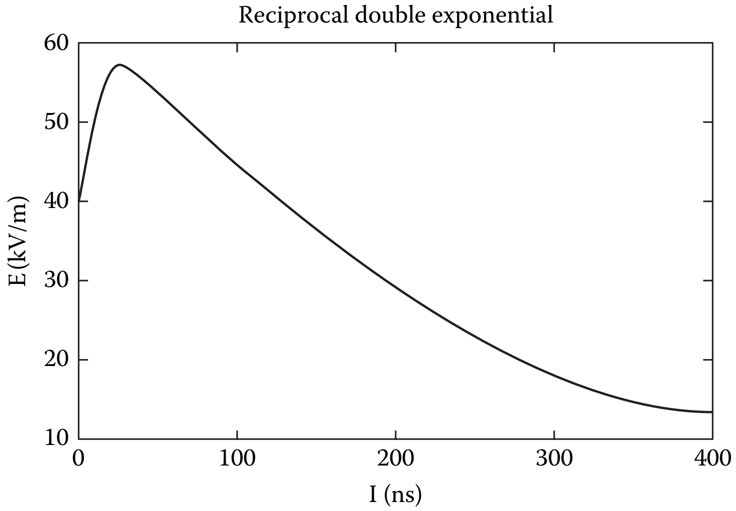

Figure 9.4 Discharge waveform for a typical lightning strike.

move from the ground to the leader column, completing the ionized column from cloud to ground. A fast and bright return stroke then moves upward along the leader column at about one third the speed of light. Peak currents from such a lightning flash may exceed 100 kA, with a total charge as high as 100 coulombs (C). Although averages are difficult to assess where lightning is concerned, a characteristic flash exhibits a 2 μs rise time, and a 10 to 40 μs decay to a 50% level. The peak current will average 18 kA for the first impulse, and about half that for the second and third impulses. Three to four strokes per flash are common.

A lightning flash is a constant-current source. Once ionization occurs, the air becomes a conductive plasma reaching 60,000°F and becomes luminous. The resistance of an object struck by lightning is of small consequence except for the power dissipation on that object, which is equivalent to I^2R. Fifty percent of all strikes will have a first discharge of at least 18 kA, 10% will exceed 60 kA, and only 1% will exceed 120 kA.

Four specific types of cloud-to-ground lightning have been identified. They are categorized in terms of the direction of motion (upward or downward) and the sign of the electric charge (positive or negative) of the initiating leader. The categories, illustrated in Figure 9.5, are defined as follows:

- *Category 1*: Negative leader cloud-to-ground discharge. By far the most common form of lightning, such discharges account for 90% or more of the cloud-to-ground flashes worldwide. Such events are initiated by a downward-moving negatively charged leader.
- *Category 2*: Positive leader ground-to-cloud discharge. This event begins with an upward-initiated flash from earth, generally from a mountaintop or tall steel structure. Category 2 discharges are relatively rare.
- *Category 3*: Positive leader cloud-to-ground discharge. Less than 10% of cloud-to-ground lightning worldwide is of this type. Positive discharges are initiated by leaders that do not exhibit the distinct steps of their negative counterparts. The largest recorded peak currents are in the 200 to 300 kA range.
- *Category 4*: Negative leader ground-to-cloud discharge. Relatively rare, this form of lightning begins with an upward leader that exhibits a negative charge. Similar to Category 2 discharges, Category 4 discharges occur primarily from a mountaintop or tall steel structure.

An idealized lightning flash is shown in Figure 9.6. The stepped leader initiates the first return stroke in a negative cloud-to-ground flash by propagating downward in a series of discrete steps, as shown. The breakdown process sets the stage for a negative charge to be lowered to the ground. A fully developed leader lowers 10 C or more of negative cloud charge to near the ground within a few tens of milliseconds. The average return leader current measures from 100 A to 1 kA. During its trip toward earth, the stepped leader branches in a downward direction, producing the characteristic lightning discharge.

The electrical potential difference between the bottom of the negatively charged leader channel and the earth can exhibit a magnitude in excess of 100 MV. As the leader tip nears ground level, the electric field at sharp objects on the ground increases until the breakdown strength of the atmosphere is exceeded. At that point, one or more upward-moving discharges are initiated, and the *attachment process*

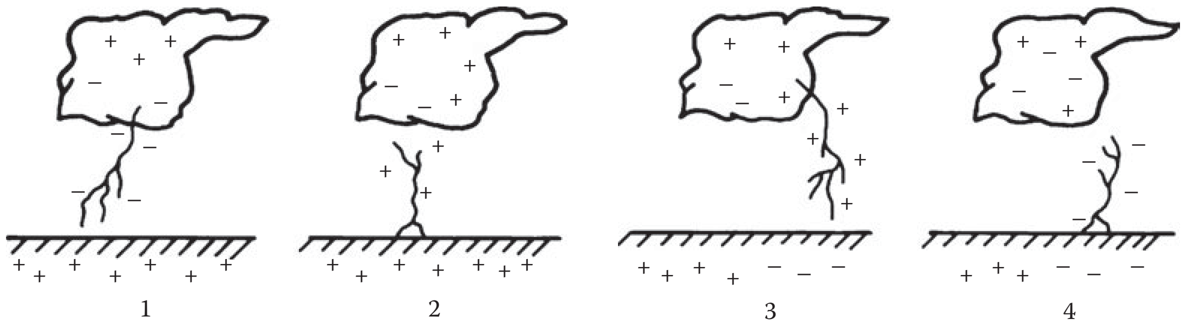

Figure 9.5 Four general types of lightning activity. (*After* [1].)

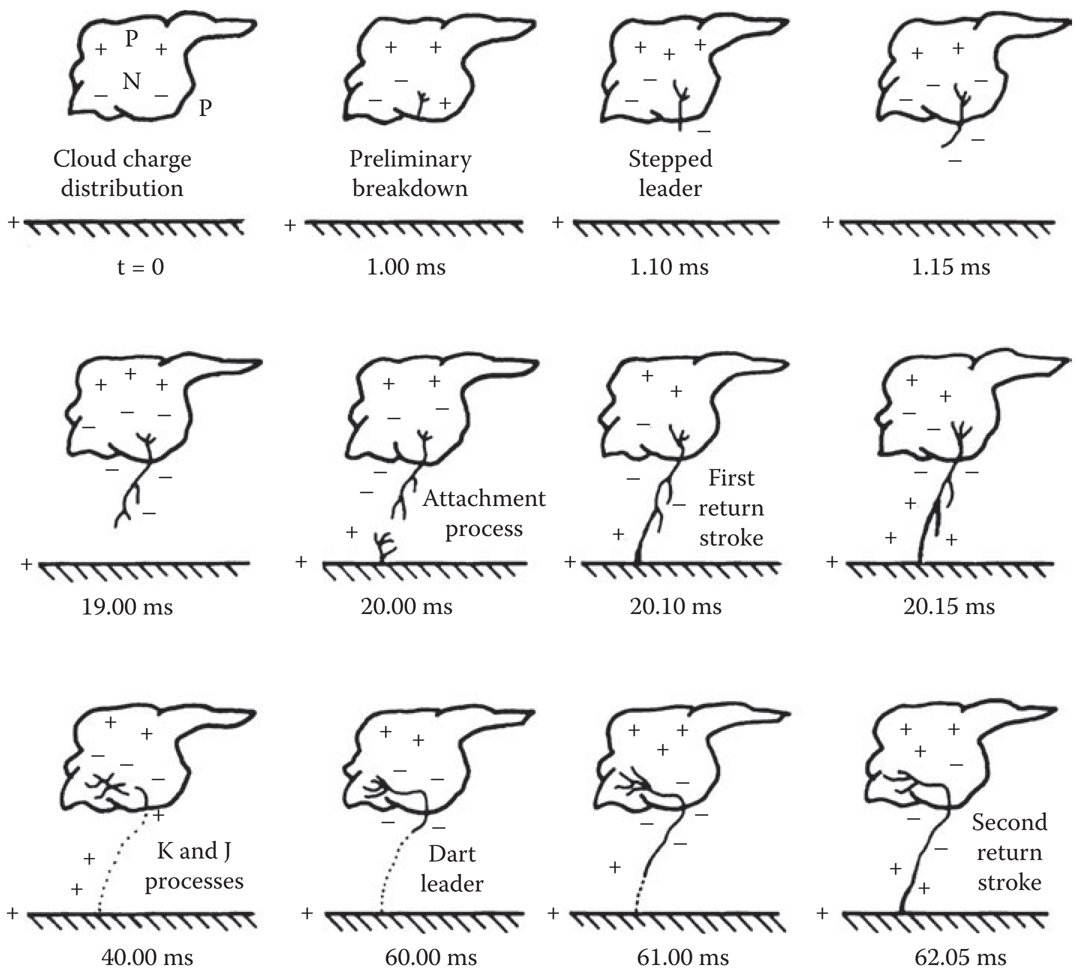

Figure 9.6 The mechanics of a lightning flash. (*After* [2].)

begins. The leader channel is discharged when the first return stroke propagates up the previously ionized and charged leader path. This process will repeat if sufficient potential exists after the initial stroke. The time between successive strokes in a flash is usually several tens of milliseconds.

9.2.2.1 Cloud-to-Cloud Activity

A cloud discharge can be defined as any lightning event that does not connect with the earth. Most lightning discharges occur within the confines of the cloud. Cloud discharges can be subdivided into *intraloud*, *intercloud*, and *cloud-to-air* flashes. Although relatively insignificant insofar as earthbound equipment is concerned, current movement between clouds can create a corresponding *earth current*.

It is estimated that only about 10 to 25% of lightning occurs from cloud to ground; most discharges consist of intracloud activity. The reason is the enormous voltage difference that builds up between the top and bottom of a storm cloud. Furthermore, the region between the top and bottom of the cloud can be more highly ionized than the region between the bottom of the cloud and the earth. Currents developed by cloud-to-cloud discharges can induce significant voltages in conductors buried in-line with the charge movement. The *windstorm effect* also can induce voltages in above- or below-ground conductors as a result of rapid changes in the electrical potential of the atmosphere.

It is unnecessary, therefore, for atmospheric charge energy to actually strike a conductor of concern, such as a transmitting tower or utility company pole. In many cases, significant voltage transients can be generated solely by induction. Cloud-to-cloud charge movements generate horizontally polarized radiation, and cloud-to-ground discharges generate vertically polarized radiation. Field strengths exceeding 70 V/m can be induced in conductors a mile or so from a large strike.

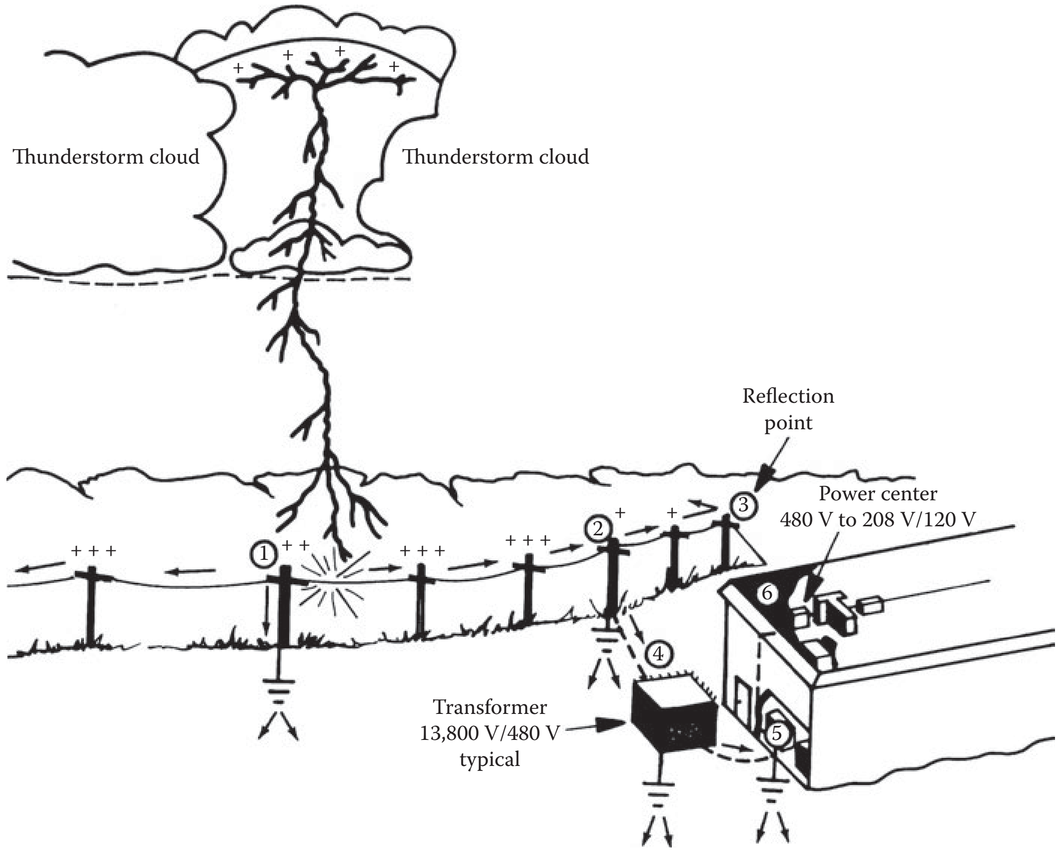

Figure 9.7 The mechanisms of lighting surge on an overhead power-distribution line.

Figure 9.7 illustrates the mechanisms of lightning damage. Traveling waves of voltage and current follow all conductive paths until the flash energy has been dissipated. Reflections occur at discontinuities, such as lightning arresters (points 1, 2, 3, and 5) and transformers (points 4 and 6).

9.2.3 Lightning Protection

Research into the physical properties of lightning and related phenomena has two basic goals: (1) to identify the character and severity of the threat, and (2) to devise methods to prevent damage resulting from atmospheric activity. Many different approaches have been taken over the years for controlling the damaging potential of lightning; some have become widely accepted, others remain controversial. The issue of lightning prevention clearly falls into the second category.

Application of the *point discharge* theory, the basis of lightning prevention schemes, is controversial to begin with. Still, it offers the promise of a solution to a serious problem faced by nearly all telecommunications operators. The goal is to dissipate static charges around a given structure at a rate sufficient to maintain the charge below the value at which a lightning flash will occur. The theory holds that discharge from the point of an electrode to a surrounding medium will follow predictable rules of behavior. The sharper the point, the greater the discharge. The greater the number of discharge points, the more efficient the dissipation system. Several static dissipators based on this theory are shown in Figure 9.8. Key design elements for such dissipators include:

- Radius of the dissipator electrode. The purpose of the dissipator is to create a high field intensity surrounding the device. Theory states that the electric field intensity will increase as the electrode radius is reduced. Dissipators, therefore, generally use the smallest-radius electrodes possible, consistent with structural integrity. There is, however, disagreement among certain dissipation-array manufacturers on this point. The optimum wire size, according to available literature, varies from 0.005-in.- to 1/8-in.-thick tapered spikes.

- Dissipator construction material. Important qualities include conductivity and durability. The dissipator should be a good conductor to provide: (1) the maximum discharge of current during normal operation, and (2) an efficient path for current flow in the event of a direct strike.
- Number of dissipator electrodes. Calculating the number of dissipator points is, again, the subject of some debate. However, because the goal of the system is to provide a low-resistance path to the atmosphere, it generally is assumed that the more discharge points, the more effective the system. Dissipator electrode requirements are determined by the type of structure being protected as well as the environmental features surrounding it.
- Density of dissipator electrodes. Experimentation by some manufacturers has shown that the smaller the radius of the dissipator electrodes, the more closely they can be arranged without reducing the overall efficiency of the dissipator. Although this convention seems reasonable, disagreement exists among dissipation-array manufacturers. Some say the points should be close together; others say they should be far apart.

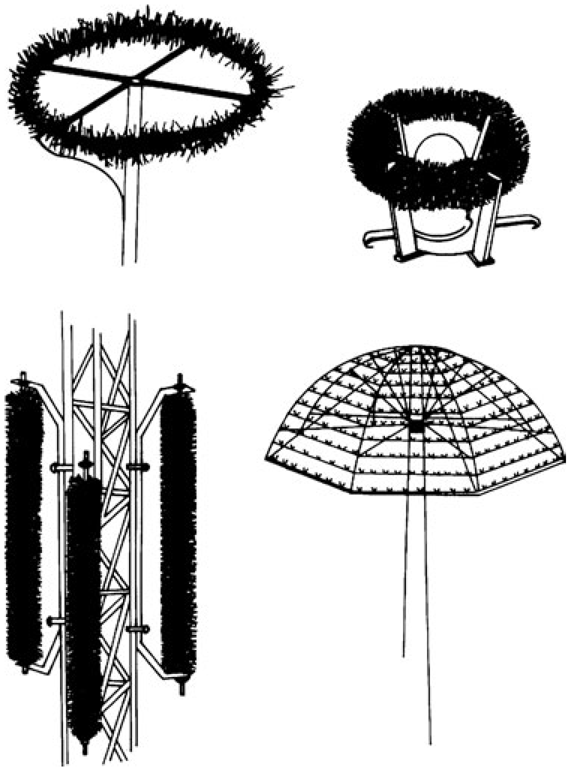

Figure 9.8 Various types of static dissipation arrays.

- Configuration of the dissipator on the tower. Disagreement abounds on this point. One school of thought supports the concept of a dedicated "umbrella-type" structure at the top of the tower as the most efficient method of protecting against a lightning flash (Figure 9.9). Another view holds that the dissipator need not be at the highest point, and that it may be more effective if one or more dissipators are placed at natural dissipation points on the structure. Such points include side-mounted antennas and other sharp elements on the tower.
- Size and deployment of grounding electrodes. Some systems utilize an extensive ground system, others do not. One manufacturer specifies a collector composed of wire radials extending from the base of the tower and terminated by ground rods. Another manufacturer does not require a ground connection to the dissipator.

Available literature indicates that from 10 μA to 10 mA flow through a properly designed dissipative system into the surrounding air during a lightning storm. Figure 9.10 charts the discharge current recorded during a period of storm activity at a protected site. Although a lightning stroke can reach several hundreds of thousands of amperes, this energy flows for a very short period of time. The concept of the dissipative array is to continuously bleed off space charge current to prevent a direct hit.

Proof that static dissipators work as intended is elusive and depends upon the definition of "proof." Empirical proof is difficult to obtain because successful performance of a static dissipator is evidenced by the absence of any results. Supporting evidence, both pro and con, is available from end-users of static dissipators, and from those who have studied this method of reducing the incidence of lightning strikes to a structure.

9.2.3.1 Protection Area

The placement of a tall structure over low-profile structures tends to protect the facilities near the ground from lightning flashes. The tall structure, typically a communications tower, is assumed to shield the facility below it from hits. This *cone of protection* is determined by the following:

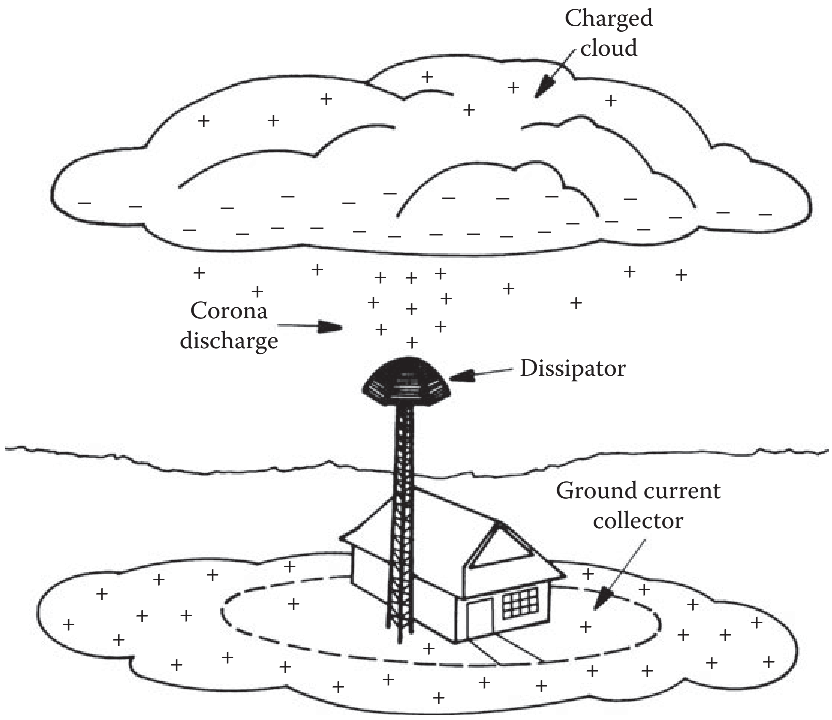

Figure 9.9 Umbrella-type dissipation array.

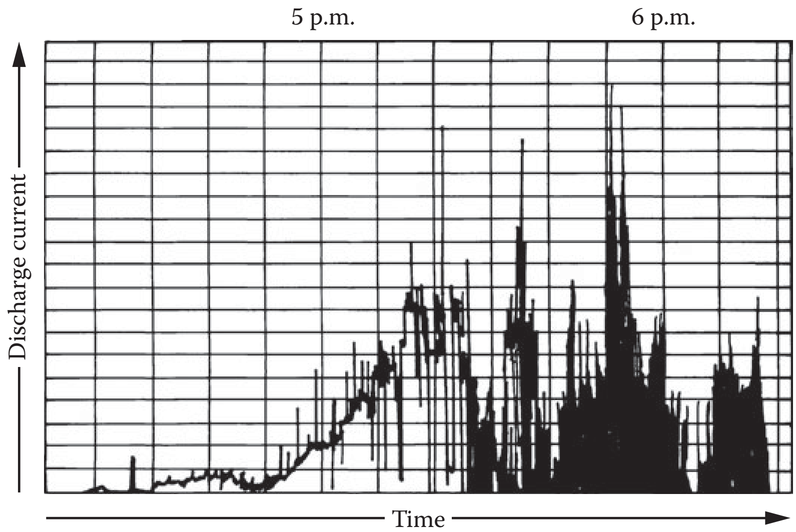

Figure 9.10 Measured discharge current of a lightning dissipation array.

- Height of the tall structure
- Height of the storm cloud above the earth

The higher the cloud, the larger the radius of the base of the protecting cone. The ratio of radius to base to height varies approximately from 1 to 2, as illustrated in Figure 9.11.

Conventional wisdom has held that a tower, whether protected with a static dissipation array or simply a tower-top lightning rod, provided a cone of protection stretching out on all sides of the structure at an angle of about 45°. Although this theory held favor for many years, modifications have been proposed. One school of thought suggests that a smaller cone of perhaps 30° from the tower is more realistic. Another suggests that the cone theory is basically flawed and, instead, proposes a "rolling sphere" approach. This theory states that areas enclosed below a 150-ft rolling sphere will enjoy protection against lightning strikes. The concept is illustrated in Figure 9.12. Note that the top of the tower shown in

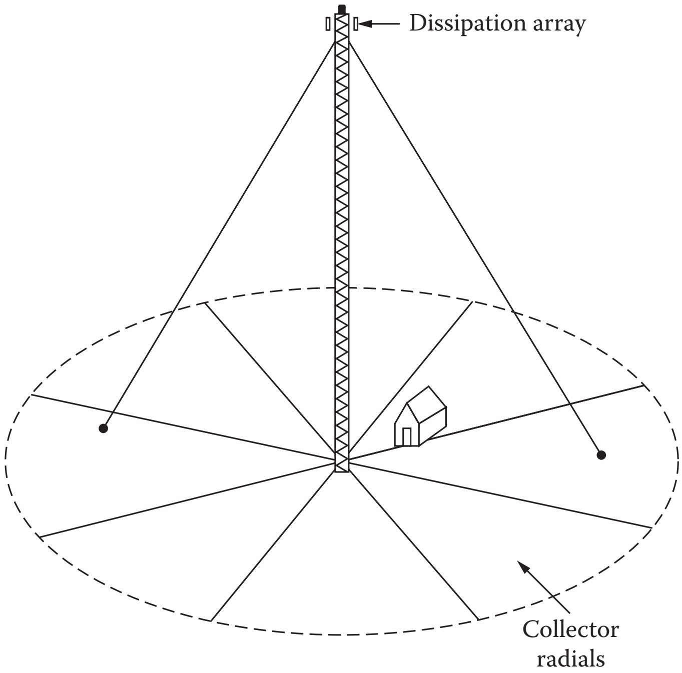

Figure 9.11 Intended protection area for a dissipation array.

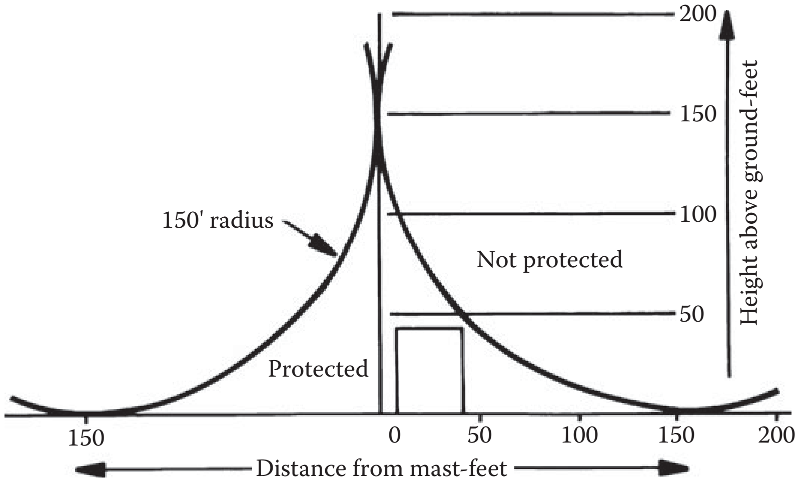

Figure 9.12 Protection zone for a tall tower under the "rolling sphere" theory.

the figure is assumed to experience limited protection. The concept, as it applies to side-mounted antennas, is shown in Figure 9.13. The antenna is protected through the addition of two horizontally mounted lightning rods, one above the antenna and one below.

9.2.4 Electrostatic Discharge

A static charge is the result of an excess or deficiency of electrons on a given surface. The relative level of electron imbalance determines the static charge. Simply stated, a charge is generated by physical contact between, and then separation of, two materials. One surface loses electrons to the other. The types of materials involved, and the speed and duration of motion between the materials, determine the charge level. Electrostatic energy is a stationary charge phenomenon that can build up in either a nonconductive material or in an ungrounded conductive material. The charge can occur in one of two ways:

- *Polarization*: Charge buildup when a conductive material is exposed to a magnetic field.

- *Triboelectric effects*: Charge buildup that occurs when two surfaces contact and then separate, leaving one positively charged and the other negatively charged.

Friction between two materials increases the triboelectric charge by increasing the surface area that experiences contact. For example, a person accumulates charge by walking across a nylon carpet; discharge occurs when the person touches a conductive surface.

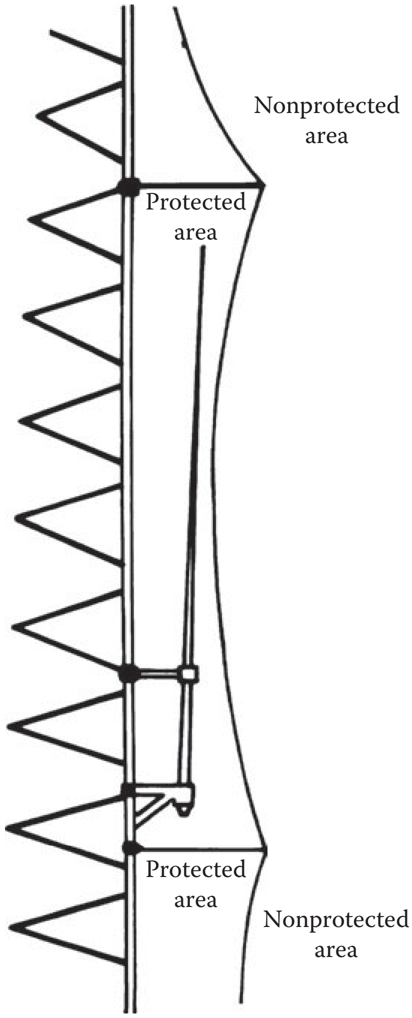

Figure 9.13 Protection zone for a side-mounted antenna under the "rolling sphere" theory.

9.2.4.1 Triboelectric Effect

Different materials have differing potentials for charge. Nylon, human and animal hair, wool, and asbestos have high positive triboelectric potential. Silicon, polyurethane, rayon, and polyester have negative triboelectric potentials. Cotton, steel, paper, and wood all tend to be relatively neutral materials. The intensity of the triboelectric charge is inversely proportional to the relative humidity (RH). As humidity increases, *electrostatic discharge* (ESD) problems decrease. For example, a person walking across a carpet can generate a 1.5 kV charge at 90% RH, but will generate as much as 35 kV at 10% RH.

When a charged object comes in contact with another object, the electrostatic charge will attempt to find a path to ground, discharging into the contacted object. The current level is very low (typically less than 0.1 nA), but the voltage can be high (25 to 50 kV).

ESD also can collect on metallic furnishings, such as chairs and equipment racks. Sharp corners and edges, however, encourage a corona that tends to bleed the charge off such objects. The maximum voltage normally expected for furniture-related ESD is about 6 to 8 kV. Because metallic furniture is much more conductive than humans, however, furniture-related ESD generally will result in higher peak discharge currents. Figure 9.14 shows a discharge waveform of a typical ESD event.

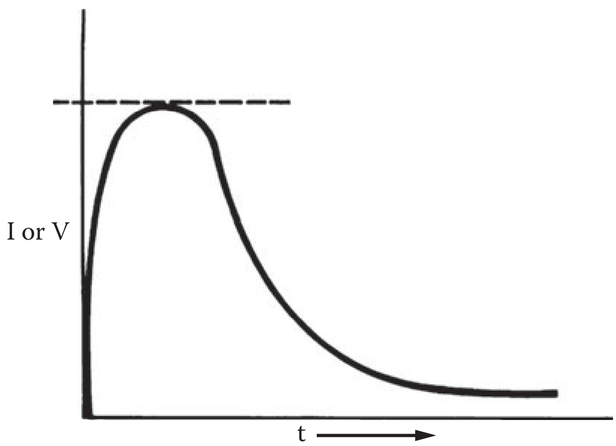

Figure 9.14 Discharge waveform for an ESD event. (After [3].)

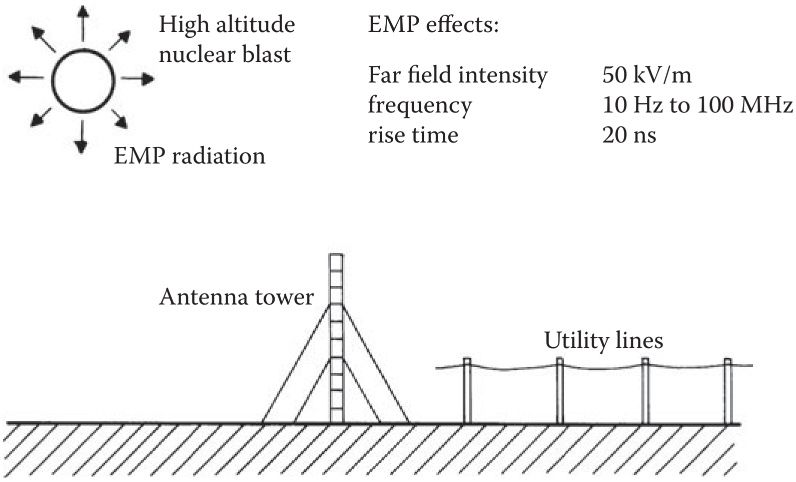

Figure 9.15 The EMP effect and how it can induce damaging voltages onto utility company lines and antenna structures. The expected parameters of an EMP event also are shown.

9.2.5 EMP Radiation

Electromagnetic pulse (EMP) radiation is the result of an intense release of electromagnetic waves that follows a nuclear explosion. (See Figure 9.15.) The amount of damaging energy is a function of the altitude of detonation and the size of the device. A low-altitude or surface burst would generate a strong EMP, covering a few thousand square kilometers. However, the effects of the radiation would be meaningless, because the blast would destroy most structures in the area. A high-altitude burst, on the other hand, presents a real threat to all types of communications and electronic systems. Such an explosion would generate an EMP with a radius of more than 1000 km, a large portion of the U.S.

The sudden release of gamma rays in a nuclear explosion would cause almost instant ionization (the removal of electrons from atoms) of the atmospheric gases that surround the detonation area. Free electrons are driven outward. In a high-altitude event, the gamma rays travel great distances before ionizing the upper atmosphere. The forced movement of these electrons, which will again recombine with atoms in the atmosphere, creates a pulsed electromagnetic field.

The amplitude and polarization of the field produced by a high-altitude detonation depends on the altitude of the burst, the yield of the device, and the orientation of the burst with respect to the receiving point. The EMP field creates a short but intense broadband radio frequency pulse with significant energy up to 100 MHz. Most of the radiated energy, however, is concentrated below 10 MHz. Figure 9.16 shows the distribution of energy as a function of frequency. The electric field can be greater than 50 kV/m, with a rise time measured in the tens of nanoseconds. Figure 9.17 illustrates the field of a simulated EMP discharge.

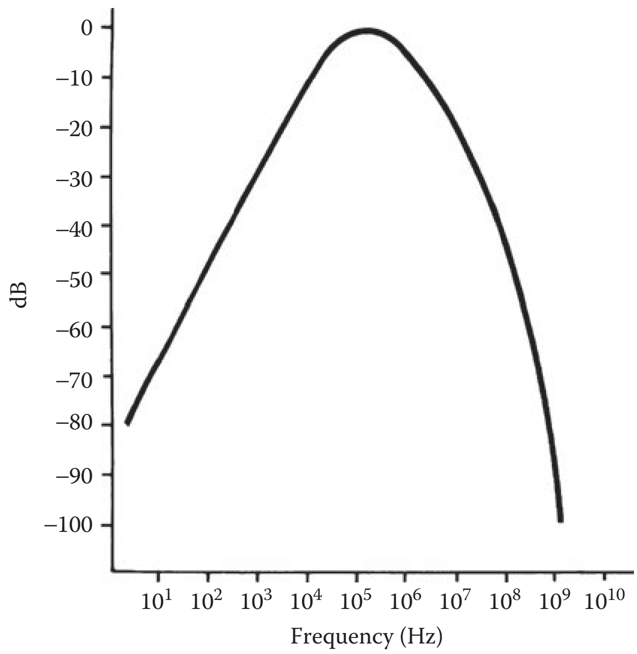

Figure 9.16 Normalized EMP spectrum. Approximately 99% of the radiated energy is concentrated between 10 kHz and 100 MHz.

Many times, lightning and other natural occurrences cause problems not because they strike a given site, but because they strike part of the utility power system and are brought into the facility via the ac lines. Likewise, damage that could result from EMP

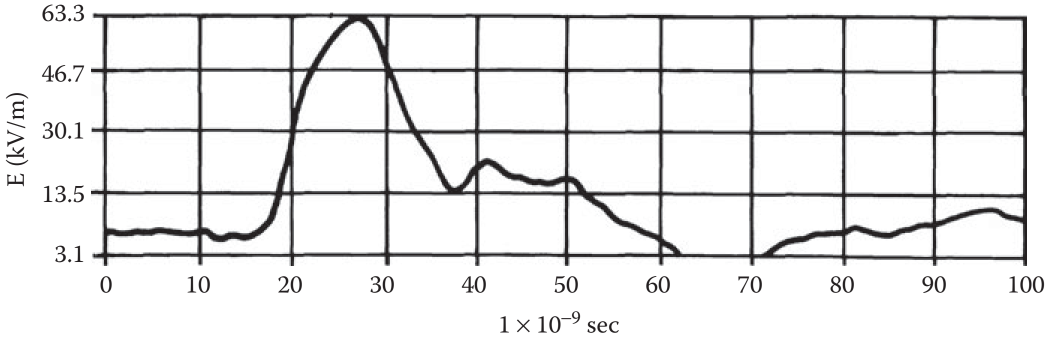

Figure 9.17 Discharge waveform for a nuclear EMP event.

Table 9.1 Effects of an EMP Event on Various Systems

Type of Conductor	Rise Time (s)	Peak Voltage (V)	Peak Current (A)
Long unshielded cable (power line, long antenna)	10^{-8} to 10^{-7}	10^5 to 5×10^6	10^3 to 10^4
HF antenna system	10^{-8} to 10^{-7}	10^4 to 10^6	500 to 10^4
VHF antenna system	10^{-9} to 10^{-8}	10^3 to 10^5	100 to 10^3
UHF antenna system	10^{-9} to 10^{-8}	100 to 10^4	10 to 100

radiation would be most severe to equipment connected to the primary power source, because it is generally the most exposed part of any facility. Table 9.1 lists the response of various systems to an EMP event.

9.2.6 Coupling Transient Energy

The utility power-distribution system can couple transient overvoltages into a customer's load through induction or direct-charge injection. As stated previously, a lightning flash a mile away from a 12 kV line can create an electromagnetic field with a strength of 70 V/m or more. Given a sufficiently long line, substantial voltages can be coupled to the primary power system without a direct hit. Likewise, the field created by EMP radiation can be coupled to the primary power lines, but in this case at a much higher voltage (50 kV/m). Considering the layout of many parts of the utility company power system — long exposed lines over mountaintops and the like — the possibility of a direct lightning flash to one or more legs of the system is a distinct one.

Lightning is a point charge-injection process, with pulses moving away from the point of injection. The amount of total energy (voltage and current) and the rise and decay times of the energy seen at the load as a result of a lightning flash are functions of the distance between the flash and the load and the physical characteristics of the power-distribution system. Determining factors include:

- Wire size
- Number and sharpness of bends
- Types of transformers
- Types of insulators
- Placement of lightning suppressors

The character of a lightning flash covers a wide range of voltage, current, and rise-time parameters. Making an accurate estimate of the damage potential of a flash is difficult. A direct hit to a utility power line causes a high-voltage, high-current wave to travel away from the point of the hit in both directions along the power line. The waveshape is sawtooth in form, with a rise time measured in microseconds or nanoseconds. The pulse travels at nearly the speed of light until it encounters a significant change in line impedance. At this point, a portion of the wave is reflected back down the line in the direction from which it came. This action creates a standing wave containing the combined voltages of the two pulses. A high-energy wave of this type can reach a potential sufficient to arc over to another parallel line, a distance of about 8 ft on a local feeder (typically 12 kV) power pole.

9.3 Equipment-Caused Transient Disturbances

Equipment-caused transients in the utility power system are a consequence of the basic nature of alternating current. A sudden change in an electric circuit will cause a transient voltage to be generated because of the stored energy contained in the circuit inductances (*L*) and capacitances (*C*). The size and duration of the transient depend on the values of *L* and *C* and the waveform applied.

A large step-down transformer, the building block of any power system, normally will generate transient waveforms when energized or de-energized. As illustrated in Figure 9.18, the stray capacitances and inductances of the secondary can generate a brief oscillating transient of up to twice the peak secondary voltage when the transformer is energized. The length of this oscillation is determined by the values of *L* and *C* in the circuit.

A more serious problem can be encountered when energizing a step-down transformer. The load is, in effect, looking into a capacitive divider from the secondary into the primary. If the interwinding capacitance is high and the load capacitance is low, a spike of as much as the full primary voltage can be induced onto the secondary, and thus, onto the load. This spike does not carry much energy because of its short duration, but sensitive equipment on the load side could be damaged upon reapplication of power to a utility company pole transformer, for example, as would occur after a power outage. A typical transformer may have 0.002 pF series capacitance from input to output. (See Figure 9.19.) A simple Faraday shielded isolation transformer can reduce this series capacitance to 30 pF, nearly two orders of magnitude lower.

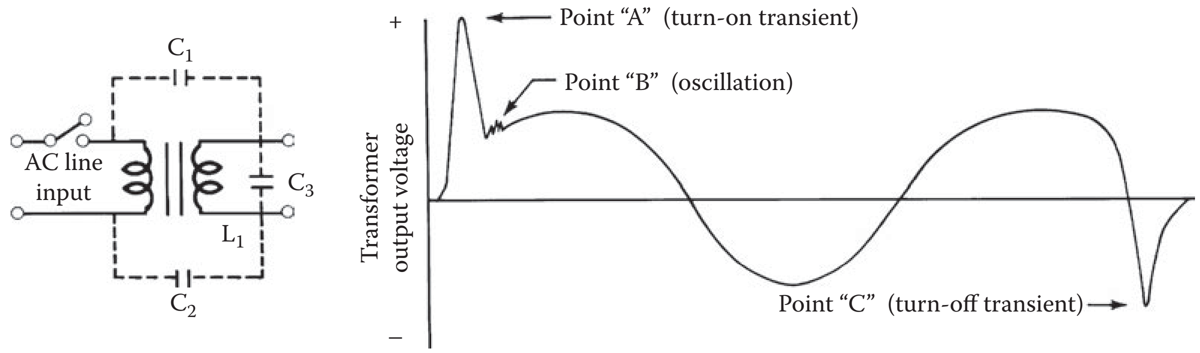

Figure 9.18 The causes of inductor turn-on and turn-off spikes. The waveforms are exaggerated to illustrate the transient effects. C_1, C_2, and C_3 are stray capacitances that form a divider network between the primary and secondary, causing the turn-on spike shown at point *A*. The oscillation shown at point *B* is caused by the interaction of the inductance of the secondary (L_1) and C_3. The spike shown at point *C* is the result of power interruption to the transformer primary, which causes the collapsing lines of flux to couple a high-voltage transient into the secondary circuit.

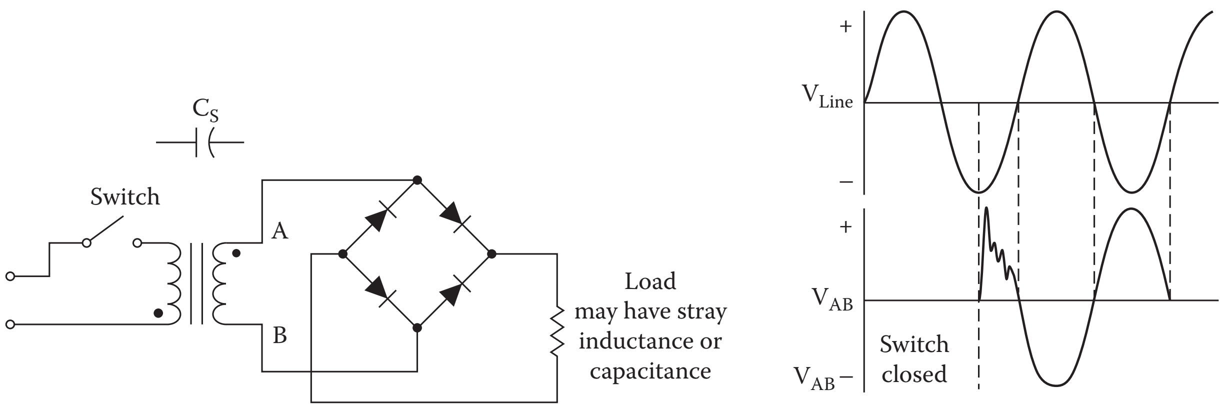

Figure 9.19 Transient produced as a result of transformer capacitance during power-on condition. (*After* [4].)

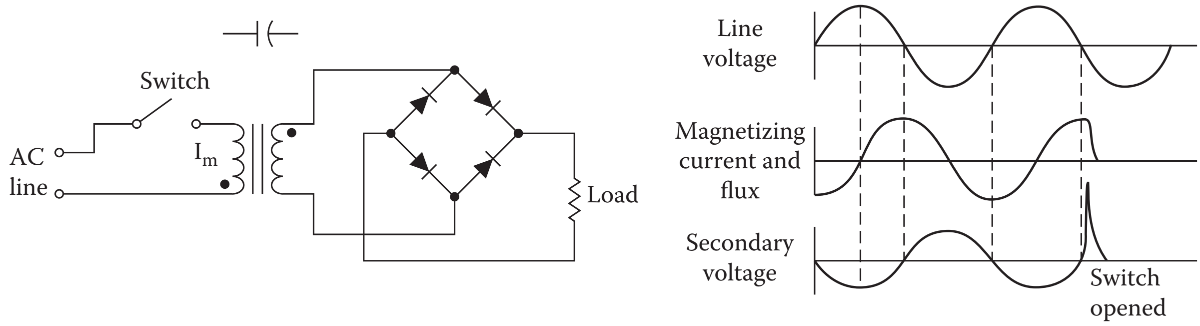

Figure 9.20 Transient generated when interrupting the transformer magnetizing current. (*After* [4].)

De-energizing a large power transformer also can cause high-voltage spikes to be generated. Interrupting the current to the primary windings of a transformer, unless switched off at or near the zero crossing, will cause the collapsing magnetic lines of flux in the core to couple a high-voltage transient into the secondary circuit, as illustrated in Figure 9.20. If a low-impedance discharge path is not present, this spike will be impressed upon the load. Transients in excess of 10 times the nominal secondary voltage have been observed when this type of switching occurs. Such spikes can have damaging results to equipment on-line. For example, the transient produced by interrupting the magnetizing current to a 150 kVA transformer can measure 9 joules (J). Whether these turn-on, turn-off transients cause any damage depends on the size of the transformer and the sensitivity of the equipment connected to the transformer secondary.

9.3.1 Utility System Faults

Various utility fault conditions can result in the generation of potentially damaging overvoltage transients. For example, the occurrence of a fault somewhere in the local power-distribution network will cause a substantial increase in current in the step-down transformer at the local area distribution substation. When a fuse located near the fault opens the circuit, the excess stored energy in the magnetic lines of flux of the transformer will cause a large oscillating transient to be injected into the system.

Routine load switching by the utility will have a similar, albeit less serious, effect. Such transient voltages can be quite frequent and, in some instances, harmful to equipment rectifier stacks, capacitors, and transformer. The magnitude of utility company switching transients usually is independent of power-system voltage ratings, as illustrated in Figure 9.21.

9.3.2 Switch Contact Arcing

Transients generated by contact bounce occur not only because of physical bouncing upon closing or opening, but also because of arcing between contacts, the result of transients that are generated when an inductive load is de-energized. The principle is illustrated in Figure 9.22. When current is interrupted to an inductor, the magnetic lines of flux will try to maintain themselves by charging stray capacitances. The current will oscillate in the inductance and capacitance at a high frequency. If sufficiently high voltages are generated in this process, an arc will jump the contacts after they have opened, clearing the oscillating current. As the contacts separate further, the process is repeated until the voltage generated by the collapsing lines of flux is no longer sufficient to jump the widening gap between the contacts. This voltage then may look for another discharge path, such as interwinding arcing or other components in parallel with the inductor. Contact arcing also may occur when an inductor is switched on, if the contacts bounce open after first closing. Figure 9.23 illustrates typical contacting characteristics for energizing a relay mechanism; de-energizing of relay contacts is illustrated in Figure 9.24.

It should be noted that the ringing of an inductive circuit exposed to a transient disturbance produces not only the overshoot that most engineers are familiar with, but also a potentially damaging undershoot. This effect is illustrated in Figure 9.25. Sudden and severe polarity reversals such as the one illustrated can have damaging effects on semiconductor devices.

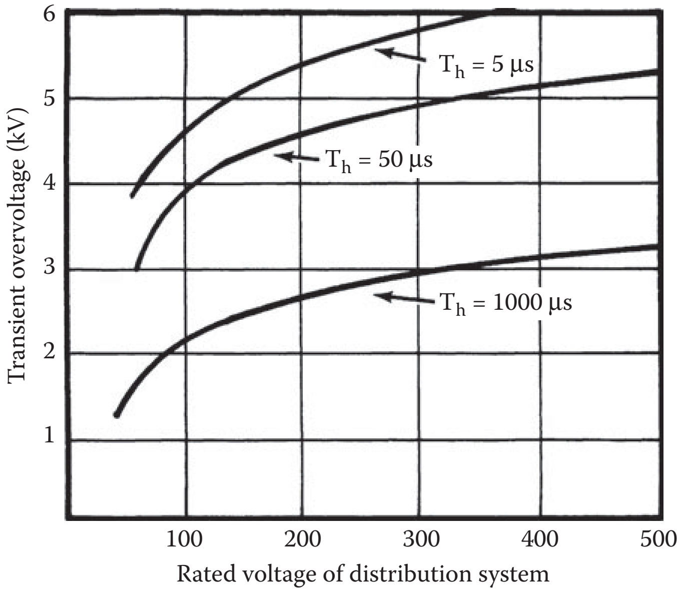

Figure 9.21 The relationship (computed and measured) between utility company system voltage and switching transient peaks. Switching transients are plotted as a function of nominal operating voltages for three values of the transient tail time to half-potential. It can be seen that there is no direct linear increase in transient amplitude as the system voltage is increased.

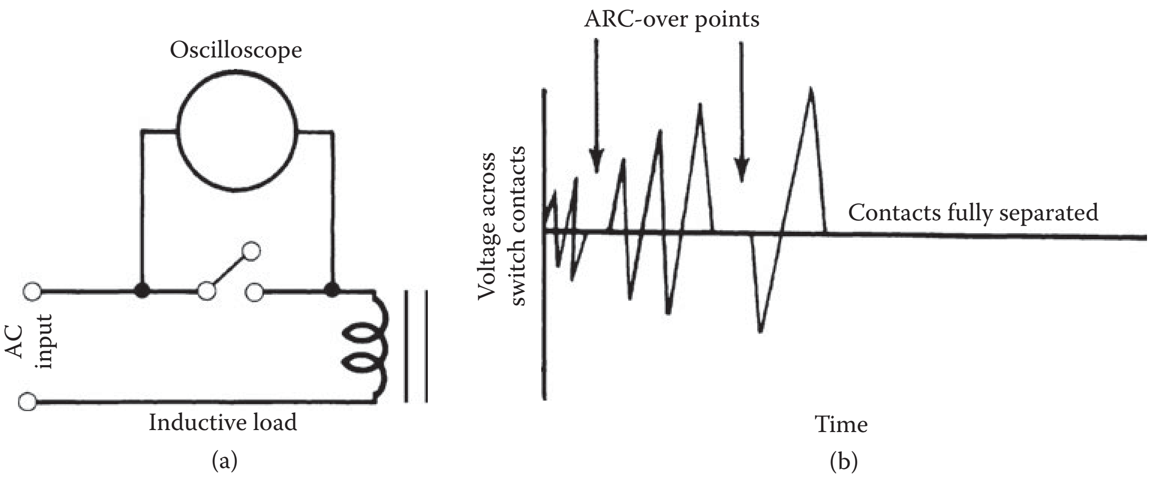

Figure 9.22 The mechanics of contact bounce: (*a*) measurement configuration; (*b*) representative waveforms. The waveforms shown are exaggerated to illustrate the transient effects. For clarity, the modulating effect of the ac line voltage is not shown.

9.3.3 Telephone System Transients

Overvoltages on telephone loops and data lines generally can be traced to the 60 Hz power system and lightning. Faults, crossed lines, and bad grounding can cause energy to be injected into or coupled onto telco circuits from utility company power lines when the cables share common poles or routing paths. Direct lightning hits to telco lines will generate huge transients on low-level audio, video, or data circuits. Buried phone company cables also are subject to damaging transients because of charge movements in the earth resulting from lightning flashes and cloud-to-loud discharge activity. Voltages can be induced in cable shield material and in the lines themselves. EMP radiation can penetrate a buried telco line in a similar manner.

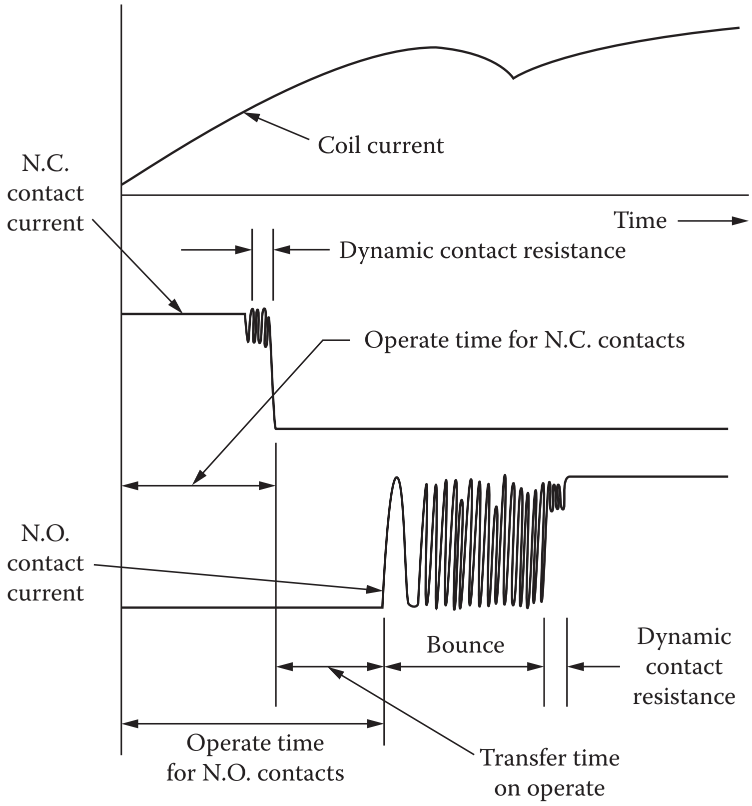

Figure 9.23 The mechanics of relay contact bounce during the energizing period.

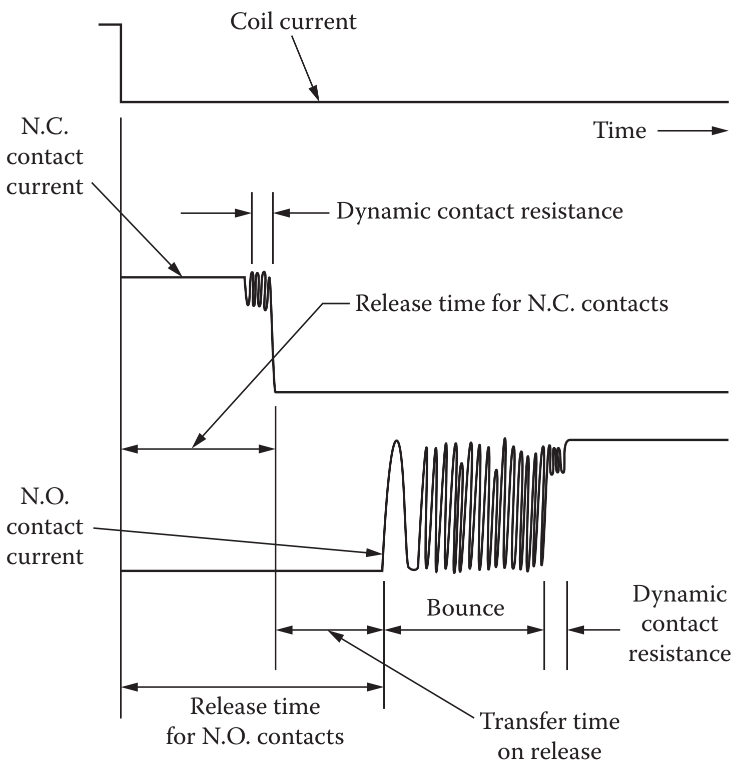

Figure 9.24 The mechanics of relay contact bounce during the de-energizing period.

Lightning or other transient currents usually travel along a telephone cable shield until dissipated, either through ground connections (in the case of pole-mounted cables) or through cable-to-earth arc-overs (in the case of buried cables). This activity usually does not cause damage to the shield material itself, but it can induce transient voltages on internal conductors, which may be harmful to central office equipment or end-user devices and systems. The characteristics of the transient that can appear at the end of a telco cable are a function of the following variables:

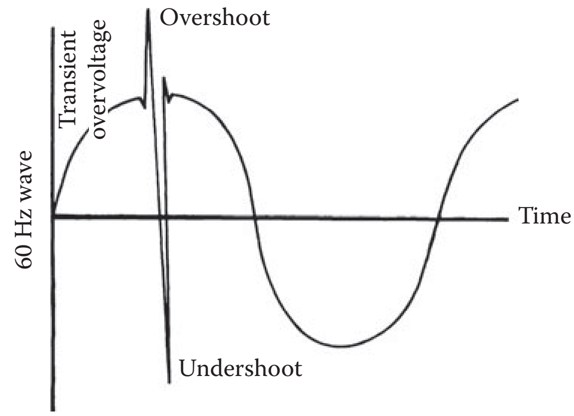

Figure 9.25 The "iceberg" effect of many transient waveforms. The overshoot often is followed by an equally damaging undershoot before leveling off.

- Distance from the disturbance to the measuring point
- Type of cable used, including the jacket thickness, shielding material and thickness, and internal conductor wire size
- Amplitude and waveform of the lightning current in the cable shield

The current-generated potential along the cable shield is capacitively coupled to the internal cable pairs, so the waveform of the transient voltage observed at the measuring point (measured between ground and either conductor of a pair) closely resembles the waveform of the lightning current. The induced spike will propagate as a traveling wave in both directions along the cable from the point of injection or region of induction.

9.3.4 Nonlinear Loads and Harmonic Energy

Motors, incandescent lighting, and heating loads are linear in nature [5]. That is, the load impedance is essentially constant regardless of the applied voltage. As illustrated in Figure 9.26, in ac circuits, the current increases proportionately as the voltage increases, and decreases proportionately as the voltage decreases. The current is in phase with the voltage for a resistive circuit with a power factor (PF) of unity. It lags the voltage by some phase angle for the more typical partially inductive circuit (with a PF commonly between 0.80 and 0.95) and leads the voltage by some phase angle in a capacitive circuit. In either case, this current is always proportional to the voltage. For a sinusoidal voltage, the current is also sinusoidal.

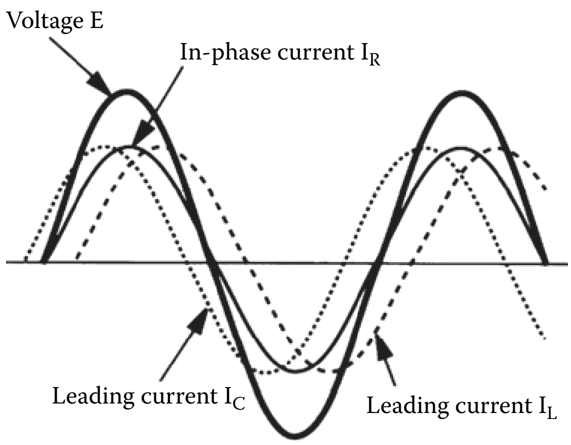

Figure 9.26 The relationship of linear current waveforms: I_R is a purely resistive circuit curent, I_L is a partically inductive (lagging) circuit current, and I_c is a particially capactive (leading) circuit current. (From [5]. Used with permission.)

A nonlinear load is one in which the load current is not proportional to the instantaneous voltage. In this case, illustrated in Figure 9.27, the load current is not continuous. Nonlinear loads typically are switched on for only a portion of the ac cycle — as in a thyristor-controlled circuit — or pulsed — as in a controlled rectifier circuit. Nonlinear load currents are nonsinusoidal, and even when the source voltage is a clean sine wave, the nonlinear load will distort the voltage wave, making it nonsinusoidal.

Certain deviations from the pure sine wave are the equivalent of adding one or more other pure sine waves of different frequencies. Any waveshape, in fact, can be reproduced exactly by adding together a series of sine waves of particular frequency, amplitude, and timing, although it may require an infinite number of these waveforms. Nonsinusoidal waveforms, therefore, consist of (and can be broken down into) some finite number of pure sine waves.

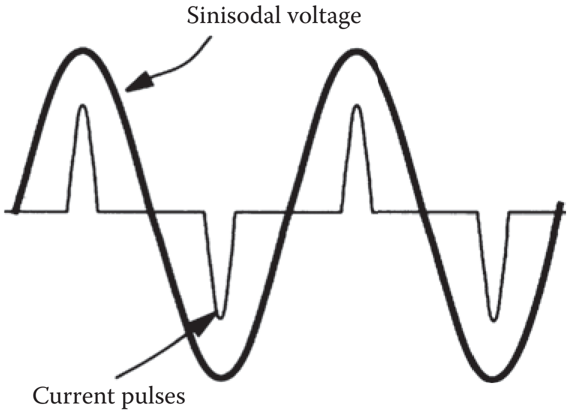

Figure 9.27 Typical waveforms of nonlinear load current. (*From* [5]. *Used with permission.*)

The most common sine waves that distort a power system are whole number multiples of the fundamental 60 Hz power frequency, commonly known as *harmonics*. Although traditional linear loads allow voltages and currents of the fundamental frequency to appear in the power system with little or no harmonic currents, nonlinear loads can introduce significant levels of harmonics into the system. Harmonic energies combine with the fundamental to form distorted waveforms of the type shown in Figure 9.28. The amount of distortion is determined by the frequency and amplitude of the harmonic currents.

In a three-phase, four-wire system, single-phase line-to-neutral load currents flow in each phase conductor and return in the common neutral conductor. The three 60 Hz phase currents are separated by 120°, and for balanced three-phase linear loads, they are equal. When these currents return in the neutral, they cancel each other, adding up to zero at all points. Thus, for balanced three-phase, 60 Hz loads, neutral current is zero.

For second harmonic currents separated by 120°, cancellation in the neutral also is complete (see Figure 9.29), resulting in zero neutral current. This is true for all even harmonics.

For third harmonic currents, the return currents from each of the three phases are in phase in the neutral (Figure 9.30), and so the total third harmonic neutral current is the arithmetic sum of the three individual third harmonic phase currents. This is also true for all odd multiples of the third harmonic (9th, 15th, 21st, and so on), which are the additive *zero sequence* currents.

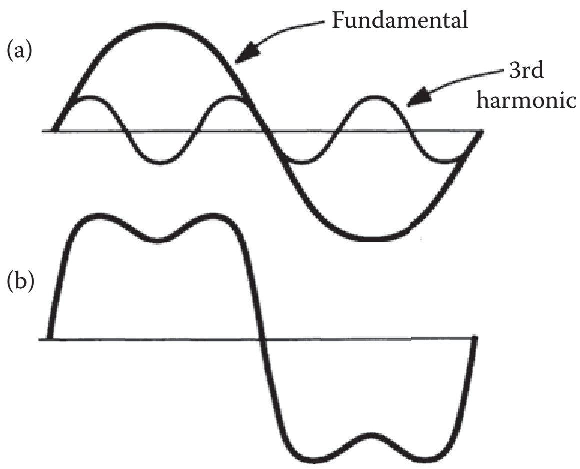

Figure 9.28 The addition of 60 Hz fundamental and 3rd harmonic waveshapes: (*a*) individual waveforms, (*b*) resulting distorted waveshape. (*From* [5]. *Used with permission.*)

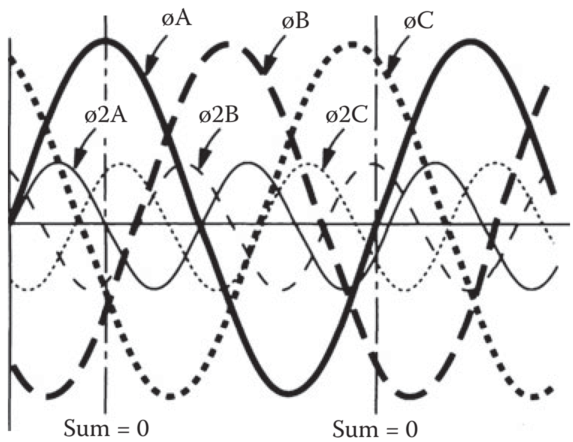

Figure 9.29 Fundamental and 2nd-harmonic currents in a three-phase, four-wire circuit. At any point, the sum of the positive (+) and negative (–) currents equals zero for the fundamental current, the 2nd-harmonic current, and — in similar fashion — all even-harmonic currents. Therefore, for balanced loads on a three-phase, four-wire system, no 60 Hz or even-harmonic currents flow in the common neutral. (*From* [5]. *Used with permission.*)

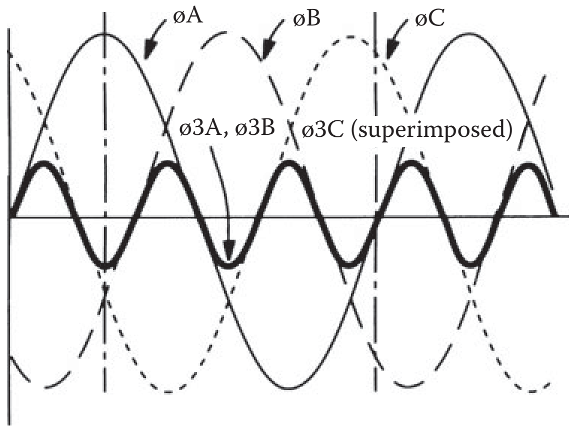

Figure 9.30 Fundamental and 3rd-harmonic currents. Third-harmonic currents are equal and in phase (the curves are superimposed). At any point, the sum of the harmonic currents equals three times the value of any one of the currents. This also is true for all odd multiples of the 3rd-harmonic (9th, 15th, 21st, and so on). Other odd harmonics are also additive, but not fully, because they are equal but not exactly in phase. The total neutral current for other odd harmonics (5th, 7th, 11th, etc.) is more than any one harmonic phase current, but less than three times any harmonic phase current. (*From* [5]. *Used with permission*.)

Other odd harmonics (5th, 7th, 11th, 13th, and so on) add in the neutral, but the total neutral-harmonic current is somewhat less than the arithmetic sum of the three harmonic phase currents. Mathematically, the total is the vector sum of the three currents. The phase angles between the three phase currents result in partial addition and partial cancellation.

The theoretical maximum neutral current with harmonics is at least 1.73 and perhaps as much as 3.00 times the phase current. (There is dispute as to the true maximum value between these limits.)

For pulsed loads, the pulses can occur in each phase at a different time. They will return in the common neutral, but they will be separated by time; therefore, there will be no cancellation. If none of the pulses overlap, the neutral current can be three times the phase current, as illustrated in Figure 9.31.

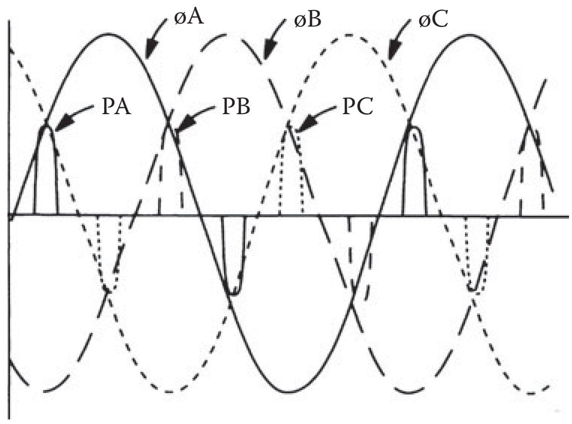

Figure 9.31 Fundamental and pulsed currents. The sum of the pulses in the neutral equals three times the rms value of any one phase pulse because there is little or no overlap or cancellation. The rms current in the neutral depends on each single-phase pulse rms current, and the pulse shape, frequency, and duration. (*From* [5]. *Used with permission*.)

The effects of additive harmonics in the neutral were first recognized in the National Electrical Code (NEC) many years ago, when Sec. 230-22 prohibited reduced neutral conductor size for that portion of the load consisting of discharge lighting. The effects of electronic equipment were recognized in the 1987 NEC when the prohibition in Sec. 230-22 against reducing the neutral was expanded to include loads from data processing and similar equipment.

Ratings of transformers and generators are based on the heating created by load currents of an undistorted 60 Hz sine wave. When the load currents are nonlinear and have a substantial harmonic content, they cause considerably more heating than the same number of amperes of a pure sine wave. There are several major reasons for this, including:

- Hysteresis
- Eddy currents
- Skin effects

These parameters were discussed in Section 1.4.

As harmonic currents are drawn by various loads, they act on the impedance of the source, causing harmonic distortion of the source voltage. Although motors are normally linear loads, when the supply voltage has harmonic distortion, motors draw harmonic currents. These harmonic currents cause excessive motor heating from higher hysteresis and eddy-current losses in the motor laminations and skin effect in the windings. Thus, motors supplied from sources with voltage distorted by other nonlinear loads also will overheat unless they are derated by a sufficient amount.

The solutions to overheating of transformers, generators, and motors as a result of nonlinear loads are the same as those for neutral overheating. The equipment must be derated or the harmonic content must be reduced by line filters, or both.

In addition to excessive heating, harmonic currents can cause other serious problems for generator installations. Modern generators use electronic means to regulate the output voltage, to control the speed of the engine or prime mover (and, thus, the output frequency of the generator), to parallel generators, and to share the load proportionately among the paralleled units. Many of these control devices use circuits that measure the zero crossing point of the voltage or current wave. At 60 Hz, this system works as intended, but with high harmonic content, there may be more zero crossings than normal for 60 Hz. This can cause hunting and instability in speed and frequency control, and can make the paralleling of generators difficult or impossible.

9.3.4.1 Harmonic Sources

Probably the largest single contributors to the problem of harmonics are the personal computer (PC), office equipment, and other sensitive electronic equipment that utilize switching-type power supplies to produce the working dc voltages they require [5]. These types of supplies generate large amounts of third-harmonic currents (180 Hz).

Switching-mode power supplies, also known simply as "switchers," are used in most modern low-voltage electronic equipment, supplying voltages of between 3 and 15 Vdc. A simplified schematic diagram of a switching-mode supply is given in Figure 9.32. Incoming 60 Hz power is rectified at line voltage by bridge rectifier BR_1 and the high dc voltage is stored in capacitor C_1. The control system switches the dc voltage from BR_1 on and off at a high frequency, which in various designs ranges from 10 to 100 kHz or higher. These high-frequency pulses are stepped down in voltage by transformer TR and rectified by diodes D_1 and D_2. The low-voltage dc is filtered by capacitor C_2 and choke L_2.

The ripple frequency of the dc output from the diodes is twice that of the switching frequency, ranging from 20 to 200 kHz. Because of the high switching frequency, transformer TR and the filter formed by the capacitor and choke can be small and lightweight compared to their 60 Hz equivalents. The output voltage is controlled by the switcher, eliminating the series regulator and its associated losses.

As the load draws power, the switcher takes energy stored in capacitor C_1, lowering the capacitor voltage. When the voltage from rectifier BR_1 exceeds the voltage on C_1, the rectifier delivers a pulse of current to the capacitor. The rectifier starts taking power from the source as the incoming voltage approaches the peak of the sine wave and stops taking power when the voltage from the rectifier drops below the voltage on the capacitor, long before the incoming sine wave voltage reaches zero. These current pulses are extremely nonlinear and high in harmonics.

Although switchers can be the source of noise and harmonic problems, they also have many advantages that dictate their use, including a typical overall efficiency in the neighborhood of 75%, compared to a linear supply efficiency of perhaps 50%, depending upon loading. The improved energy storage of a switching supply also offers longer ride-through — about 16 ms (one cycle) compared to about 4 ms for

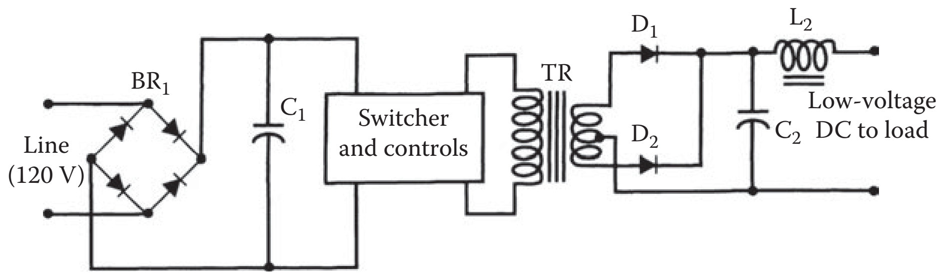

Figure 9.32 Simplified block diagram of a switching-mode power supply. (*From* [5]. *Used with permission.*)

a linear supply. Furthermore, the linear supply usually requires the input voltage to be held to within 10% of nominal, whereas the switcher can tolerate voltage dips of approximately 20%.

Although switchers constitute a major source of harmonic currents, there are many other possible sources. Depending upon the nature of the loads that predominate in a particular facility, these other sources may actually be the main contributors of harmonic currents. Such loads include:

- Fluorescent ballasts. In fluorescent lighting fixtures with conventional magnetic ballasts, the third-harmonic current content is typically in the range of 13 to 20% of the fundamental 60 Hz frequency. Electronic ballasts generate an even higher third-harmonic component, as high as 80% .
- Adjustable speed drives. For power quality considerations, adjustable speed drives can be divided into two basic groups: (1) *voltage source inverter* (VSI) drives, and (2) *current source inverter* (CSI) drives. VSIs use large capacitors in the dc link to provide constant voltage to the inverter. The inverter then chops the dc voltage to provide the variable frequency ac voltage to the motor. CSI drives, on the other hand, are used for larger horsepower applications where custom designs are justified. The dc link consists of a large choke to keep the dc current relatively constant. The inverter then chops this current waveform to provide the variable frequency ac signal to the motor.
- Static UPS systems. In static UPS systems, the incoming ac is rectified to dc, which is then inverted by pulsing circuits back to ac to obtain constant-frequency 60 or 415 Hz ac power. The rectifier voltage control is obtained with thyristors (SCRs). These are gated on (conducting) at any point in the cycle, turn off automatically as the voltage passes through zero, and are gated on again at the same point in each subsequent half-cycle. Output distortion of the UPS for a given load depends on the UPS design and output impedance. Thus, most UPS manufacturers specify the output voltage distortion of their equipment; 5% *total harmonic distortion* (THD) is typical. However, many add a disclaimer, such as "Based on linear loads."
- Controlled rectifiers. A characteristic of all controlled rectifiers is that they are nonlinear and draw currents of high harmonic content from the source. Phase-controlled rectifiers using thyristors do not begin to conduct until gated on; they shut off at or near the zero-crossing.

9.3.5 Carrier Storage

Although the carrier storage phenomenon is rarely a source of serious transient disturbances, its effects should be considered in any critical application. When a silicon diode switches from a forward conduction mode to a reverse blocking state, the presence of stored carriers at the device junction can prevent an immediate cessation of current. These stored carriers have the effect of permitting current to flow in the reverse direction during a brief portion of the ac cycle.

The carrier storage current is limited only by the applied voltage and external circuit design. The current flow is brief, as carriers are removed rapidly from the junction by internal recombination and the sweeping effects of the reverse current. This removal of carriers causes the diode to revert to its blocking condition, and the sudden cessation of what can be a large reverse current may cause damaging voltage transients in the circuit if there is appreciable system inductance and if transient suppression has not been included in the system design.

The reverse current caused by carrier storage usually is not excessive in normal operation of power rectifier circuits. Carrier storage does not, in itself, constitute a hazard, especially at ac power-line frequencies. The carrier storage effect can, however, lead to complications in certain switching arrangements. For example, current will tend to "free-wheel" through rectifier diodes after the supply voltage has been removed in an inductive circuit until the stored energy has been dissipated. If the supply voltage is reapplied while this free-wheeling process is under way, some of the diodes in the circuit will be required to conduct in a forward direction, but others will be required to block. While the latter diodes are recovering from the carrier storage free-wheeling current, a short-circuit effect will be experienced by the source, causing potentially damaging surge currents.

9.3.6 Transient-Generated Noise

Problems can be caused in a facility by transient overvoltages not only through device failure, but also because of logic state upsets. Studies have shown that an upset in the logic of typical digital circuitry can occur with transient energy levels as low as 1×10^{-9} J. Such logic-state upsets can result in microcomputer latchup, lost or incorrect data, program errors, and control-system shutdown. Transient-induced noise is a major contributor to such problems.

Utility company transients, lightning, and ESD are the primary sources of random, unpredictable noise. Unless properly controlled, these sources represent a significant threat to equipment reliability. Although more predictable, other disturbance sources, such as switch contact arcing and SCR switching, also present problems for equipment users.

9.3.6.1 ESD Noise

The upper frequency limit for an ESD discharge can exceed 1 GHz. Determining factors include the voltage level, relative humidity, speed of approach, and shape of the charged object. At such frequencies, circuit board traces and cables function as fairly efficient receiving antennas.

Electrical noise associated with ESD may enter electronic equipment by either conduction or radiation. In the near field of an ESD (within a few tens of centimeters), the primary type of radiated coupling can be either inductive or capacitive, depending on the impedances of the ESD source and the receiver. In the far field, electromagnetic field coupling predominates. Circuit operation is upset if the ESD-induced voltages or currents exceed typical signal levels in the system. Coupling of an ESD voltage in the near field is determined by the impedance of the circuit:

- For a high-impedance circuit, capacitive coupling will dominate and ESD-induced voltages will be the major problem.
- For a low-impedance circuit, inductive coupling will dominate and ESD-induced currents will be the major problem.

9.3.6.2 Contact Arcing

Switch contact arcing and similar repetitive transient-generating operations can induce significant broadband noise into an electrical system. Noise generated in this fashion is best controlled at its source, almost always an inductive load. Noise can travel through power lines and create problems for microcomputer equipment, either through direct injection into the system power supply, or through coupling from adjacent cables or printed wiring board (PWB) traces.

9.3.6.3 SCR Switching

SCR power controllers are a potential source of noise-induced microcomputer problems. Each time an SCR is triggered into its active state in a resistive circuit, the load current goes from zero to the load-limited current value in less than a few microseconds. This step action generates a broadband spectrum of energy, with an amplitude inversely proportional to frequency. Electronic equipment using full-wave SCR control in a 60 Hz circuit can experience such noise bursts 120 times a second.

In an industrial environment, where various control systems may be spaced closely, electrical noise can cause latchup problems or incorrect data in microcomputer equipment, or interaction between SCR firing units in machine controllers. Power-line cables within a facility can couple noise from one area of a plant to another, further complicating the problem. The solution to the SCR noise problem is found by looking at both the source of the interference and the susceptible hardware. The use of good transient-suppression techniques in the application of SCR power controllers will eliminate noise generation in all but the most critical of applications.

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10

Power Disturbance Characterization

10.1 Introduction

Short-term ac voltage disturbances can be classified into four major categories, as illustrated in Figure 10.1. The categories are defined according to peak value and duration:

- *Voltage surge*: An increase of l0 to 35% above the nominal line voltage for a period of 16 ms to 30 s.
- *Voltage sag*: A decrease of 10 to 35% below the nominal line voltage for a period of 16 ms to 30 s.
- *Transient disturbance*: A voltage pulse of high energy and short duration impressed upon the ac waveform. The overvoltage pulse can be 1 to 100 times the nominal ac potential and can last up to 15 ms. Rise times measure in the nanosecond range.
- *Momentary power interruption*: A decrease to zero voltage of the ac power-line potential, lasting from 33 to 133 ms. Longer-duration interruptions are considered power outages.

Voltage surges and sags occasionally result in operational problems for equipment on-line, but automatic protection or correction circuits generally take appropriate actions to ensure that there is no equipment damage. Such disturbances can, however, garble computer system data if the disturbance transition time (the rise/fall time of the disturbance) is sufficiently fast. System hardware also may be stressed if there is only a marginal power supply reserve or if the disturbances are frequent.

Momentary power interruptions can cause a loss of volatile memory in computer-driven systems and place severe stress on hardware components, especially if the ac supply is allowed to surge back automatically without soft-start provisions. Successful system reset may not be accomplished if the interruption is sufficiently brief.

Although voltage sags, surges, and momentary interruptions can cause operational problems for equipment used today, the possibility of complete system failure because of one of these mechanisms is relatively small. The greatest threat to the proper operation of electronic equipment rests with transient overvoltage disturbances on the ac line. Transients are difficult to identify and difficult to eliminate. Many devices commonly used to correct sag and surge conditions, such as ferroresonant transformers or motor-driven autotransformers, are of limited value in protecting a load from high-energy, fast-rise-time disturbances.

In the computer industry, research has shown that a significant number of unexplained problems resulting in disallowed states of operation actually are caused by transient disturbances on the utility feed. With the increased use of microcomputers in industry, this consideration cannot be ignored. Because of the high potential that transient disturbances typically exhibit, they not only cause data and program errors, but also can damage or destroy electric components. This threat to electronic equipment involves sensitive integrated circuits and many other common devices, such as capacitors, transformers, rectifiers, and power semiconductors. Figure 10.2 illustrates the vulnerability of common components to high-energy pulses. The effects of transient disturbances on electronic devices are often cumulative, resulting in gradual deterioration and, ultimately, catastrophic failure.

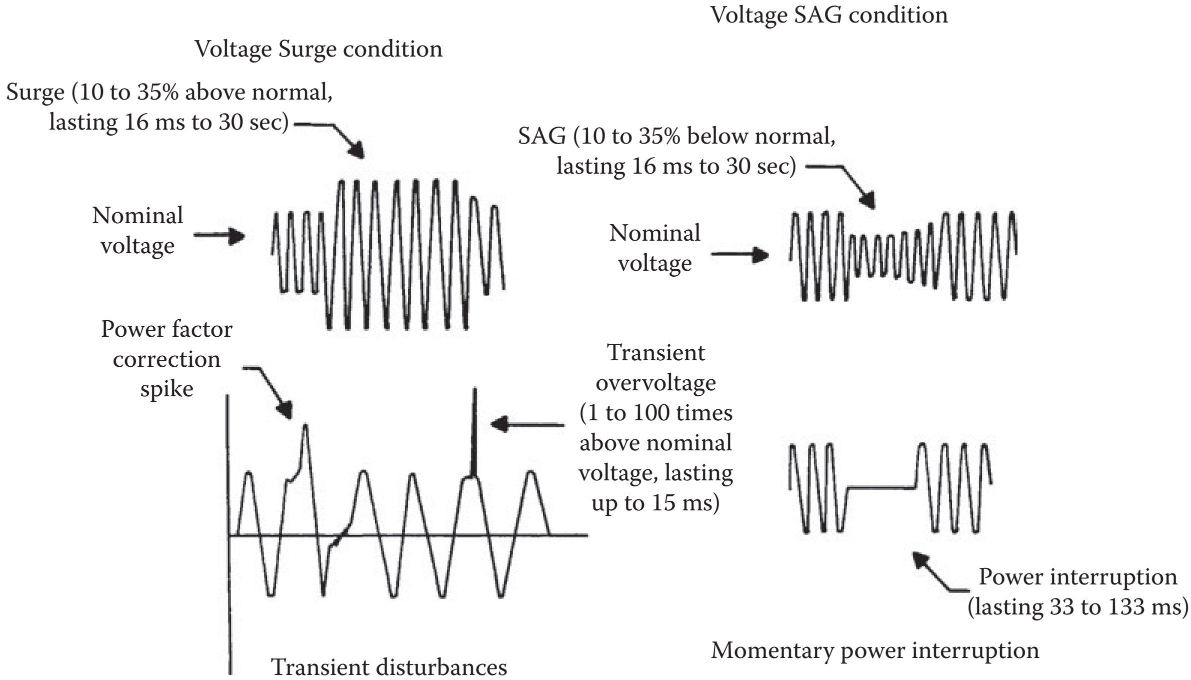


Figure 10.1 The four basic classifications of short-term power-line disturbances.

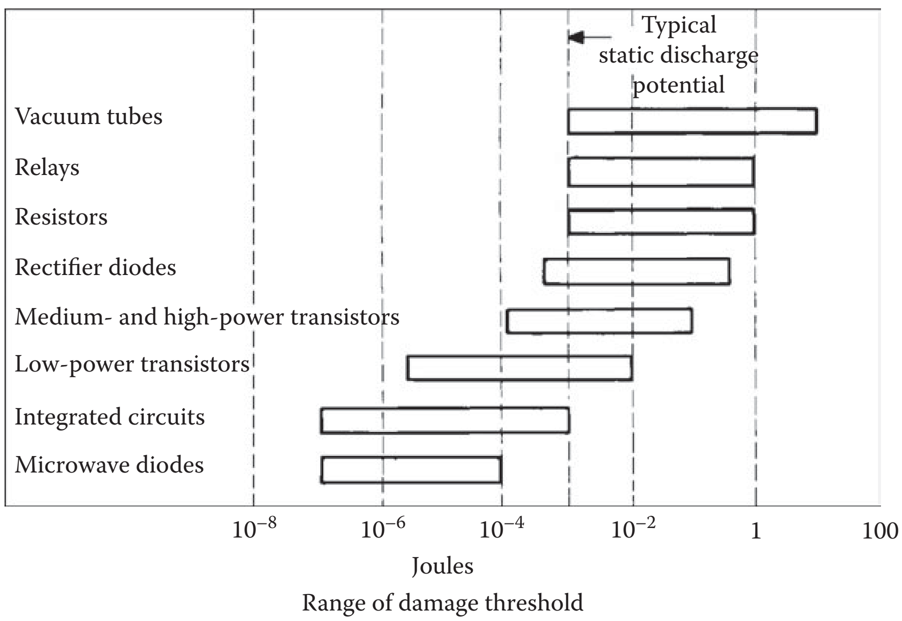


Figure 10.2 An estimation of the susceptibility of common electric devices to damage from transient disturbances. The vertical line marked "discharge" represents the energy level of a discharge that typically can be generated by a person who touches a piece of equipment after walking across a carpeted floor.

10.2 Standards of Measurement

Various test procedures and standards have been developed to enable system designers to evaluate the effectiveness of proposed protective measures. These range from simulation of lightning currents, voltages, and electric and magnetic fields to the generation of typical lightning-induced current and voltage transients expected to appear at the terminals of electronic equipment. Damaging effects can be divided into two basic categories:

- **Direct effects:** Damage to metal and insulator surfaces, and ignition of flammable vapors resulting from direct lightning attachment.
- **Indirect effects:** Damage resulting from the currents and voltages induced in internal circuits by lightning that has struck the exterior of a structure or a vehicle.

Because it is difficult to assess the threat posed by transient disturbances without guidelines on the nature of transients in ac power systems, a number of separate standards have been developed for individual component groups. The best known was developed by a working group of the Institute of Electrical and Electronics Engineers (IEEE) to simulate indirect lightning effects. IEEE suggested two waveforms, one unidirectional and the other oscillatory, for measuring and testing transient suppression components and systems in ac power circuits with rated voltages of up to 1 kV rms line-to-ground. The guidelines also recommend specific source impedance or short-circuit current values for transient analysis.

The voltage and current amplitudes, waveshapes, and source impedance values suggested in the American National Standards Institute/IEEE guide (ANSI/IEEE standard C62.41-1980) were designed to approximate the vast majority of high-level transient disturbances, but were not intended to represent worst-case conditions — a difficult parameter to predict. The timing of a transient overvoltage with respect to the power line waveform is also an important parameter in the examination of ac disturbances. Certain types of semiconductors exhibit failure modes that are dependent on the position of a transient on the sine wave.

Figure 10.3 shows the ANSI/IEEE representative waveform for an indoor-type spike (for 120 to 240 Vac systems). Field measurements, laboratory observations, and theoretical calculations have shown that most transient disturbances in low-voltage indoor ac power systems have oscillatory waveshapes, instead of the unidirectional wave most often thought to represent a transient overvoltage. The oscillatory nature of the indoor waveform is the result of the natural resonant frequencies of the ac distribution system. Studies by the IEEE show that the oscillatory frequency range of such disturbances extends from 30 Hz to 100 kHz, and that the waveform changes, depending upon where it is measured in the power distribution system.

The waveform shown in Figure 10.3 is the result of extensive study by the IEEE and other independent organizations of various ac power circuits. The representative waveshape for 120 and 240 V systems is described as a 0.5 μs to 100 kHz ring wave. This standard indoor spike has a rise time of 0.5 μs, then decays while oscillating at 100 kHz. The amplitude of each peak is approximately 60% of the preceding peak.

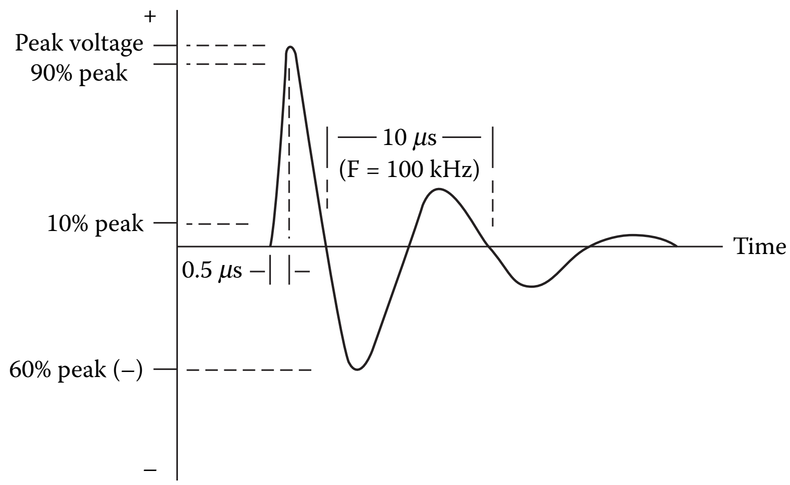


Figure 10.3 The suggested ANSI/IEEE indoor-type transient overvoltage test waveform (0.5 μs to 100 kHz ring wave, open-circuit voltage).

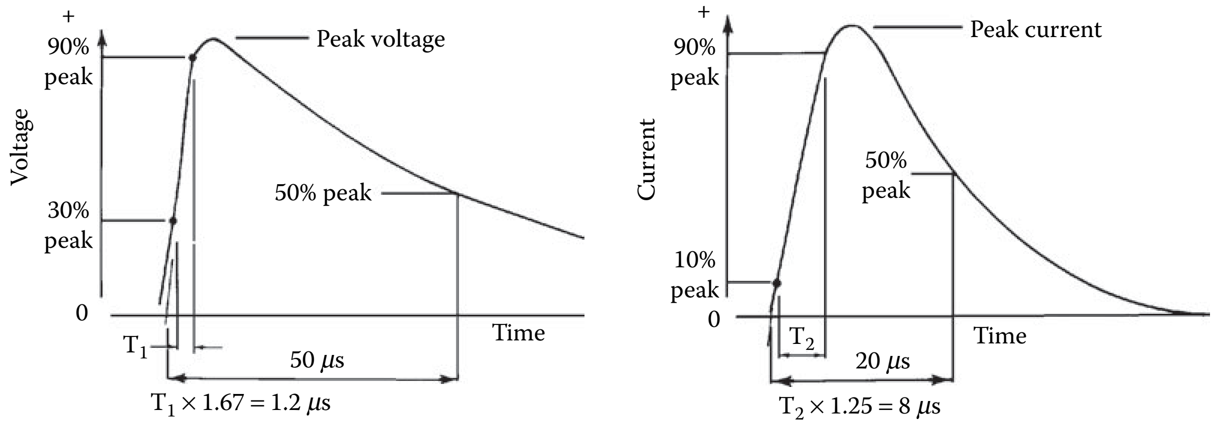


Figure 10.4 The unidirectional waveshape for outdoor-type transient overvoltage test analysis based on ANSI Standard C62.1: (*a*) open-circuit waveform, (*b*) discharge current waveform.

Figure 10.4 shows the ANSI/IEEE representative waveforms for an outdoor-type spike. The classic lightning overvoltage pulse has been established at a 1.2/50 µs waveshape for a voltage wave and an 8/20 µs waveshape for a current wave. Accordingly, the ANSI/IEEE standard waveshape is defined as 1.2/50 µs open-circuit voltage (voltage applied to a high-impedance device), and 8/20 µs discharge current (current in a low-impedance device).

The test waveshapes, although useful in the analysis of components and systems, are not intended to represent all transient patterns seen in low-voltage ac circuits. Lightning discharges can cause oscillations, reflections, and other disturbances in the utility company power system that can appear at the service drop entrance as decaying oscillations.

Unfortunately, most lightning disturbance standard waveforms address one or two characteristics of a discharge. Furthermore, standard waveforms are intended to represent typical events, not worst-case events. In testing to determine the immunity of a system to a direct lightning strike, a conservative approach is generally taken, in that the characteristics of a relatively severe flash are adopted. Figure 10.5 shows a test waveform specified for aerospace vehicles (MIL-STD-1757A). The current waveform includes one initial and one subsequent stroke, between which flows continuing current. Peak currents are 200 kA for the first stroke and 100 kA for the subsequent stroke. The total charge transfer is in excess of 200 C.

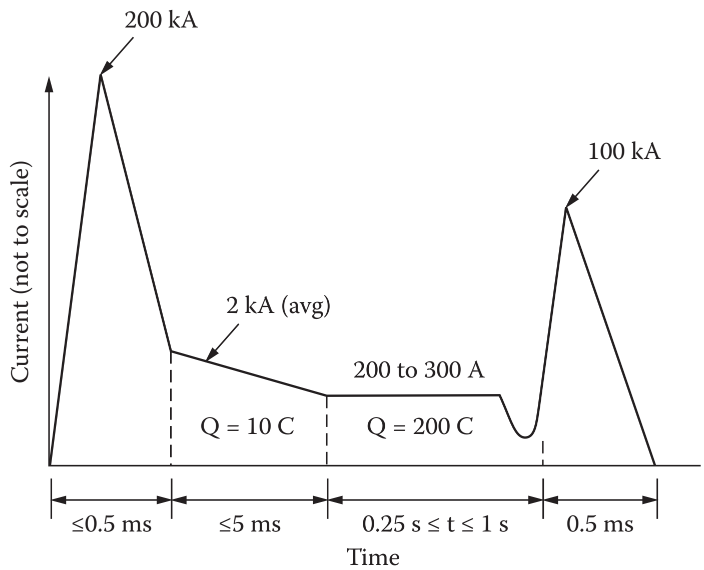


Figure 10.5 Lightning test current waveform specified in MIL STD-1757A. (*After* [1].)

10.2.1 Assessing the Threat

High-speed digital ac line monitoring instruments provide a wealth of information on the quality of incoming utility power at a facility. Such instruments have changed the business of assessing the threat posed by unprocessed ac from an educated guess to a fine science. Sophisticated monitoring equipment can give the user a complete, detailed look at what is coming in from the power company. Such monitoring devices provide data on the problems that can be expected when operating data processing, communications, or other sensitive electronic equipment from an unprotected ac line. Power-quality surveys are available from a number of consulting firms and power-conditioning companies. The typical procedure involves installing a sophisticated voltage-monitoring unit at the site to be used for a period of several weeks to several months. During that time, data is collected on the types of disturbances the load equipment is likely to experience.

The type of monitoring unit used is of critical importance. It must be a high-speed system that stores disturbance data in memory and delivers a printout of the data on demand. Conventional chart recorders are too slow and lack sufficient sensitivity to accurately show short-duration voltage disturbances. Chart recorders can confirm the presence of long-term surge and sag conditions, but provide little useful data on transients.

10.2.2 Fundamental Measurement Techniques

Most power system measurements involve characterizing fundamental parameters. These include voltage, phase, and frequency. Most other tests consist of measuring these fundamental parameters and displaying the results in combination by using some convenient format. Measurements are made on equipment and systems to check performance under specified conditions and to assess suitability for use in a particular application. The measurements can be used to verify specified system performance or as a way of comparing several pieces of equipment for use in a system. Measurements can also be used to identify components in need of adjustment or repair.

Measurement of voltage is fundamental to ac operation. Voltage can be measured either in absolute terms or in relative terms. Power demand is an example of an absolute level measurement; it does not require any reference. Gain and loss are examples of relative, or ratio, measurements.

Distortion measurements are a way of quantifying the amount of unwanted components added to a signal by a piece of equipment. The most common technique is total harmonic distortion (THD), but others can be used. Distortion measurements express the amount of unwanted signal components relative to the desired signal, usually as a percentage or decibel value. This is another example of multiple level measurements that are combined to give a new measurement figure.

The simplest definition of a level measurement is the alternating current amplitude at a particular place in the system under test. However, in contrast to direct current measurements, there are many ways of specifying ac voltage. The most common methods include:

- Root-mean-square
- Average response
- Peak

10.2.2.1 Root-Mean-Square

The rms technique measures the effective power of the ac signal. It specifies the value of the dc equivalent that would dissipate the same power if either were applied to a load resistor. This process is illustrated in Figure 10.6. The input signal is squared, and the average value is found. This is equivalent to finding the average power. The square root of this value is taken to transfer the signal from a power value back to a voltage. For the case of a sine wave, the rms value is 0.707 of its maximum value.

Assume that the signal is no longer a sine wave, but rather a sine wave and several harmonics. If the rms amplitude of each harmonic is measured individually and added, the resulting value will be the same

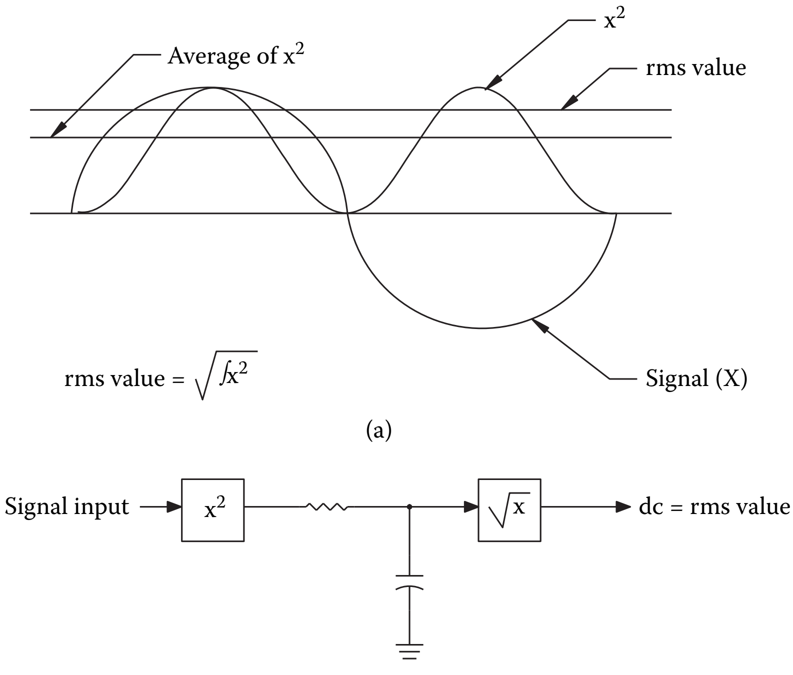


Figure 10.6 Root-mean-square (rms) voltage measurements: (*a*) the relationship of rms and average values, (*b*) the rms measurement circuit.

as an rms measurement on the signals together. Because rms voltages cannot be added directly, it is necessary to perform an rms addition. Each voltage is squared, and the squared values are added as follows:

$$V_{rmstotal} = \sqrt{V^2_{rms1} + V^2_{rms2} + V^2_{rms3} + \ldots + V^2_{rmsn}} \tag{10.1}$$

Note that the result is not dependent on the phase relationship of the signal and its harmonics. The rms value is determined completely by the amplitude of the components. This mathematical predictability is useful in practical applications of level measurement, enabling measurements made at different places in a system to be correlated. It is also important in correlating measurements with theoretical calculations.

10.2.2.2 Average-Response Measurement

The average-responding voltmeter measures ac voltage by rectifying it and filtering the resulting waveform to its average value, as shown in Figure 10.7. This results in a dc voltage that can be read on a standard dc voltmeter. As shown in the figure, the average value of a sine wave is 0.637 of its maximum amplitude. Average-responding meters are usually calibrated to read the same as an rms meter for the case of a single sine wave signal. This results in the measurement being scaled by a constant K of 0.707/0.637, or 1.11. Meters of this type are called *average-responding*, *rms calibrated*. For signals other than sine waves, the response will be different and hard to predict.

If multiple sine waves are applied, the reading will depend on the phase shift between the components and will no longer match the rms measurement. A comparison of rms and average-response measurements is made in Figure 10.8 for various waveforms. If the average readings are adjusted as described previously to make the average and rms values equal for a sine wave, all the numbers in the *average* column should be increased by 11.1%, whereas the *rms-average* numbers are reduced by 11.1%.

10.2.2.3 Peak-Response Measurement

Peak-responding meters measure the maximum value that the ac signal reaches as a function of time. This approach is illustrated in Figure 10.9. The signal is full-wave-rectified to find its absolute value and then passed through a diode to a storage capacitor. When the absolute value of the voltage rises above the

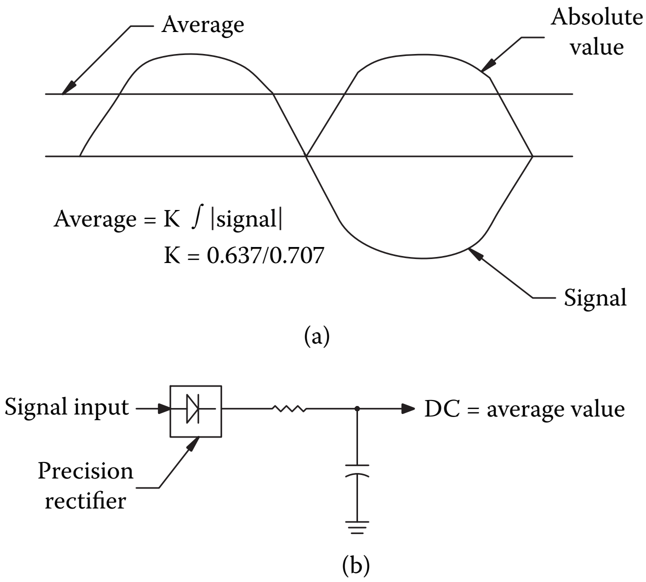
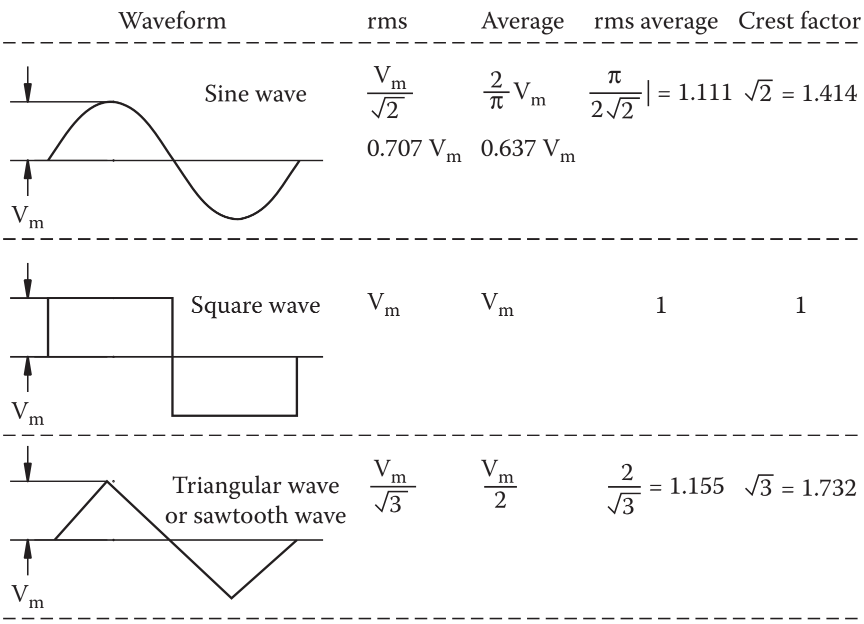


Figure 10.7 Average voltage measurements: (*a*) illustration of average detection, (*b*) average measurement circuit.



Waveform	rms	Average	rms average	Crest factor
Sine wave	$\frac{V_m}{\sqrt{2}}$ $0.707\ V_m$	$\frac{2}{\pi} V_m$ $0.637\ V_m$	$\frac{\pi}{2\sqrt{2}} = 1.111$	$\sqrt{2} = 1.414$
Square wave	V_m	V_m	1	1
Triangular wave or sawtooth wave	$\frac{V_m}{\sqrt{3}}$	$\frac{V_m}{2}$	$\frac{2}{\sqrt{3}} = 1.155$	$\sqrt{3} = 1.732$

Figure 10.8 Comparison of rms and average voltage characteristics.

value stored on the capacitor, the diode will conduct and increase the stored voltage. When the voltage decreases, the capacitor will maintain the old value. Some means for discharging the capacitor is required to allow measuring a new peak value. In a true peak detector, this is accomplished by a solid-state switch. Practical peak detectors usually include a large value resistor to discharge the capacitor gradually after the user has had a chance to read the meter.

The ratio of the true peak to the rms value is called the *crest factor*. For any signal but an ideal square wave, the crest factor will be greater than 1, as demonstrated in Figure 10.10. As the measured signal become more peaked, the crest factor increases.

The *peak-equivalent sine* is another method of specifying waveform amplitude. This value is the rms level of a sine wave having the same peak-to-peak amplitude as the signal under consideration. This is the peak value of the waveform scaled by the correction factor 1.414, corresponding to the peak-to-rms ratio of a sine wave. This technique is useful when specifying test levels of waveforms in distortion measurement.

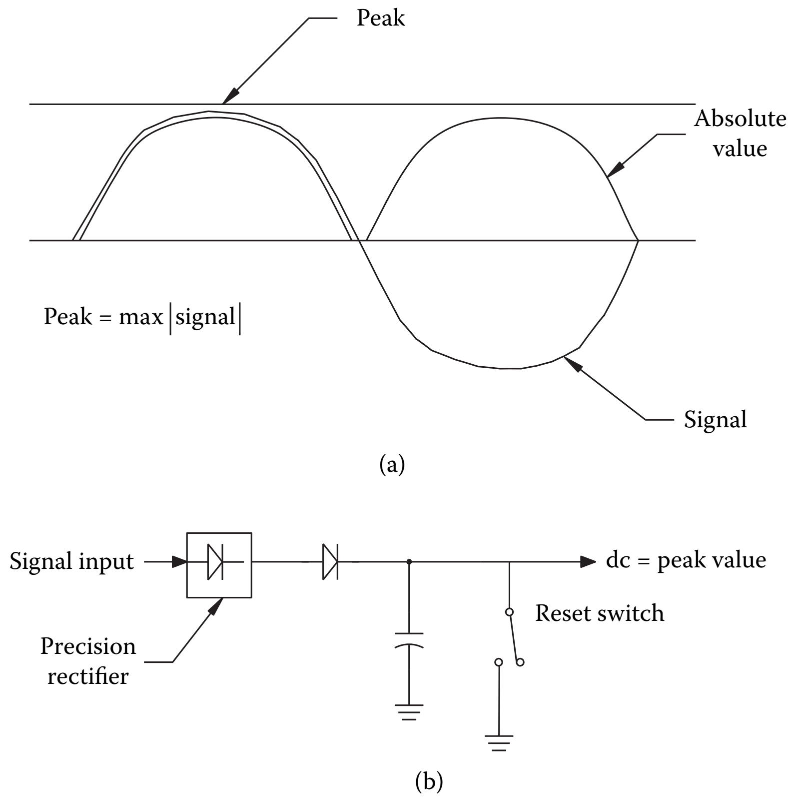


Figure 10.9 Peak voltage measurements: (*a*) illustration of peak detection, (*b*) peak measurement circuit.

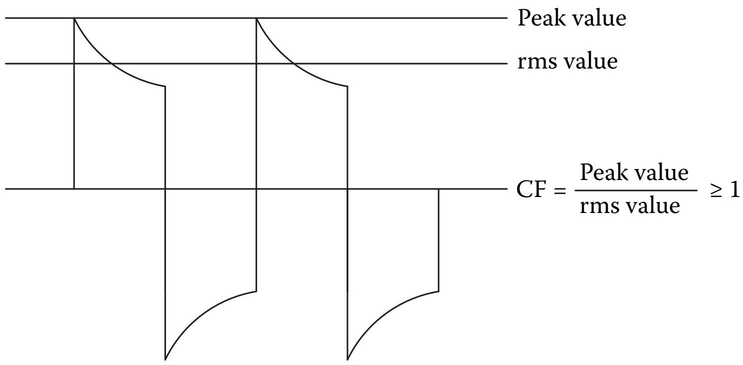


Figure 10.10 The crest factor of ac waveforms.

10.2.2.4 Meter Accuracy

Accuracy is a measure of how well an instrument quantifies a signal at a midband frequency. This sets a basic limit on the performance of the meter in establishing the absolute amplitude of a waveform. It also is important to look at the flatness specification to see how well this performance is maintained with changes in frequency. Flatness describes how well the measurements at any other frequency track those at the reference.

Meters often have a specification on accuracy that changes with voltage range, being most accurate only in the range in which the instrument was calibrated. A meter with 1% accuracy on the 2 V range and 1% accuracy per step would be 3% accurate on the 200 V scale. In many instruments, an additional accuracy derating is given for readings as a% age of full scale, making readings at less than full scale less accurate.

10.2.3 Digital Measurement Instruments

Power quality monitors are sophisticated instruments that can not only identify ac power problems, but also provide the following useful supplementary data, including:

- Ambient temperature
- Relative humidity
- Presence of radio frequency interference (RFI)
- Sample voltage monitoring for ac and dc test points
- Harmonic distortion content of the ac input signal

Digital technology offers a number of significant advantages beyond the capabilities of analog instruments. Digital ac line monitors can store in memory the signal being observed, permitting in-depth analysis impossible with previous technologies. Because the waveform resides in memory, the data associated with the waveform can be transferred to a remote computer for real-time processing, or for processing at a later time.

The *digital storage oscilloscope* (DSO) is the forerunner of most digital ac line monitors. DSO technology forms the basis for most monitoring instruments. Figure 10.11 shows a block diagram of a DSO. Instead of being amplified and applied directly to the deflection plates of a cathode ray tube (CRT), the waveform first is converted into a digital representation and stored in memory. To reproduce the waveform on the CRT, the data is sequentially read and converted back into an analog signal for display.

The analog-to-digital (A/D) converter transforms the input analog signal into a sequence of digital bits. The amplitude of the analog signal, which varies continuously in time, is sampled at preset intervals. The analog value of the signal at each sample point is converted into a binary number. This *quantization* process is illustrated in Figure 10.12. The sample rate of a digital oscilloscope must be greater than two times the highest frequency to be measured. The higher the sampling rate relative to the input signal, the greater the measurement accuracy. A sample rate ten times the input signal is sufficient for most applications. This rule of thumb applies for single-shot signals, or signals that are changing constantly. The sample rate also can be expressed as the *sampling interval*, or the period of time between samples. The sample interval is the inverse of the sampling frequency.

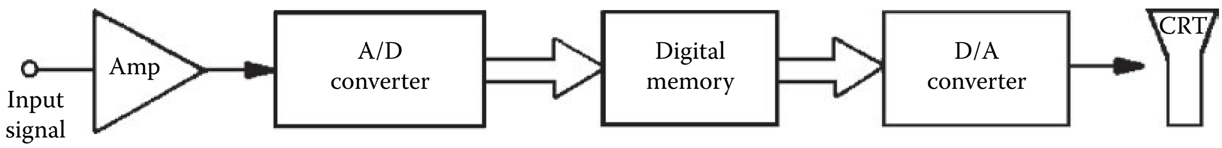


Figure 10.11 Simplified block diagram of a digital storage oscilloscope.

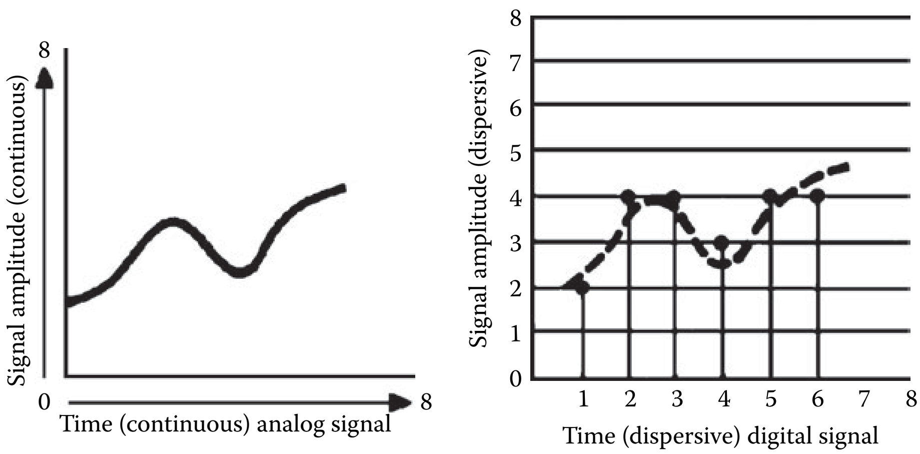


Figure 10.12 Illustration of the quantization process.

10.2.4 Digital Monitor Features

Advanced components and construction techniques have led to lower costs for digital instruments as well as higher performance. Digital monitors can capture and analyze transient signals from any number of sources. Automated features reduce testing and troubleshooting costs through the use of recallable instrument setups, direct parameter readout, and unattended monitoring. Digital monitors offer the following features:

- High resolution (determined by the quality of the analog-to-digital converter).
- Memory storage of digitized waveforms.
- Automatic setup for repetitive signal analysis. For complex multichannel configurations that are used often, front-panel storage/recall can save dozens of manual selections and adjustments. When multiple memory locations are available, multiple front-panel setups can be stored to save even more time.
- Auto-ranging. Many instruments will adjust automatically for optimum sweep, input sensitivity, and triggering. The instrument's microprocessor automatically configures the front panel for optimum display. Such features permit the operator to concentrate on making measurements, rather than adjusting the instrument.
- Instant hardcopy output from printers and plotters.
- Remote programmability via GPIB or dial-up modem (including the Internet) for automated test applications.
- Trigger flexibility. Single-shot digitizing monitors capture transient signals and allow the user to view the waveform that preceded the trigger point. Figure 10.13 illustrates the use of pre-/post-trigger for waveform analysis.
- Signal analysis. Intelligent systems can make key measurements and comparisons. Display capabilities include voltage peak, mean voltage, rms value, rise time, fall time, and frequency.

Digital memory storage offers a number of additional benefits, including:

- Reference memory. A previously acquired waveform can be stored in memory and compared with a sampled waveform. This feature is especially useful for identifying the source of a transient disturbance. Because certain transients have a characteristic "signature" waveform, it is possible to identify the source of a transient by examining an image of the disturbance on a CRT or suitable device. Nonvolatile battery-backed memory permits reference waveforms to be transported to field sites.
- Simple data transfers to a host computer for analysis or archive.
- Local data analysis through the use of a built-in microprocessor.
- Cursors capable of providing a readout of delta and absolute voltage and time.
- Full bandwidth capture of long-duration waveforms, thus permitting storage of all the signal details. The waveform can be expanded after capture to expose the details of a particular section.

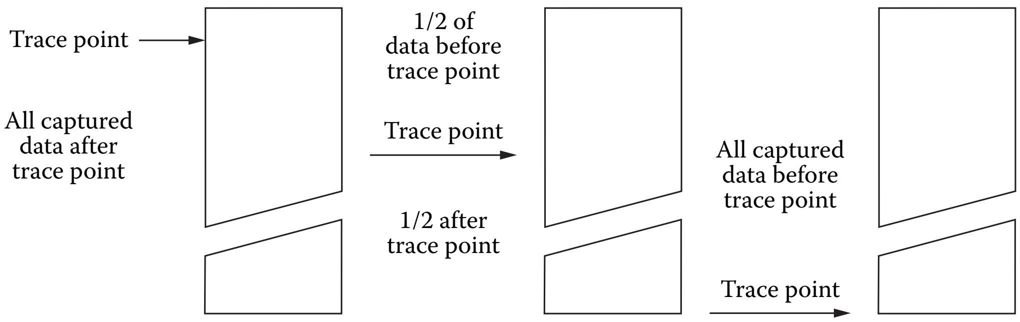


Figure 10.13 The use of a pre-/posttrigger function for waveform analysis.

10.3 Reliability Considerations

Electrical energy is transmitted from the point of generation to end users through a highly complex transmission and control system. This network consists of a grid of conductors with numerous embedded components. A typical system may consist of thousands of nodes. The network is further complicated by the interconnection of individual systems. These interconnected systems must be capable of supplying energy despite diverse and challenging physical conditions. Detailed reliability analysis is required to provide an acceptable level of performance to customers.

It is not uncommon for a utility system to experience load swings of as much as 150 MW/min, mainly the result of changing heavy industrial loads. Such fluctuations introduce a host of challenges to reliability engineers. Primary design requirements include:

- The ability to handle large, constantly changing load demands from customers.
- A strong power source to provide for high inrush currents typically experienced at industrial plants.
- Rapid and effective fault isolation. Failures in one part of the system should have minimal effect on other portions of the network.

Utility companies are meeting these goals with improved reliability analysis, more operating reserve, and computerized control systems. Rapid response to load changes and fault conditions is necessary to ensure reliable service to customers. Improved telemetry systems provide system controllers with more accurate information on the state of the network, and advanced computer control systems enable split-second decisions that minimize service disruptions.

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11

Power System Protection Methods

11.1 Introduction

Utility companies make a good-faith attempt to deliver clean, well-regulated power to their customers. Most disturbances on the ac line are beyond the control of the utility company. Large load changes imposed by customers on a random basis, PF correction switching, lightning, and accident-related system faults all combine to produce an environment in which tight control over ac power quality is difficult to maintain. Therefore, the responsibility for ensuring ac power quality must rest with the users of sensitive equipment.

The selection of a protection method for a given facility is as much an economic question as it is a technical one. A wide range of power-line conditioning and isolation equipment is available. A logical decision about how to proceed can be made only with accurate, documented data on the types of disturbances typically found on the ac power service to the facility. The protection equipment chosen must be matched to the problems that exist on the line. Using inexpensive basic protectors may not be much better than operating directly from the ac line. Conversely, the use of a sophisticated protector designed to shield the plant from every conceivable power disturbance may not be economically justifiable.

Purchasing transient-suppression equipment is only one element in the selection equation. Consider the costs associated with site preparation, installation, and maintenance. Also consider the operating efficiency of the system. Protection units that are placed in series with the load consume a certain amount of power and, therefore, generate heat. These considerations may not be significant, but they should be taken into account. Prepare a complete life-cycle cost analysis of the protection methods proposed. The study may reveal that the long-term operating expense of one system outweighs the lower purchase price of another.

The amount of money a facility manager is willing to spend on protection from utility company disturbances generally depends on the engineering budget and how much the plant has to lose. Spending $250,000 on systemwide protection for a highly computerized manufacturing center is easily justified. At smaller operations, justification may not be so easy.

11.2 The Key Tolerance Envelope

The susceptibility of electronic equipment to failure because of disturbances on the ac power line has been studied by many organizations. The benchmark study was conducted by the Naval Facilities Engineering Command (Washington, DC). The far-reaching program, directed from 1968 to 1978 by Lt. Thomas Key, identified three distinct categories of recurring disturbances on utility company power systems. As shown in Table 11.1, it is not the magnitude of the voltage, but the duration of the disturbance that determines the classification.

In the study, Key found that most data processing (DP) equipment failure caused by ac line disturbances occurred during bad weather, as shown in Table 11.2. According to a report on the findings, the incidence of thunderstorms in an area can be used to predict the number of failures. The type of power-transmission system used by the utility company also was found to affect the number of disturbances observed on power company lines (Table 11.3). For example, an analysis of utility system problems in Washington, DC , Norfolk, VA, and Charleston, SC, demonstrated that underground power-distribution systems experienced one-third fewer failures than overhead lines in the same areas. Based on his research, Key developed the “recommended voltage tolerance envelope” shown in Figure 11.1. The design goals illustrated are recommendations to computer manufacturers for implementation in new equipment.

Table 11.1 Types of Voltage Disturbances Identified in the Key Report (*After* [1].)

Parameter	Type 1	Type 2	Type 3
Definition	Transient and oscillatory overvoltage	Momentary undervoltage or overvoltage	Power outage
Causes	Lightning, power network switching, operation of other loads	Power system faults, large load changes, utility company equipment malfunctions	Power system faults, unacceptable load changes, utility equipment malfunctions
Threshold (1)	200–400% of rated rms voltage or higher (peak instantaneous above or below rated rms)	Below 80–85% and above 110% of rated rms voltage	Below 80–85% of rated rms voltage
Duration	Transients 0.5–200 μs wide and oscillatory up to 16.7 ms at frequencies of 200 Hz to 5 kHz and higher	From four–six cycles, depending on the type of power system distribution equipment	From 2–60 s if correction is automatic; from 15 min to 4 hr if manual

(1) The approximate limits beyond which the disturbance is considered to be harmful to the load equipment.

Table 11.2 Causes of Power-Related Computer Failures, Northern Virginia, 1976 (*After* [1].)

	Disturbance		
Recorded Cause	Undervoltage	Outage	Number of Computer Failures
Wind and lightning	37	14	51
Utility equipment failure	8	0	8
Construction or traffic accident	8	2	10
Animals	5	1	6
Tree limbs	1	1	2
Unknown	21	2	23
Totals	80	20	100

Table 11.3 Effects of Power System Configuration on Incidence of Computer Failures (*After* [1].)

	Number of Disturbances		
Configuration	Undervoltage	Outage	Recorded Failures
Overhead radial	12	6	18
Overhead spot network	22	1	23
Combined overhead, weighted (1)	16	4	20
Underground radial	6	4	10
Underground network	5	0	5
Combined underground, weighted (1)	5	2	7

(1) The combined averages weighted based on the length of time monitored (30 to 53 months).

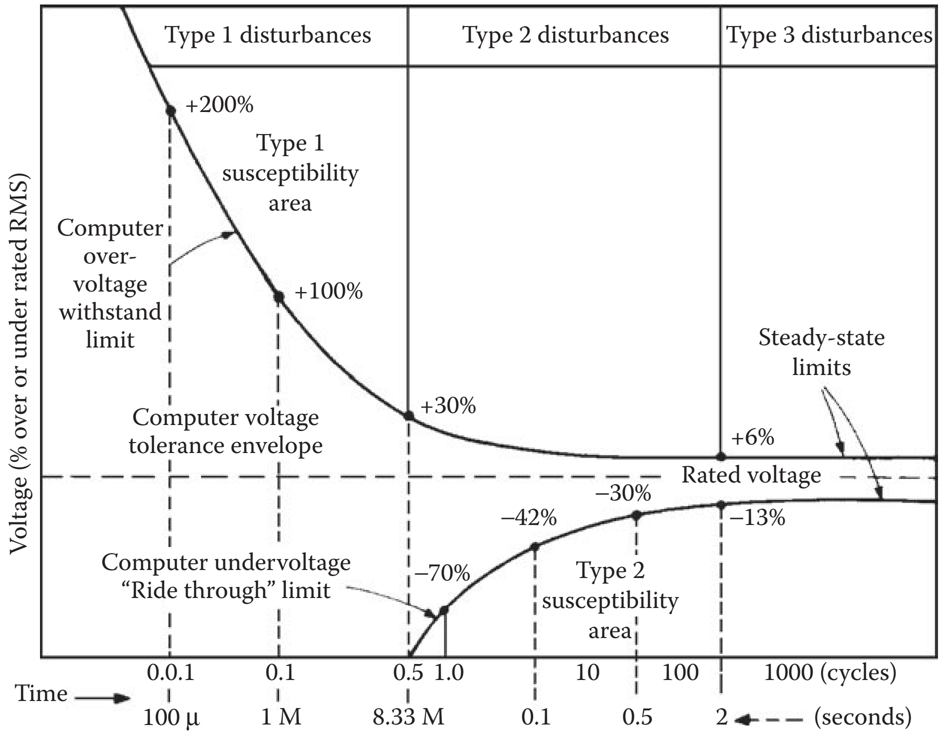

Figure 11.1 The recommended voltage tolerance envelope for computer equipment. This chart is based on pioneering work done by the Naval Facilities Engineering Command. The study identified how the magnitude *and* duration of a transient pulse must be considered in determining the damaging potential of a spike. The design goals illustrated in the chart are recommendations to computer manufacturers for implementation in new equipment. (*After* [1].)

11.3 Assessing the Lightning Hazard

As identified by Key in his Naval Facilities study, the extent of lightning activity in an area significantly affects the probability of equipment failure caused by transient activity. The threat of a lightning flash to a facility is determined, in large part, by the type of installation and its geographic location. The type and character of the lightning flash are also important factors.

The *Keraunic number* of a geographic location describes the likelihood of lightning activity in that area. Figure 11.2 shows the *Isokeraunic map* of the U.S., which estimates the number of lightning days per year across the country. On average, 30 storm days occur per year across the continental U.S. This number does not fully describe the lightning threat because many individual lightning flashes occur during a single storm.

The structure of a facility has a significant effect on the exposure of equipment to potential lightning damage. Higher structures tend to collect and even trigger localized lightning flashes. Because storm clouds tend to travel at specific heights above the earth, conductive structures in mountainous areas more readily attract lightning activity. The *plant exposure factor* is a function of the size of the facility and the Isokeraunic rating of the area. The larger the physical size of an installation, the more likely it is to be hit by lightning during a storm. The longer a transmission line (ac or RF), the more lightning flashes it is likely to receive.

The relative frequency of power problems is seasonal in nature. As shown in Figure 11.3, most problems are noted during June, July, and August. These high problem rates can be traced primarily to increased thunderstorm activity.

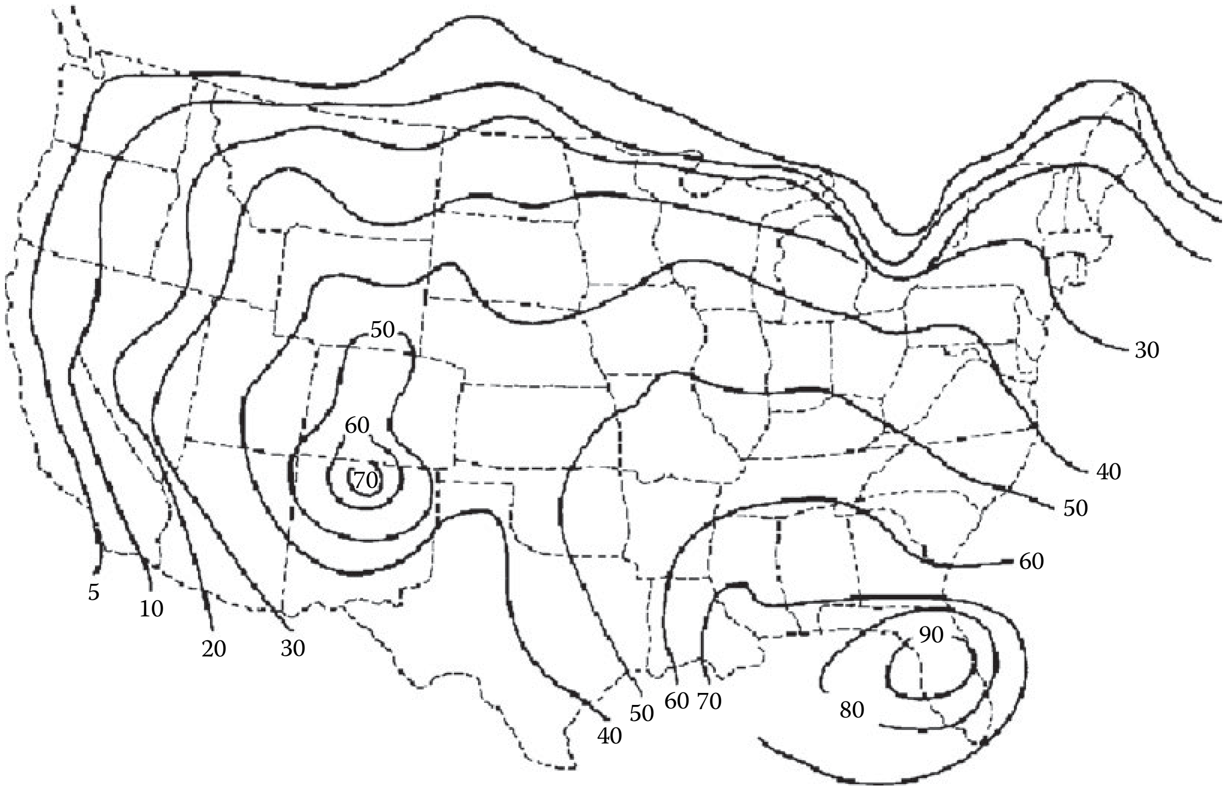

Figure 11.2 The Isokeraunic map of the U.S., showing the approximate number of lightning days per year.

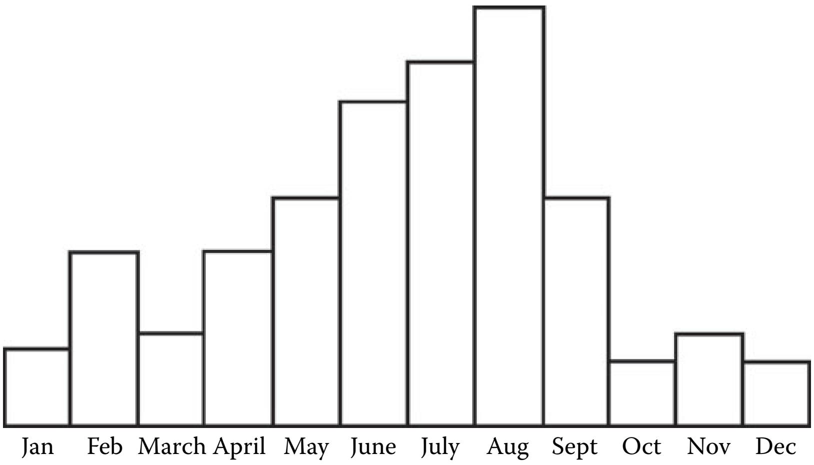

Figure 11.3 The relative frequency of power problems in the U.S., classified by month.

11.4 FIPS Publication 94

In 1983, the U.S. Department of Commerce published a guideline summarizing the fundamentals of powering, grounding, and protecting sensitive electronic devices [2]. The document, known as Federal Information Processing Standards (FIPS) Publication Number 94, was first reviewed by governmental agencies and then was sent to the Computer Business Equipment Manufacturers Association (CBEMA) for review. When the CBEMA group put its stamp of approval on the document, the data processing industry finally had an overarching guideline for power quality.

FIPS Pub. 94 was written to cover *automatic data processing* (ADP) equipment, which at that time constituted the principal equipment that was experiencing difficulty running on normal utility-supplied power. Since then, IEEE standard P1100 was issued, which applies to all sensitive electronic equipment. FIPS Pub. 94 is a guideline intended to provide a cost/benefit course of action. As a result, it can be relied upon to give the best solution to typical problems that will be encountered, for the least amount of money.

In addition to approving the FIPS Pub. 94 document, the CBEMA group provided a curve that had been used as a guideline for their members in designing power supplies for modern electronic equipment. The CBEMA curve from the FIPS document is shown in Figure 11.4. Note the similarity to the Key tolerance envelope shown in Figure 11.1.

The curve is a susceptibility profile. In order to better explain its meaning, the curve has been simplified and redrawn in Figure 11.5. The vertical axis of the graph is the percentage of voltage that is applied to the power circuit, and the horizontal axis is the time factor involved (in µs to s). In the center of the chart is the acceptable operating area, and on the outside of that area is a danger area on top and bottom. The danger zone at the top is a function of the tolerance of equipment to excessive voltage levels. The danger zone on the bottom sets the tolerance of equipment to a loss or reduction in applied power. The CBEMA guideline states that if the voltage supply stays within the acceptable area given by the curve, the sensitive load equipment will operate as intended.

11.5 Protection Alternatives

A facility can be protected from ac line disturbances in two basic ways: the *systems* approach or the *discrete device* approach. Table 11.4 outlines the major alternatives available:

- Uninterruptible power system (UPS) and standby generator
- UPS stand-alone system
- Secondary ac spot network
- Secondary selective ac network
- Motor-generator (m-g) set

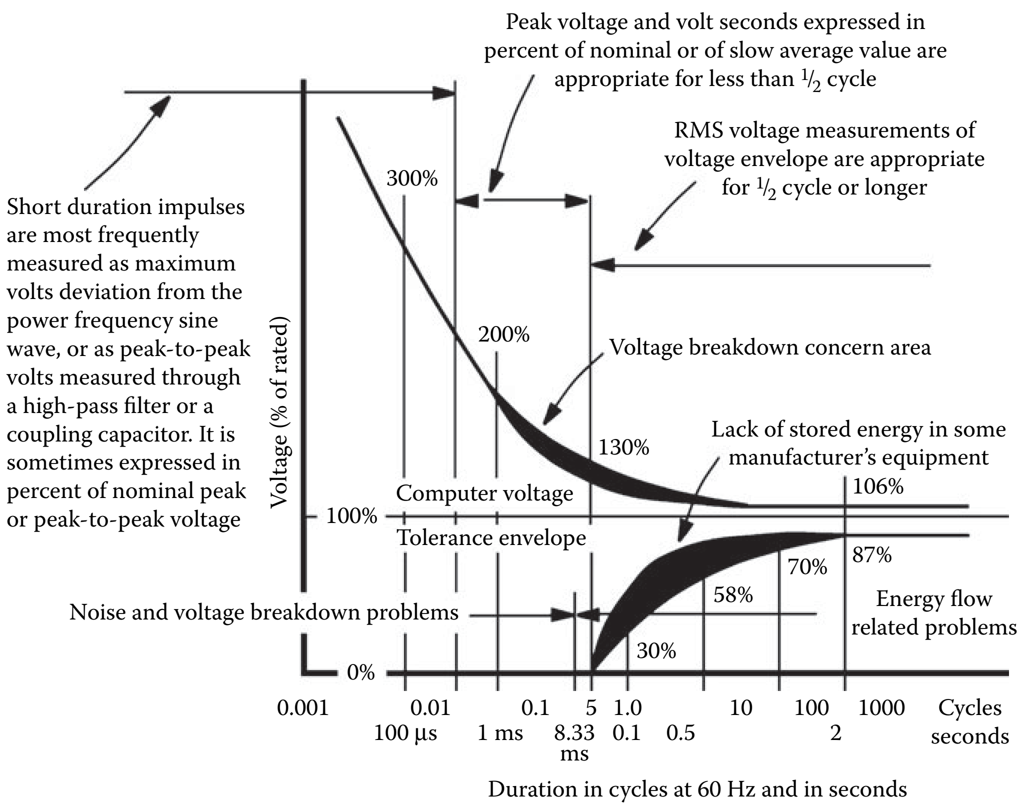

Figure 11.4 The CBEMA curve from FIPS Pub. 94. (*From* [2]. *Used with permission.*)

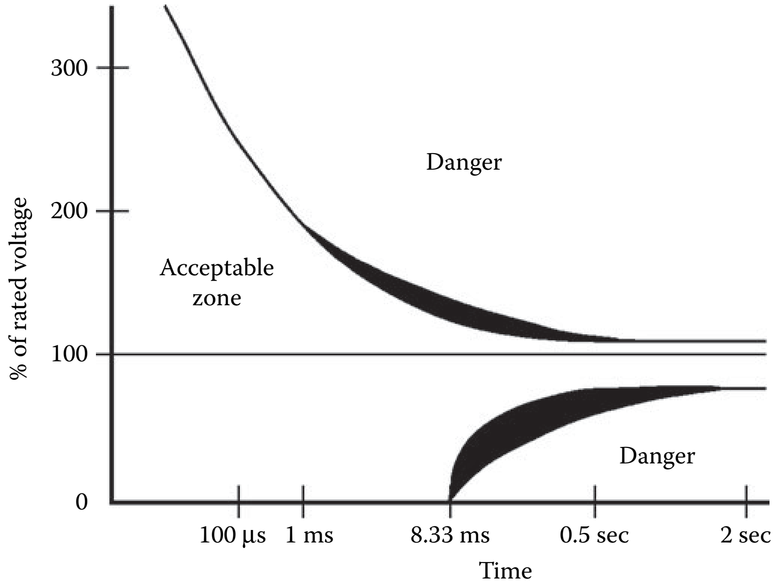

Figure 11.5 A simplified version of the CBEMA curve. Voltage levels outside the *acceptable zone* result in potential system shutdown and hardware and software loss. (*From* [2]. *Used with permission*.)

Table 11.4 Types of Systemwide Protection Equipment Available to Facility Managers and the AC Line Abnormalities That Each Approach Can Handle (*After* [1] *and* [2].)

System	Type 1	Type 2	Type 3
UPS system and standby generator	All source transients; no load transients	All	All
UPS system	All source transients; no load transients	All	All outages shorter than the battery supply discharge time
Secondary spot network (1)	None	None	Most, depending on the type of outage
Secondary selective network (2)	None	Most	Most, depending on the type of outage
Motor-generator set	All source transients; no load transients	Most	Only brown-out conditions
Shielded isolation transformer	Most source transients; no load transients	None	None
Suppressors, filters, lightning arrestors	Most transients	None	None
Solid-state line-voltage regulator/filter	Most source transients; no load transients	Some, depending on the response time of the system	Only brown-out conditions

(1) Dual power feeder network.
(2) Dual power feeder network using a static (solid-state) transfer switch.

- Shielded isolation transformer
- Suppressors, filters, and lightning arrestors
- Solid-state line-voltage regulator/filter

Table 11.5 lists the relative benefits of each protection method. Because each installation is unique, a thorough investigation of the facility needs should be conducted before purchasing any equipment. The systems approach offers the advantages of protection engineered to a particular application and need, and (usually) high-level factory support during equipment design and installation. The systems approach also means higher costs for the end user.

11.5.1 Specifying System-Protection Hardware

Developing specifications for systemwide power-conditioning/backup hardware requires careful analysis of various factors before a particular technology or a specific vendor is selected. Key factors in this process relate to the load hardware and load application. The electrical power required by a sensitive load may vary widely, depending on the configuration of the system. The principle factors that apply to system specification include the following:

- Power requirements, including voltage, current, power factor, harmonic content, and transformer configuration
- Voltage-regulation requirements of the load
- Frequency stability required by the load, and the maximum permissible *slew rate* (the rate of change of frequency per second)
- Effects of unbalanced loading
- Overload and inrush current capacity
- Bypass capability
- Primary/standby path transfer time
- Maximum standby power reserve time
- System reliability and maintainability
- Operating efficiency

An accurate definition of *critical applications* will aid in the specification process for a given site. The potential for future expansion also must be considered in all plans.

Power requirements can be determined either by measuring the actual installed hardware or by checking the nameplate ratings. Most nameplate ratings include significant safety margins. Moreover, the load normally will include a *diversity factor*; all individual elements of the load will not necessarily be operating at the same time.

Every load has a limited tolerance to noise and harmonic distortion. Total harmonic distortion (THD) is a measure of the quality of the waveform applied to the load. It is calculated by taking the geometric sum of the harmonic voltages present in the waveform and expressing that value as a percentage of the fundamental voltage. Critical DP loads typically can withstand 5% THD, where no single harmonic exceeds 3%. The power-conditioning system must provide this high-quality output waveform to the load, regardless of the level of noise or distortion present at the ac input terminals.

If a power-conditioning/standby system does not operate with high reliability, the results often can be disastrous. In addition to threats to health and safety, there is a danger of lost revenue or inventory, and hardware damage. Reliability must be considered from three different viewpoints:

- Reliability of utility ac power in the area.
- Impact of line-voltage disturbances on DP loads.
- Ability of the protection system to maintain reliable operation when subjected to expected and unexpected external disturbances.

The environment in which the power-conditioning system operates will have a significant effect on reliability. Extremes of temperature, altitude, humidity, and vibration can be encountered in various applications. Extreme conditions can precipitate premature component failure and unexpected system shutdown. Most power-protection equipment is rated for operation from 0 to 40°C. During a commercial power failure, however, the ambient temperature of the equipment room can easily exceed either value, depending on the exterior temperature. Operating temperature derating typically is required for altitudes in excess of 1000 ft.

Table 11.5 Relative Merits of Systemwide Protection Equipment (*After* [1] *and* [2]).

System	Strong Points	Weak Points	Technical Profile
UPS system and standby generator	Full protection from power outage failures and transient disturbances; ideal for critical DP and life-safety loads	Hardware is expensive and may require special construction; electrically and mechanically complex; noise may be a problem; high annual maintenance costs	Efficiency 80–90%; typical high impedance presented to the load may be a consideration; frequency stability good; harmonic distortion determined by UPS system design
UPS system	Completely eliminates transient disturbances; eliminates surge and sag conditions; provides power outage protection up to the limits of the battery supply; ideal for critical load applications	Hardware is expensive; depending on battery supply requirements, special construction may be required; noise may be a problem; periodic maintenance required	Efficiency 80–90%; typical high impedance presented to the load may be a consideration; frequency stability good; harmonic content determined by inverter type
Secondary spot network (1)	Simple; inexpensive when available in a given area; protects against local power interruptions; no maintenance required by user	Not available in all locations; provides no protection from areawide utility failures; provides no protection against transient disturbances or surge/sag conditions	Virtually no loss, 100% efficient; presents low impedance to the load; no effect on frequency or harmonic content
Secondary selective network (2)	Same as above; provides faster transfer from one utility line to the other	Same as above	Same as above
Motor-generator set	Electrically simple; reliable power source; provides up to 0.5 s power-fail ride-through in basic form; completely eliminates transient and surge/sag conditions	Mechanical system requires regular maintenance; noise may be a consideration; hardware is expensive; depending upon m-g set design, power-fail ride-through may be less than typically quoted by manufacturer	Efficiency 80–90%; typical high impedance presented to the load may be a consideration; frequency stability may be a consideration, especially during momentary power-fail conditions; low harmonic content
Shielded isolation transformer	Electrically simple; provides protection against most types of transients and noise; moderate hardware cost; no maintenance required	Provides no protection from brown-out or outage conditions	No significant loss, essentially 100% efficient; presents low impedance to the load; no effect on frequency stability; usually low harmonic content
Suppressors, filters, lightning arrestors	Components inexpensive; units can be staged to provide transient protection exactly where needed in a plant; no periodic maintenance required	No protection from Type 2 or 3 disturbances; transient protection only as good as the installation job	No loss, 100% efficient; some units subject to power-follow conditions; no effect on impedance presented to the load; no effect on frequency or harmonic content
Solid-state line-voltage regulator/filter	Moderate hardware cost; uses a combination of technologies to provide transient suppression and voltage regulation; no periodic maintenance required	No protection against power outage conditions; slow response time may be experienced with some designs	Efficiency 92–98%; most units present low impedance to the load; usually no effect on frequency; harmonic distortion content may be a consideration

(1) Dual power feeder network.
(2) Dual power feeder network using a static (solid-state) transfer switch.

Table 11.6 lists key power-quality attributes that should be considered when assessing the need for power-conditioning hardware.

Table 11.6 Power-Quality Attributes for Data Processing Hardware (*After* [2].)

		Acceptable Limits for DP Systems	
Environmental Attribute	Typical Environment	Normal	Critical
Line frequency	±0.1 to ±3%	±1%	±0.3%
Rate of frequency change	0.5 to 20 Hz/s	1.5 Hz/s	0.3 Hz/s
Over- and under-voltage	±5 to +6, –13.3%	+5 to –10%	±3%
Phase imbalance	2 to 10%	5% max	3% max
Tolerance to low power factor	0.85 to 0.6 lagging	0.8 lagging	less than 0.6 lagging, or 0.9 leading
Tolerance to high steady-state peak current	1.3 to 1.6 peak, rms	1.0 to 2.5 peak, rms	Greater than 2.5 peak, rms
Harmonic voltages	0 to 20% total rms	10 to 20% total, 5 to 10% largest	5% max total, 3% largest
Voltage deviation from sine wave	5 to 50%	5 to 10%	3 to 5%
Voltage modulation	Negligible to 10%	3% max	1% max
Surge/sag conditions	+10, –15%	+20, –30%	+5, –5%
Transient impulses	2 to 3 times nominal peak value (0 to 130% Vs)	Varies; 1.0 to 1.5 kV typical	Varies; 200 to 500 V typical
RFI/EMI normal and common modes	10 V up to 20 kHz, less at high freq.	Varies widely; 3 V typical	Varies widely; 0.3 V typical
Ground currents	0 to 10 A plus impulse noise current	0.001 to 0.5 A or more	0.0035 A or less

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12

Motor-Generator Set

12.1 Introduction

As the name implies, a motor-generator (m-g) set consists of a motor powered by the ac utility supply that is mechanically tied to a generator, which feeds the load. (See Figure 12.1.) Transients on the utility line will have no effect on the load when this arrangement is used. Adding a flywheel to the motor-to-generator shaft will protect against brief power dips (up to 0.5 s on many models). Figure 12.2 shows the construction of a typical m-g set. The attributes of an m-g include the following:

- An independently generated source of voltage can be regulated without interaction with line-voltage changes on the power source. Utility line changes of ±20% commonly can be held to within ±1% at the load.
- The rotational speed and inertial momentum of the rotating mass represents a substantial amount of stored rotational energy, preventing sudden changes in voltage output when the input is momentarily interrupted.
- The input and output windings are separated electrically, preventing transient disturbances from propagating from the utility company ac line to the load.
- Stable electrical characteristics for the load: (1) output voltage and frequency regulation, (2) ideal sine wave output, and (3) true 120° phase shift for three-phase models.
- Reduced problems relating to the power factor presented to the utility company power source.

The efficiency of a typical m-g ranges from 65 to 89%, depending on the size of the unit and the load. Motor-generator sets have been used widely to supply 415 Hz power to mainframe computers that require this frequency.

12.2 System Configuration

There are a number of types of motor-generator sets, each having its own characteristics, advantages, and disadvantages. A simplified schematic diagram of an m-g is shown in Figure 12.3. The type of motor that drives the set is an important design element. Direct-current motor drives can be controlled in speed independently of the frequency of the ac power source from which the dc is derived. Use of a dc motor thereby gives the m-g set the capability to produce power at the desired output frequency, regardless of variations in input frequency. The requirement for rectifier conversion hardware, control equipment, and commutator maintenance are drawbacks to this approach that must be considered.

The simplest and least-expensive approach to rotary power conditioning involves the use of an induction motor as the mechanical source. Unfortunately, the rotor of an induction motor turns slightly slower than the rotating field produced by the power source. This results in the generator being unable to produce 60 Hz output power if the motor is operated at 60 Hz and the machines are directly coupled end-to-end at their shafts, or are belted in a 1:1 ratio. Furthermore, the shaft speed and output frequency of the generator decreases as the load on the generator is increased. This potential for varying output frequency may be acceptable where the m-g set is used solely as the input to a power supply in which the ac is rectified and converted to dc. However, certain loads cannot tolerate frequency changes greater than 1 Hz/s and frequency deviations of more than 0.5 Hz from the nominal 60 Hz value.

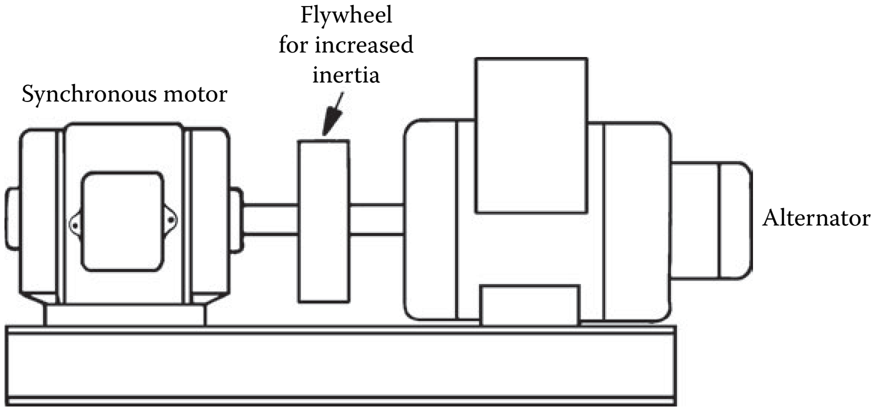

Figure 12.1 Two-machine motor-generator set with an optional flywheel to increase inertia and carry-through capability.

Low-slip induction motor-driven generators are available that can produce 59.7 Hz at full load, assuming 60 Hz input. During power interruptions, the output frequency will drop further, depending upon the length of the interruption. The capability of the induction motor to restart after a momentary power interruption is valuable. Various systems of variable-speed belts have been tried successfully. Magnetically controlled slipping clutches have been found to be largely unsatisfactory. Other approaches to make the induction motor drive the load at constant speed have produced mixed results.

Figure 12.2 Construction of a typical m-g set. (*Courtesy of Computer Power Protection.*)

Using a synchronous motor with direct coupling or a cogged 1:1 ratio belt drive guarantees that the output frequency will be equal to the motor input frequency. Although the synchronous motor is more expensive, it is more efficient and can be adjusted to provide a unity PF load to the ac source. The starting characteristics and the mechanical disturbance following a short line-voltage interruption depend, to a large extent, on motor design. Many synchronous motors that are not required to start under load have weak starting torque and may use a *pony motor* to aid in starting. This approach is shown in Figure 12.4.

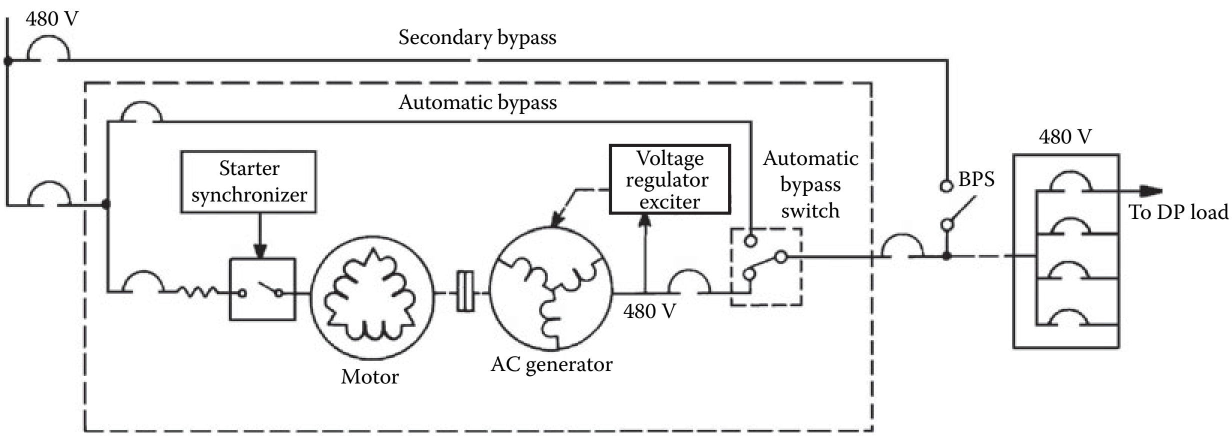

Figure 12.3 Simplified schematic diagram of an m-g set with automatic and secondary bypass capability. (*After* [1].)

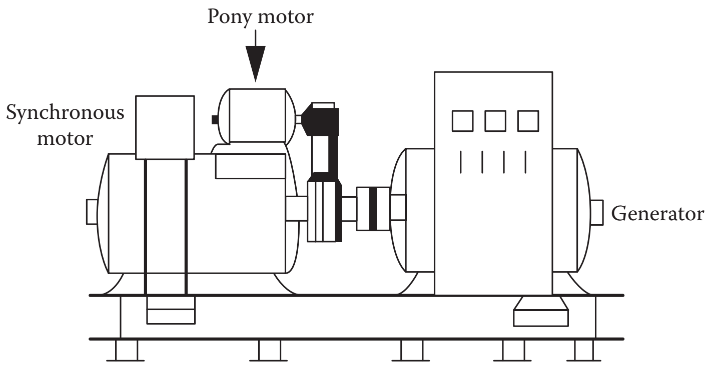

Figure 12.4 Use of a pony motor for an m-g set to aid in system starting and restarting. (*After* [1].)

Those motors designed to start with a load have starting pole face windings that provide starting torque comparable to that of an induction motor. Such motors can be brought into synchronism while under load with proper selection of the motor and automatic starter system. Typical utility company ac interruptions are a minimum of six cycles (0.1 s). Depending upon the design and size of the flywheel used, the ride-through period can be as much as 0.5 s or more. The generator will continue to produce output power for a longer duration, but the frequency and rate of frequency change will most likely fall outside of the acceptable range of most DP loads after 0.5 s.

If input power is interrupted and does not return before the output voltage and frequency begin to fall outside acceptable limits, the generator output controller can be programmed to disconnect the load. Before this event, a warning signal is sent to the DP control circuitry to warn of impending shutdown and to initiate an orderly interruption of active computer programs. This facilitates easy restart of the computer after the power interruption has passed.

It is important for users to accurately estimate the length of time that the m-g set will continue to deliver acceptable power without input to the motor from the utility company. This data facilitates accurate power-fail shutdown routines. It is also important to ensure that the m-g system can handle the return of power without operating overcurrent protection devices because of high inrush currents that may be required to accelerate and synchronize the motor with the line frequency. Protection against the latter problem requires proper programming of the synchronous motor controller to correctly disconnect and then reconnect the field current supply. It may be worthwhile to delay an impending shutdown for 100 ms or so. This would give the computer time to prepare for the event through an orderly interruption. It also would be useful if the computer were able to resume operation without shutdown, in case utility power returns within the ride-through period. Control signals from the m-g controller should be configured to identify these conditions and events to the DP system.

Generators typically used in m-g sets have substantially higher internal impedance than equivalent kVA-rated transformers. Because of this situation, m-g sets sometimes are supplied with an oversized generator that will be lightly loaded, coupled with a smaller motor that is adequate to drive the actual load. This approach reduces the initial cost of the system, decreases losses in the motor, and provides a lower operating impedance for the load.

Motor-generator sets can be configured for either horizontal installation, as shown previously, or for vertical installation, as illustrated in Figure 12.5.

The most common utility supply voltage used to drive the input of an m-g set is 480 V. The generator output for systems rated at about 75 kVA or less is typically 208 Y/120 V. For larger DP systems, the most economical generator output is typically 480 V. A 480 to 208 Y/120 V three-phase isolating transformer usually is included to provide 208 Y/120 V power to the computer equipment.

12.2.1 Motor Design Considerations

Both synchronous and induction motors have been used successfully to drive m-g sets, and each has advantages and disadvantages. The major advantage of the synchronous motor is that while running

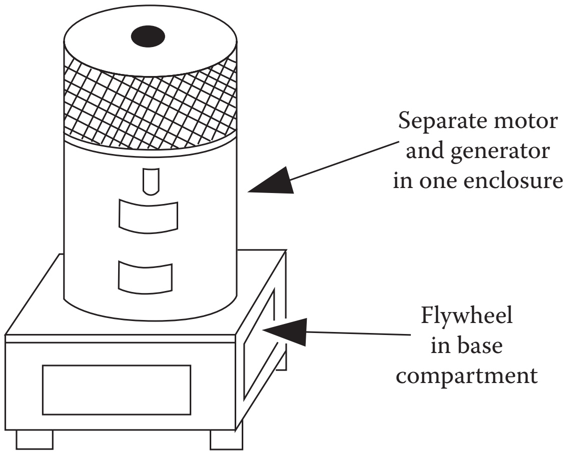

Figure 12.5 Vertical m-g set with an enclosed flywheel. (*After* [1].)

normally, it is synchronized with the supply frequency. An 1800 rpm motor rotates at exactly 1800 rpm for a supply frequency of exactly 60 Hz. The generator output, therefore, will be exactly 60 Hz. Utility frequencies *average* 60 Hz; utilities vary the frequency slowly to maintain this average value under changing load conditions. Research has shown that utility operating frequencies typically vary from 58.7 to 60.7 Hz. Although frequency tolerances permitted by most computer manufacturers are usually given as ±0.5 Hz on a nominal 60 Hz system, these utility variations are spread over a 24-hour period or longer and generally do not result in problems for the load.

The major disadvantage of a synchronous motor is that the device is difficult to start. A synchronous motor must be started and brought up to *pull-in* speed by an auxiliary winding on the armature, known as the *armortisseur* winding. The pull-in speed is the minimum speed (close to synchronous speed) at which the motor will pull into synchronization if excitation is applied to the field. The armortisseur winding is usually a squirrel-cage design, although it may be of the wound-rotor type in some cases. This winding allows the synchronous motor to start and come up to speed as an induction motor. When pull-in speed is achieved, automatic sensing equipment applies field excitation, and the motor locks in and runs as a synchronous machine. As discussed previously, some large synchronous motors are brought up to speed by an auxiliary pony motor.

The armortisseur winding can produce only limited torque, so synchronous motors usually are brought up to speed without a load. This requirement presents no problem for DP systems upon initial startup. However, in the event of a momentary power outage, problems can develop. When the utility ac fails, the synchronous motor must be disconnected from the input immediately, or it will act as a generator and feed power back into the line, thus rapidly depleting its stored (kinetic) rotational energy. During a power failure, the speed of the motor rapidly drops below the pull-in speed, and when the ac supply returns, the armortisseur winding must reaccelerate the motor under load until the field can be applied again. This requires a large winding and a sophisticated control system. When the speed of the m-g set is below synchronous operation, the generator output frequency may be too low for proper computer operation.

The induction motor has no startup problems, but it does have *slip*. To produce torque, the rotor must rotate at slightly lower speed than the stator field. For a nominal 1800 rpm motor, the actual speed will be about 1750 rpm, varying slightly with the load and the applied input voltage. This represents a slip of about 2.8%. The generator, if driven directly or on a common shaft, will have an output frequency of about 58.3 Hz. This is below the minimum permissible operating frequency for most computer hardware. Special precision-built low-slip induction motors are available with a slip of approximately 0.5% at a nominal motor voltage of 480 V. With 0.5% slip, speed at full load will be about 1791 rpm, and the directly driven or common-shaft generator will have an output frequency of 59.7 Hz. This frequency is within tolerance, but close to the minimum permissible frequency.

A belt-and-pulley system adjustable-speed drive is a common solution to this problem. By making the pulley on the motor slightly larger in diameter than the pulley on the generator (with the actual diameters adjustable) the generator can be driven at synchronous speed.

Voltage sags have no effect on the output frequency of a synchronous motor-driven m-g set until the voltage gets so low that the torque is reduced to a point at which the machine pulls out of synchronization. Resynchronization then becomes a problem. On an induction motor, when the voltage sags, slip increases and the machine slows down. The result is a drop in generator output frequency. The adjustable-speed drive between an induction motor and the generator solves the problem for separate machines. If severe voltage sags are anticipated at a site, the system can be set so that nominal input voltage from the utility company produces a frequency of 60.5 Hz, 0.5 Hz on the high side of nominal frequency. Figure 12.6 charts frequency vs. motor voltage for three operating conditions:

- Slip compensation set high (curve A)
- Slip compensation set for 60 Hz (curve B)
- No slip compensation (curve C)

Through proper adjustment of slip compensation, considerable input-voltage margins can be achieved.

12.2.1.1 Single-Shaft Systems

There are two basic m-g set machine mechanical designs used for DP applications: (1) separate motor-generator systems, and (2) single-shaft, single-housing units. Both designs can use either a synchronous or induction motor. In each case, there are advantages and disadvantages. The separate machine design (discussed previously) uses a motor driving a physically separate generator by means of a coupling shaft or pulley. In an effort to improve efficiency and reduce costs, manufacturers also have produced various types of single-shaft systems.

The basic concept of a single-shaft system is to combine the motor and generator elements into a single unit. A common stator eliminates a number of individual components, making the machine less expensive to produce and mechanically more efficient. The common-stator set substantially reduces mechanical energy losses associated with traditional m-g designs, and it improves system reliability, as well. In one design, the stator is constructed so that alternate slots are wound with input and output

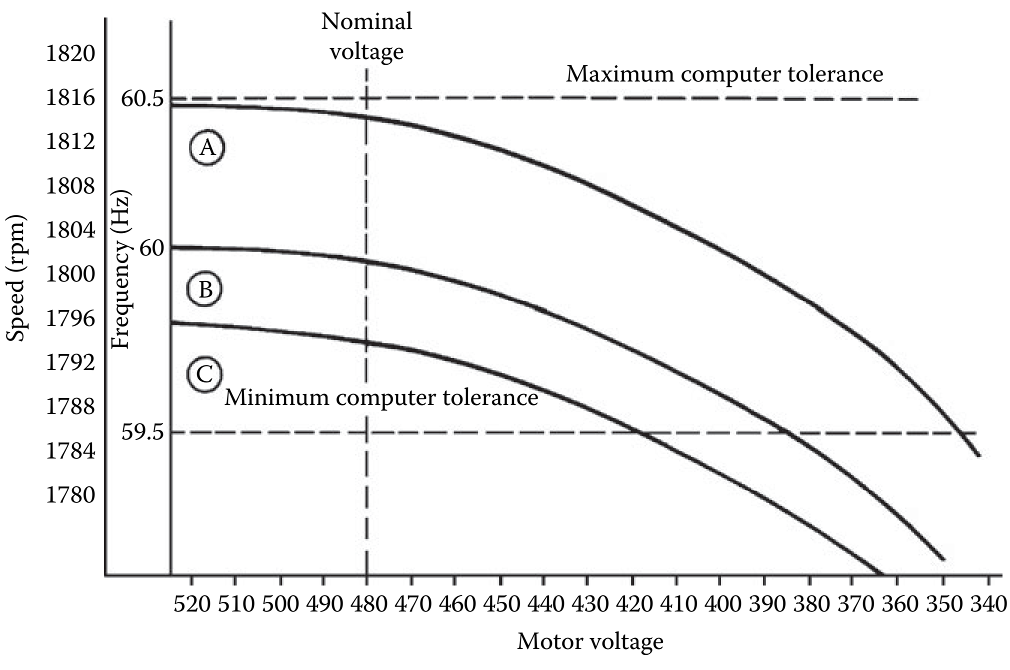

Figure 12.6 Generator output frequency vs. motor input voltage for an induction-motor-based m-g set.

windings. When it is fed with a three-phase supply, a rotating magnetic field is created, causing the dc-excited rotor to spin at a synchronous speed. By controlling the electrical characteristics of the rotor, control of the output at the secondary stator windings is accomplished.

Common-stator machines offer lower working impedance for the load than a comparable two-machine system. For example, a typical 400 kVA machine has approximately an 800 kVA frame size. The larger frame size yields a relatively low-impedance power source capable of clearing subcircuit fuses under fault conditions. The output of the unit typically can supply up to seven times the full-load current under fault conditions. Despite the increase in frame size, the set is smaller and lighter than comparable systems because of the reduced number of mechanical parts.

12.2.2 Flywheel Considerations

In an effort to achieve higher energy and power densities, m-g set designers have devoted considerable attention to the flywheel element itself. New composite materials and power electronics technologies have resulted in compact flywheel "batteries" capable of high linear velocity at the outside radius of the flywheel (*tip speed*) [2]. The rotational speed of the flywheel is important because the stored energy in a flywheel is proportional to the square of its rotational speed. Therefore, an obvious method for maximizing stored energy is to increase the speed of the flywheel. All practical designs, however, have a limiting speed, which is determined by the stresses developed within the wheel resulting from inertial loads. These loads are also proportional to the square of rotational speed. Flywheels built of composite materials weigh less and, hence, develop lower inertial loads at a given speed. In addition, composites are often stronger than conventional engineering metals, such as steel. This combination of high strength and low weight enables extremely high tip speeds, relative to conventional wheels.

For a given geometry, the limiting *energy density* (energy per unit mass) of a flywheel is proportional to the ratio of material strength to weight density, otherwise known as the *specific strength*. Table 12.1 illustrates the advantage that composite materials offer in this respect.

Recent advances in composite materials technology may allow nearly an order of magnitude advantage in the specific strength of composites when compared to even the best common engineering metals. The result of this continuous research in composites has been flywheels capable of operation at rotational speeds in excess of 100,000 rpm, with tip speeds in excess of 1000 m/s.

These high speeds bring with them new challenges. The ultrahigh rotational speeds that are required to store significant kinetic energy in these systems virtually rule out the use of conventional mechanical bearings. Instead, most systems run on magnetic bearings. This relatively recent innovation uses magnetic forces to levitate a rotor, eliminating the frictional losses inherent in rolling element and fluid film bearings. Unfortunately, aerodynamic drag losses force most high-speed flywheels to operate in a partial vacuum, which complicates the task of dissipating the heat generated by ohmic losses in the bearing electromagnets and rotor. In addition, active magnetic bearings are inherently unstable and require sophisticated control systems to maintain proper levitation.

The integrated generator of these systems is usually a rotating-field design, with the magnetic field supplied by rare-earth permanent magnets. Because the specific strength of these magnets is typically just fractions of that of the composite flywheel, they must spin at much lower tip speeds; in other words, they must be placed very near the hub of the flywheel. This compromises the power density of the generator.

Table 12.1 Specific Strength of Selected Materials (*After* [3].)

Material	Specific Strength (in.^{3})
Graphite/epoxy	3,509,000
Boron/epoxy	2,740,000
Titanium and alloys	1,043,000
Wrought stainless steel	982,000
Wrought high-strength steel	931,000
7000 series aluminum alloys	892,000

An alternative is to mount them closer to the outer radius of the wheel, but contain their inertial loads with the composite wheel itself. Obviously, this forces the designer to either derate the machine speed or operate closer to the stress limits of the system.

12.2.3 Maintenance Considerations

Because m-g sets require some maintenance that necessitates shutdown, most systems provide bypass capability so the maintenance work can be performed without having to take the computer out of service. If the automatic bypass contactor, solid-state switch, and control hardware are in the same cabinet as other devices that also need to be de-energized for maintenance, a secondary bypass is recommended. After the automatic bypass path has been established, transfer switching to the secondary bypass can be enabled, taking the m-g set and its automatic bypass system out of the circuit completely. Some automatic bypass control arrangements are designed to transfer the load of the generator to the bypass route with minimum disturbance. This requires the generator output to be synchronized with the bypass power before closing the switch and opening the generator output breaker. However, with the load taken off the generator, bypass power no longer will be synchronized with it. Consequently, retransfer of the load back to the generator may occur with some disturbance. Adjustment for minimum disturbance in either direction requires a compromise in phase settings, or a means to shift the phase before and after the transfer.

The use of rotating field exciters has eliminated the need for slip rings in most m-g designs. Brush inspection and replacement, therefore, are no longer needed. However, as with any rotating machinery, bearings must be inspected and periodically replaced.

12.2.4 Motor-Generator UPS

Critical DP applications that cannot tolerate even brief ac power interruptions can use the m-g set as the basis for an uninterruptible source of power through the addition of a battery-backed dc motor to the line-driven ac motor shaft. This concept is illustrated in Figure 12.7. The ac motor normally supplies power to drive the system from the utility company line. The shafts of the three devices all are interconnected, as shown in the figure. When ac power is present, the dc motor serves as a generator to charge the

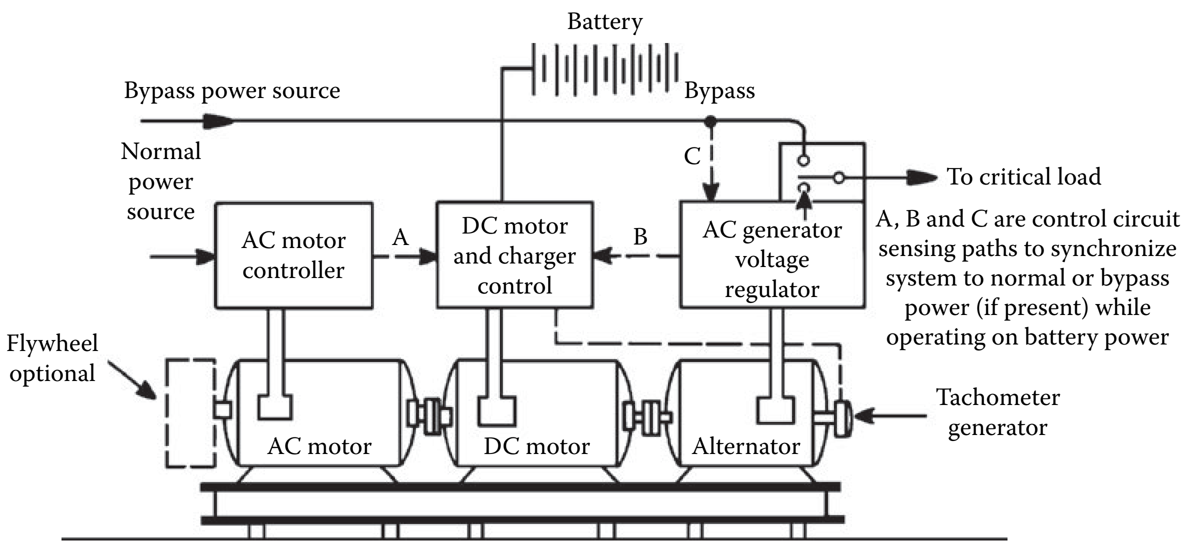

Figure 12.7 Uninterruptible m-g set with ac and dc motor drives. (*After* [1].)

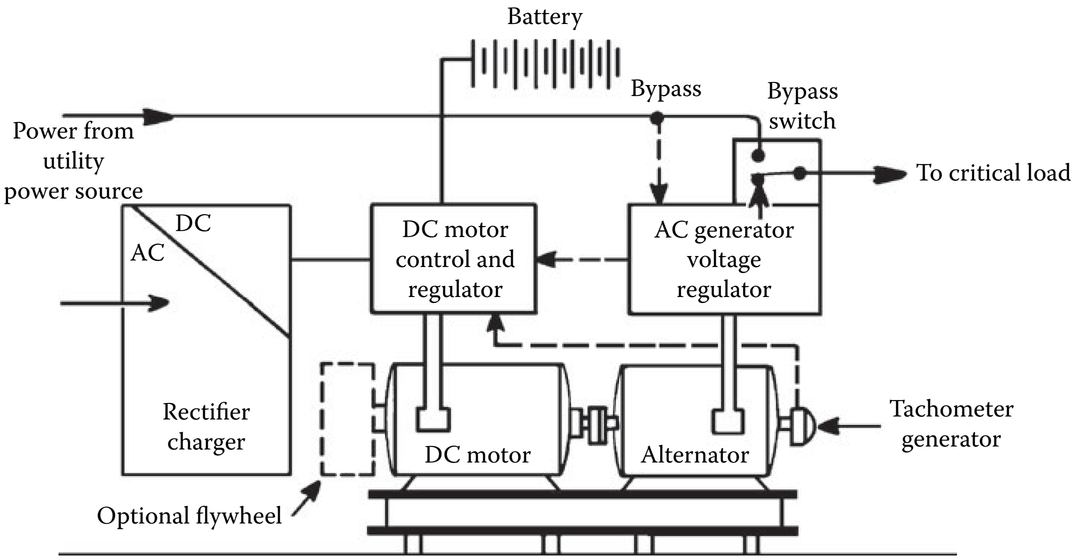

Figure 12.8 Uninterruptible m-g set using a single dc drive motor. (*After* [1].)

battery bank. When line voltage is interrupted, the dc motor is powered by the batteries. Figure 12.8 shows a modified version of this basic m-g UPS using only a dc motor as the mechanical power source. This configuration eliminates the inefficiency involved in having two motors in the system. Power from the utility source is rectified to provide energy for the dc motor, plus power for charging the batteries. A complex control system to switch the ac motor off and the dc motor on in the event of a utility power failure is not needed in this design.

The m-g UPS also can be built around a synchronous ac motor, as illustrated in Figure 12.9. Utility ac energy is rectified and used to drive an inverter, which provides a regulated frequency source to power the synchronous motor. The output from the dc-to-ac inverter need not be a well-formed sine wave, or a well-regulated source. The output from the generator will provide a well-regulated sine wave for the load. The m-g set also can be operated in a bypass mode that eliminates the rectifier, batteries, and inverter from the current path, operating the synchronous motor directly from the ac line.

An m-g UPS set using a common-stator machine is illustrated in Figure 12.10. A feedback control circuit adjusts the firing angle of the inverter to compensate for changes in input power. This concept is taken a step further in the system shown in Figure 12.11. A solid-state inverter bypass switch is added to improve efficiency. During normal operation, the bypass route is enabled, eliminating losses across the

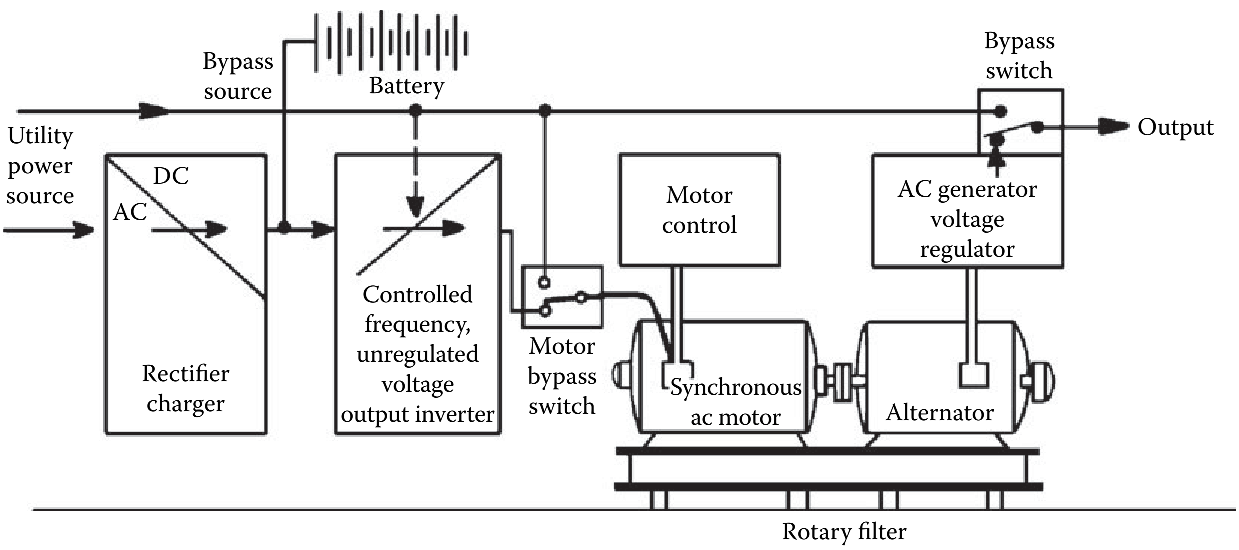

Figure 12.9 Uninterruptible m-g set using a synchronous ac motor. (*After* [1].)

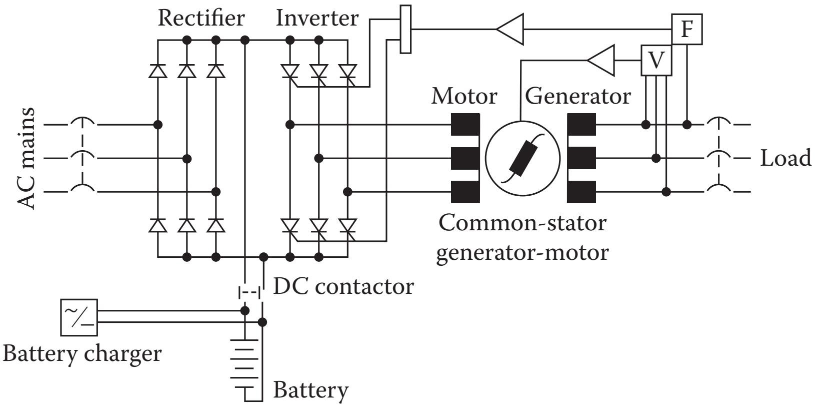

Figure 12.10 Common-stator UPS m-g set. The firing angle of the SCR inverters is determined by a feedback voltage from the generator output.

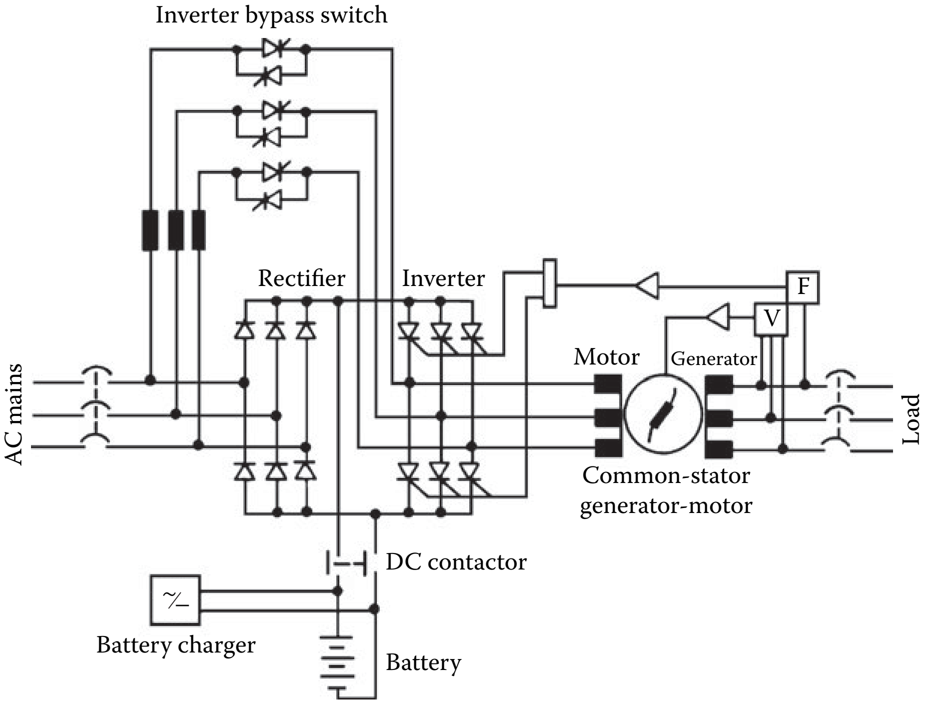

Figure 12.11 Common-stator UPS m-g set with a solid-state inverter bypass switch.

rectifier diodes. When the control circuitry senses a drop in utility voltage, the inverter is switched on, and the bypass switch is deactivated. A simplified installation diagram of the inverter/bypass system is shown in Figure 12.12. Magnetic circuit breakers and chokes are included as shown. An isolation transformer is inserted between the utility input and the rectifier bank. The static inverter is an inherently simple design; commutation is achieved via the windings. Six thyristors are used. Under normal operating conditions, 95% of the ac power passes through the static switch; 5% passes through the inverter. This arrangement affords maximum efficiency, while keeping the battery bank charged and the rectifiers and inverter thyristors preheated. Preheating extends the life of the components by reducing the extent of thermal cycling that occurs when the load suddenly switches to the battery backup supply. The static switch allows for fast disconnect of the input ac when the utility power fails.

12.2.5 Kinetic Battery Storage System

As outlined previously, one of the parameters that limits the ride-through period of an m-g set is the speed decay of the flywheel/generator combination. As the flywheel slows down, the output frequency

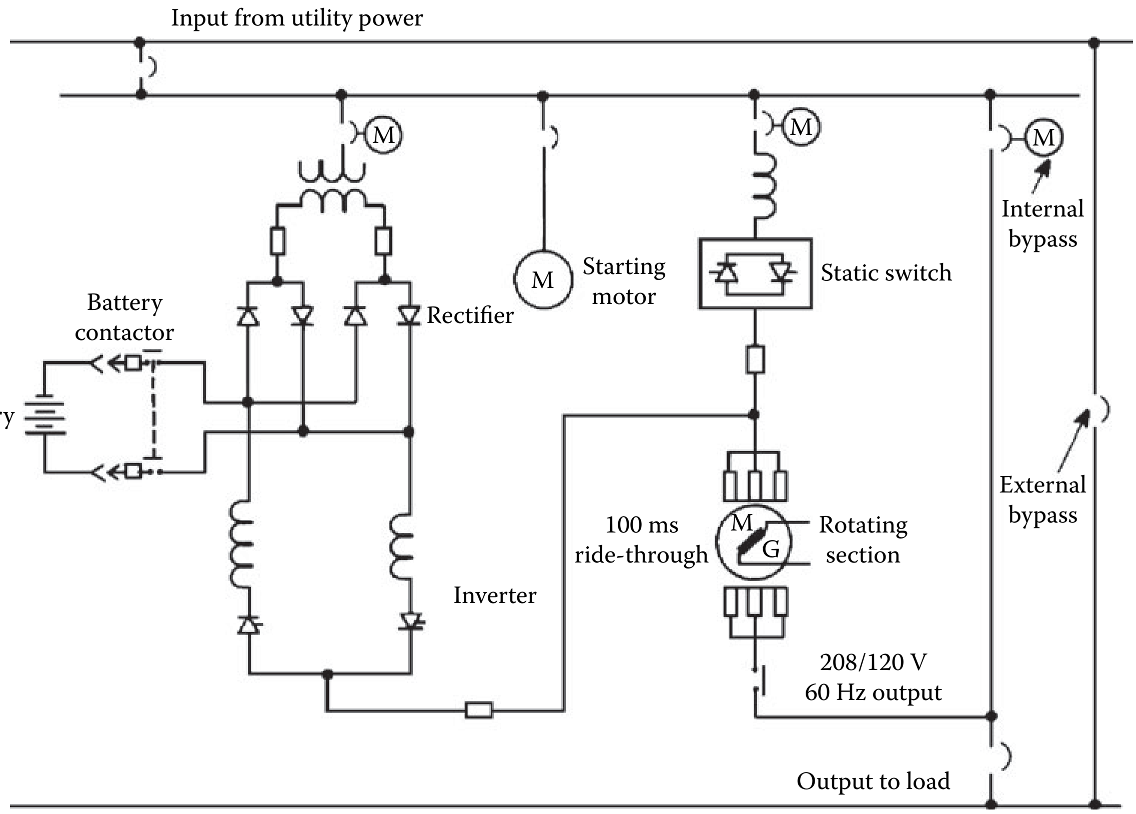

Figure 12.12 Power flow diagram of a full-featured UPS m-g set.

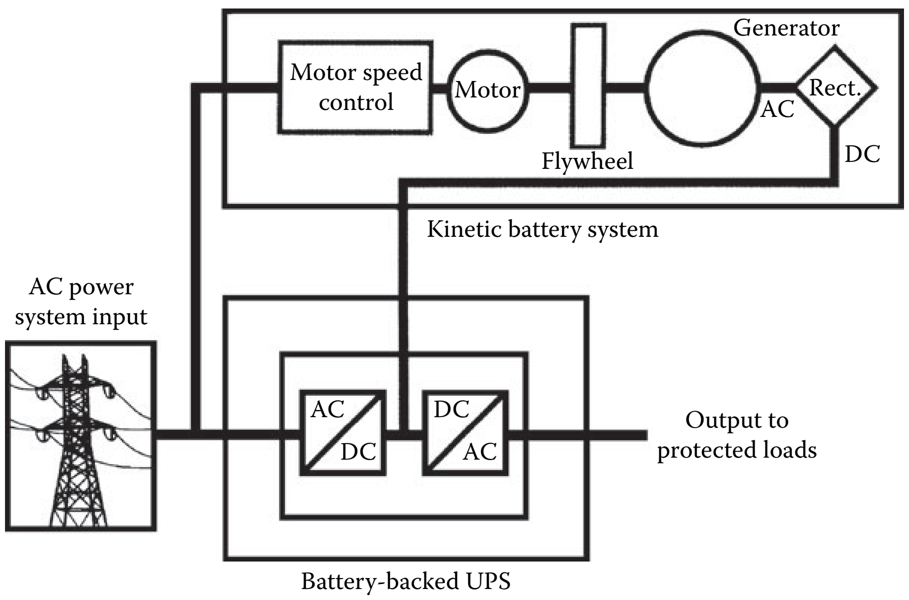

Figure 12.13 Functional block diagram of a kinetic battery m-g system for powering a UPS. (*After* [4].)

drops. This limits the useful ride-through period to 0.5 s or so. Figure 12.13 shows an ingenious modification of the classic power conditioning template that extends the potential ride-through considerably. As shown in the figure, an m-g set is used in a UPS-based system as an element of the dc supply grid. The major components of the system include:

- Steel flywheel for energy storage
- Small drive motor, sized at 15 to 20% of the rated system output, to start the flywheel and maintain its normal operating speed
- Variable speed drive (VSD) to slowly ramp the flywheel up to speed and maintain it at the desired rpm
- Generator to convert the kinetic energy stored in the flywheel into electrical energy
- Diode bridge rectifier to convert the ac generator output to dc for use by the UPS bus, which continues to draw usable energy essentially independent of flywheel rpm

Because the ac output of the generator is converted to dc, frequency is no longer a limiting factor, which allows the dc voltage output to be maintained over a much greater range of the flywheel's rpm envelope.

In operation, the small drive motor spins the flywheel while the variable speed drive maintains the proper motor speed [4]. Because the amount of stored kinetic energy increases by the square of the flywheel rpm, it is possible to greatly increase stored energy, and thus ride-through, by widening the flywheel's usable energy output range. These factors permit typical ride-through times from 10 s to several minutes, depending on loading and other operating conditions. The benefits of this approach include the reduced cycling of battery supplies and engine-generator systems.

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