UNIT III

Electrical Power Distribution Systems

Once electrical power has been produced, it must be distributed to the location where it is used. Unit III deals with *electrical power distribution systems.* The fundamentals of distribution systems are discussed in Chapter 8. This chapter provides an overview of distribution systems, *transformer* operation, and *conductor* characteristics. Chapter 9 examines specialized power distribution *equipment* such as protective devices, high-voltage equipment, and switch gear. Then, Chapter 10, *Single-Phase and Three-Phase Distribution Systems,* discusses the types of distribution systems used today. *Ground-fault interrupters* are also discussed extensively in this chapter, since their use is becoming widespread in electrical power distribution systems.

Figure III shows the *electrical power systems model* used in this book and the major topics of Unit III, Electrical Power Distribution Systems.

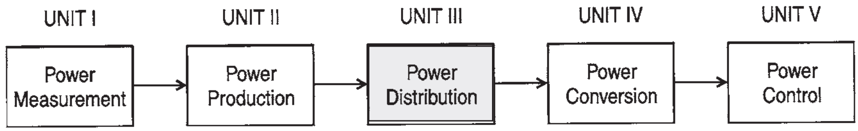

Figure III. Electrical power systems model

Power Distribution Fundamentals (Chapter 8)
Power Distribution Equipment (Chapter 9)
Single-phase and Three-phase Distribution Equipment (Chapter 10)

UNIT OBJECTIVES

Upon completion of this unit, you should be able to:

1. List several purposes of transformers.
2. Describe the construction of a transformer.
3. Explain transformer action.

4. Calculate turns ratio, voltage ratio, current ratio, and the power and efficiency of transformers.
5. Explain the purpose of isolation transformers, autotransformers, and current transformers.
6. Explain factors that cause losses in transformer efficiency.
7. Investigate the characteristics of transformers.
8. Describe the transmission and distribution of electrical power.
9. Compare underground, overhead, and HVDC power transmission systems.
10. Explain parallel operation of electrical power systems.
11. Describe ring, radial, and network power distribution systems.
12. Explain circular mil sizing of copper and aluminum electrical conductors.
13. Calculate cross-sectional area, resistance, or ampacity of round, square, or rectangular copper or aluminum conductors.
14. Describe the types of insulation used for conductors in electrical distribution systems.
15. Describe the following equipment used at substations for electrical power distribution:
    High-Voltage Fuses
    High-Voltage Circuit Breakers
    High-Voltage Disconnect Switches
    Lightning Arrestors
    High-Voltage Insulators
    High-Voltage Conductors
    Voltage Regulators
16. Describe the following types of protective equipment used in electrical distribution systems:
    Plug Fuses
    Cartridge Fuses
    Time-Lag Fuses
    Low-Voltage Circuit Breakers
    Protective Relays
    Motor Fault Current Protection
    Overheating Protection
    Undervoltage Protection
17. Describe the following in relation to electrical power distribution systems:
    Feeder Lines

Branch Circuits
Safety Switches
Distribution Panelboards
Low-Voltage Switchgear
Service Entrance

18. Explain the operation of single-phase / two-wire and single-phase / three-wire power distribution systems.
19. Explain the operation of three-phase / three-wire, three-phase / four-wire, and three-phase / three-wire with neutral power distribution systems.
20. Describe and sketch diagrams of delta-delta, delta-wye, wye-wye, wye-delta, and open delta three-phase transformer connection methods.
21. Describe the following in relation to grounding of electrical power systems:
    System Ground
    Equipment Ground
    Ground Fault Circuit Interrupters
22. Explain the use of the National Electric Code (NEC) as a standard for electrical power distribution design in the United States.
23. Calculate voltage drop in an electrical circuit using a conductor table or circular mil formula.
24. Calculate voltage drop in a branch circuit or feeder circuit for a single-phase or three-phase distribution system.
25. Determine grounding conductor size by using the proper tables.
26. Describe the following in relation to electrical power systems:
    Nonmetallic Sheathed Cable
    "Hot" Conductor
    Neutral Conductor
    Safety Ground
    AWG and MCM Conductor Sizing
    Metal-Clad Cable
    Rigid Conduit
    Electrical Metallic Tubing (EMT)
    Uninterruptible Power Supply (UPS)
    Power Line Filter
    Power Conditioner
    Floor-Mounted Raceway
    Conduit Connectors

Wire Connectors
Plastic Conduit and Enclosures
Power Outlet Design
International Power Sources

Chapter 8

Power Distribution Fundamentals

Power distribution systems are a very important part of electrical power systems. In order to transfer electrical power from an alternating current (AC) or a direct current (DC) source to the place where it will be used, some type of distribution network must be utilized. The method used to distribute power from where it is produced to where it is used can be quite simple. For example, a battery can be connected directly to a motor, with only a set of wires.

More complex *power distribution systems* are used, however, to transfer electrical power from the power plant to industries, homes, and commercial buildings. Distribution systems usually employ such equipment as transformers, circuit breakers, and protective devices.

IMPORTANT TERMS

Chapter 8 deals with electrical power distribution fundamentals. After studying this chapter, you should have an understanding of the following terms:

Power Transmission System
Underground Distribution System
High-Voltage Direct Current (HVDC) Distribution System
Cryogenic Cable
Parallel Operation
Radial Distribution System
Ring Distribution System
Network Distribution System
Transformer
Primary Winding

Secondary Winding
Transformer Core
Closed-Core Transformer Construction
Shell-Core Transformer Construction
Efficiency
Power Losses
Step-Up Transformer
Step-Down Transformer
Transformer Voltage Ratio
Transformer Current Ratio
Multiple Secondary Transformer
Autotransformer
Transformer Polarity
Transformer Volt-Ampere Rating
Transformer Malfunction
Conductor
Circular Mil (cmil)
American Wire Gauge (AWC)
Resistivity
Ampacity
Insulation

OVERVIEW OF ELECTRICAL POWER DISTRIBUTION

The *distribution* of electrical power in the United States is normally in the form of *three-phase, 60-Hz alternating current.* This power, of course, can be manipulated or changed in many ways by the use of electrical circuitry. For instance, a rectification system is capable of converting the 60-Hz AC into a form of DC, as was discussed in Chapter 7. Also, *single-phase* power is generally suitable for lighting and small appliances, such as those used in the home or residential environment. However, where a large amount of electrical power is required, three-phase power is more economical.

The *distribution* of electrical power involves a very complex system of *interconnected* power transmission lines. These *transmission lines* originate at the electrical power-generating stations located throughout the United States. The ultimate purpose of these power transmission and distribution systems is to supply the electrical power necessary for *industrial, residential,* and *commercial* use. From the point of view of the systems, we may say that the overall electrical power system delivers power from the source to the load that is connected to it. A typical *electrical power distribution system* is shown in Figure 8-1.

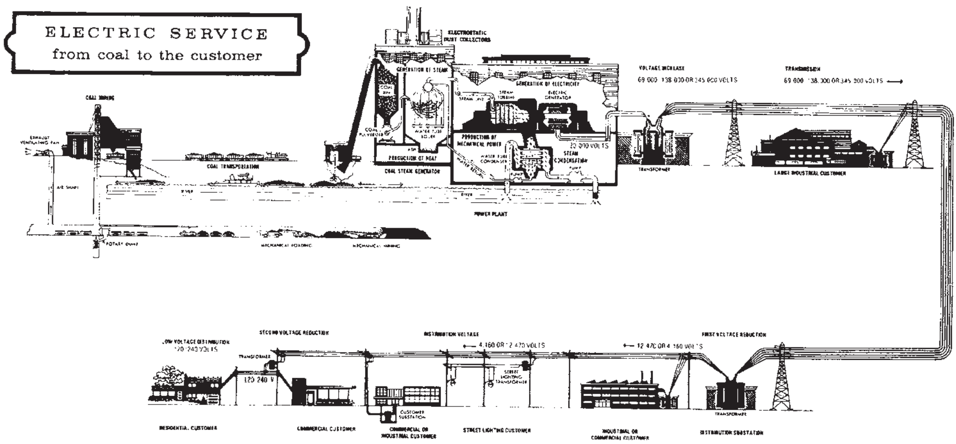

Figure 8-1. A typical electrical power distribution system (*Courtesy Kentucky Utilities Company*)

Industries use almost 50 percent of all the electrical power produced, so three-phase power is distributed directly to most industries. Electrical *substations* use massive *transformers* and associated equipment, such as oil-filled *circuit breakers,* high-voltage *conductors,* and huge strings of *insulators,* in distributing power to industry. From these substations, power is distributed to the industrial sites to energize the *industrial* machinery, to *residential* homes, and to *commercial* users of electrical power.

POWER TRANSMISSION AND DISTRIBUTION

Power *transmission* and *distribution* systems are used to interconnect electrical power production systems and to provide a means of delivering electrical power from the generating station to its point of utilization. Most electrical power systems east of the Rocky Mountains are interconnected with one another in a parallel circuit arrangement. These interconnections of power production systems are monitored and controlled, in most cases, by a computerized *control center.* Such control centers provide a means of data collection and recording, system monitoring, frequency control, and signaling. Computers have become an important means of assuring the efficient operation of electrical power systems.

The *transmission* of electrical power requires many long, interconnected power lines, to carry the electrical current from where it is produced to where it is used. However, overhead power transmission lines require much planning to ensure the best use of our land. The location of *overhead transmission lines* is limited by zoning laws and by populated areas, highways, railroads, and waterways, as well as other topographical and environmental factors. Today, an increased importance is being placed upon environmental and aesthetic factors. *Power transmission lines* ordinarily operate at voltage levels from 12 kV to 500 kV of AC. Common transmission line voltages are in the range of 50 to 150 kV of AC. *High-voltage direct current* overhead transmission lines may become economical, although they are not being used extensively at the present time.

Another option is ultra high-voltage *transmission lines,* which use higher AC transmission voltages. Also, underground transmission methods for urban and suburban areas must be considered, since the right-of-way for overhead transmission lines is limited. AC overhead transmission voltages have increased to levels in the range of 765 kV, with research now dealing with voltages of over 1000 kV. One advantage of overhead cables is their ability to dissipate heat. The use of *cryogenic cable* may bring about a solution to heat dissipation problems in conductors.

Underground Distribution

The use of *underground cable* is ordinarily confined to the short lengths required in congested urban areas. The cost of underground cable is much more than that of aerial cable. To improve underground cable power-handling capability, research is being done in forced-cooling techniques, such as circulating-oil and compressed-gas insulation. Another possible method is the use of *cryogenic cables* or *superconductors,* which operate at extremely low temperatures and have a large power-handling capability.

High-voltage Direct Current Transmission

An alternative to transmitting AC voltages for long distances is *high-voltage direct current (HVDC)* power transmission. *HVDC* is suitable for long-distance overhead power lines, or for underground power lines. DC power lines are capable of delivering more power per conductor than equivalent AC power lines. Because of its fewer power losses, *HVDC* is even more desirable for underground distribution. The primary disadvantage of *HVDC* is the cost of the necessary AC-to-DC conversion equipment. There are, however, some *HVDC* systems in operation in the United States. At present, *HVDC systems* have been designed for transmitting voltages in the range of 600 kV. The key to the future development of *HVDC* systems may be the production of solid state power conversion systems with higher voltage and current rating. With a continued developmental effort, *HVDC* should eventually playa more significant role in future electrical power transmission systems.

Cryogenic Cable

There are some *problems* involved in installing an overhead electrical power distribution system, particularly in urban areas. One of these problems is obtaining a right-of-way for the overhead cable through heavily populated areas. The difficulty is caused primarily by the unattractive appearance of the lines and the potential danger of the high voltage. The problems associated with overhead transmission lines have led to the development of *cryogenic cable* for underground power distribution. *Cryogenic cables* are not considered to be superconductive, but they do have greater electrical conductivity at very low temperatures. These cables, which are still in the developmental stage, will use a metallic conductor cooled to the temperature of liquid nitrogen. One advantage of cryogenic cable over conventional cable is that its greater conductive characteristics will give it a lower line loss (I × R loss).

One design of a *cryogenic cable* is shown in Figure 8-2. This design involves the use of three separate cables, each having a hollow center for cooling purposes. The conductive portion of the cables is stranded aluminum. The aluminum conductors are wrapped with an insulating material that contains liquid nitrogen. Cryogenic cable has considerable potential in any future development of electrical power systems.

Parallel Operation of Power Systems

Electrical power *distribution systems* are operated in a *parallel* circuit arrangement. When more power sources (generators) in parallel are added, a greater load demand or current requirement can be met. On a smaller scale, this is like connecting two or more batteries in parallel to provide greater current capacity. Two *parallel-connected three-phase alternators* are depicted in Figure 8-3. Most power plants have more than one alternator connected to any single set of power lines inside the plant. These power

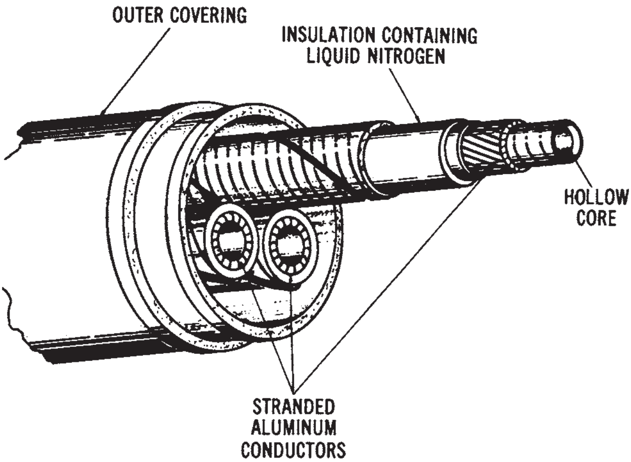

Figure 8-2. Construction of a cryogenic cable

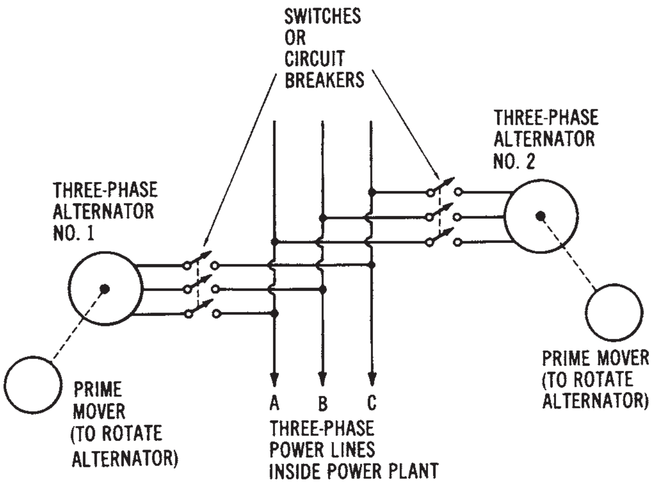

Figure 8-3. Parallel connection of two three-phase alternators

lines, or *"bus" lines,* are usually large, copper bar conductors that can carry very high amounts of current. At low-load demand times, only one alternator would be connected to the bus lines.

Figure 8-4 expands the concept of *parallel-connected* systems. An illustration of two power plants joined together through a distribution substation is shown. The two power plants might be located 100 miles apart, yet they are connected in parallel to supply power to a specified region. If, for some reason (such as repairs on one alternator), the output of one power plant is reduced, the other power plant is still available to supply power to the requesting localities. It is also possible for power plant number one to supply part of the load requirement ordinarily supplied by power plant number two, or vice versa. These regional *distribution systems* of parallel-connected power sources provide automatic compensation for any increased load demand in any area.

The major *problem* of parallel-connected distribution systems occurs when excessive *load demands* are encountered by several power systems in a single region. If all of the power plants in one area are operating near their peak power-output capacity, there is no back-up capability. The *equipment-protection* system for each power plant, and also for each alternator in the power plant, is designed to disconnect it from the system when its maximum power limits are reached. When the power demand on one part of the distribution system becomes excessive, the protective equipment will disconnect that part of the system. This places an even greater load on the remaining parts of the system. The excessive load now could cause other parts of the system to disconnect. This cycle could continue until the entire system is inoperative. This is what occurs when *blackouts* of power systems take place. No electrical power can be supplied to any part of the

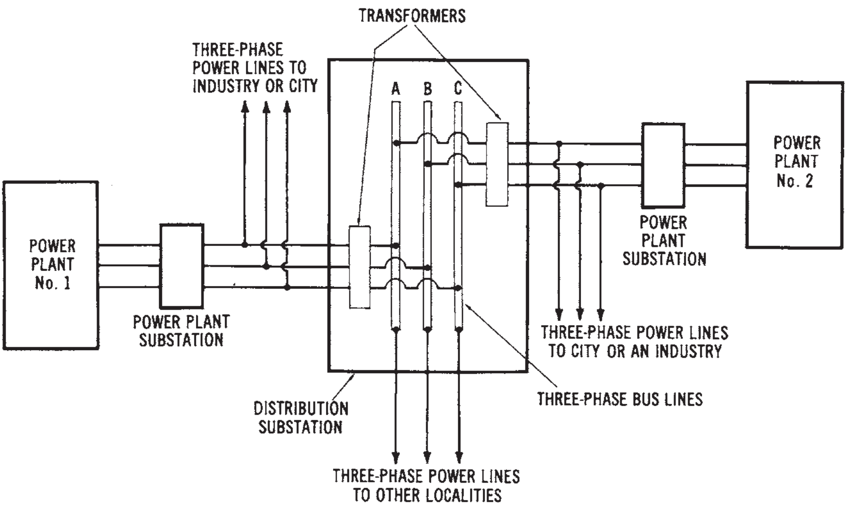

Figure 8-4. Joining two power plants in parallel as part of a regional power system

system until most of the power plants are put back in operation. The process of putting the output of a power plant back *on-line,* when the system is down during power outages, can be a long and difficult procedure.

RADIAL, RING, AND NETWORK DISTRIBUTION SYSTEMS

There are three general classifications of electrical power distribution systems. These are the *radial, ring,* and *network* systems shown in Figures 8-5 through 8-7. Radial systems are the simplest type, since the power comes from one power source. A generating system supplies power from the substation through radial lines that are extended to the various areas of a community (Figure 8-5). *Radial systems* are the least reliable in terms of continuous service, since there is no back-up distribution system connected to the single power source. If any power line opens, one or more loads are interrupted. There is more likelihood of power outages. However, the radial system is the least expensive. This system is used in remote areas where other distribution systems are not economically feasible.

Ring distribution systems (Figure 8-6) are used in heavily populated areas. The distribution lines encircle the service area. Power is delivered from one or more power sources into substations near the service area. The power is then distributed from the substations through the radial power lines. When a power line is opened, no interruption to other loads occurs. The *ring system* provides a more continuous service than the radial system. Additional power lines and a greater circuit complexity make the ring system more expensive.

Network distribution systems (Figure 8-7) are a combination of the radial and ring systems. They usually result when one of the other systems is expanded. Most of the distribution systems in the United States are network systems. This system is more complex, but it provides very reliable service to consumers. With a network system, each load is fed by two or more circuits.

USE OF TRANSFORMERS FOR POWER DISTRIBUTION

The heart of a *power distribution system* is an electrical device known as a *transformer.* This device is capable of controlling massive amounts of power for efficient distribution. Transformers are also used for many other

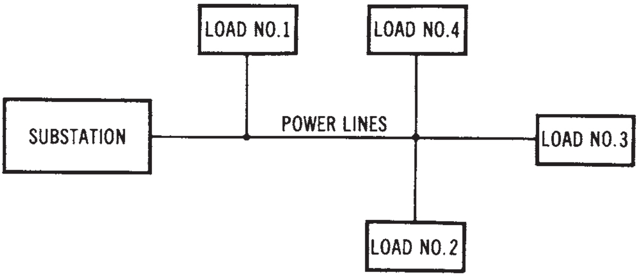

Figure 8-5. A radial power distribution system

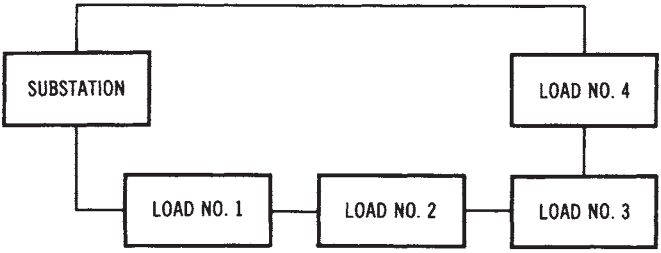

Figure 8-6. A ring power distribution system

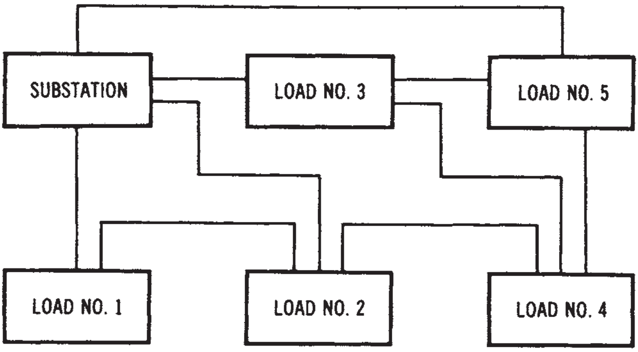

Figure 8-7. A network power distribution system

applications. A knowledge of transformer operation is essential for understanding power distribution systems. The distribution of AC power is dependent upon the use of transformers at many points along the line of the power distribution system.

It is economically feasible to transmit electrical power over long distances at high voltages since less current is required at high voltages, and therefore line loss (I^2R) is reduced significantly. A typical high-voltage transmission line may extend a distance of 50 to 100 miles from the generating station to the first substation. These high-voltage power transmission lines typically operate at 100,000 to 500,000 volts by using *step-up transformers* to increase the voltage produced by the AC generators at the power station. Various *substations* are encountered along the power distribution system, where transformers are used to reduce the high transmission voltages to a voltage level such as 480 volts, which is suitable for industrial motor loads, or to 120/240 volts for residential use.

Transformers provide a means of converting an AC voltage from one value to another. The basic construction of a *transformer* is illustrated in Figure 8-8. Notice that the transformer shown consists of two sets of windings that are not physically connected. The only connection between the primary and secondary windings is the magnetic coupling effect known as *mutual induction,* which takes place when the circuit is energized by an AC voltage. The laminated iron core plays an important role in transferring *magnetic flux* from the *primary winding* to the *secondary winding*.

Transformer Operation

If an AC current, which is constantly changing in value, flows in the

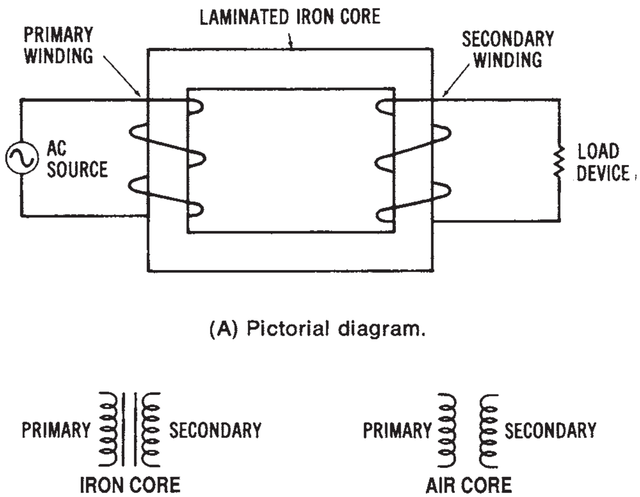

Figure 8-8. Basic transformer construction: (A) Pictorial design, (B) Schematic diagram

primary winding, the magnetic field produced around the primary winding will be transferred to the secondary winding. Thus, an *induced voltage* is developed across the *secondary winding.* In this way, electrical energy can be transferred from the source (primary-winding circuit) to a load (secondary-winding circuit).

The efficient transfer of energy from the primary to the secondary windings of a transformer depends on the *coupling* of the magnetic field between these two windings. Ideally, all magnetic lines of force developed around the primary winding would be transferred by magnetic coupling to the secondary winding. However, a certain amount of *magnetic loss* takes place as some lines of force escape to the surrounding air.

Transformer Core Construction

In order to decrease the amount of *magnetic loss,* transformer windings are wound around *iron cores.* Iron cores concentrate the magnetic lines of force, so that better coupling between the primary and secondary windings is accomplished. Two types of transformer cores are illustrated in Figure 8-9. These cores are made of laminated iron to reduce undesirable *eddy currents,* which are induced into the core material. These eddy currents cause power losses. The diagram of Figure 8-9A shows a *closed-core transformer* construction. The transformer windings of the closed-core type are placed along the outside of the metal core. Figure 8-9B shows the *shell-core* type of construction. The shell-core construction method produces better magnetic coupling, since the transformer windings are surrounded by metal on both sides. Note that the primary and secondary windings of both types are placed adjacent to one another for better magnetic coupling.

Transformer Efficiency and Losses

Transformers are very efficient electrical devices. A typical efficiency rating for a transformer is around 98 percent. *Efficiency* of electrical equipment is expressed as:

$$\text{Efficiency (\%)} = \frac{P_{out}}{P_{in}} \times 100$$

where:

P_{out} is the power output in watts, and
P_{in} is the power input in watts.

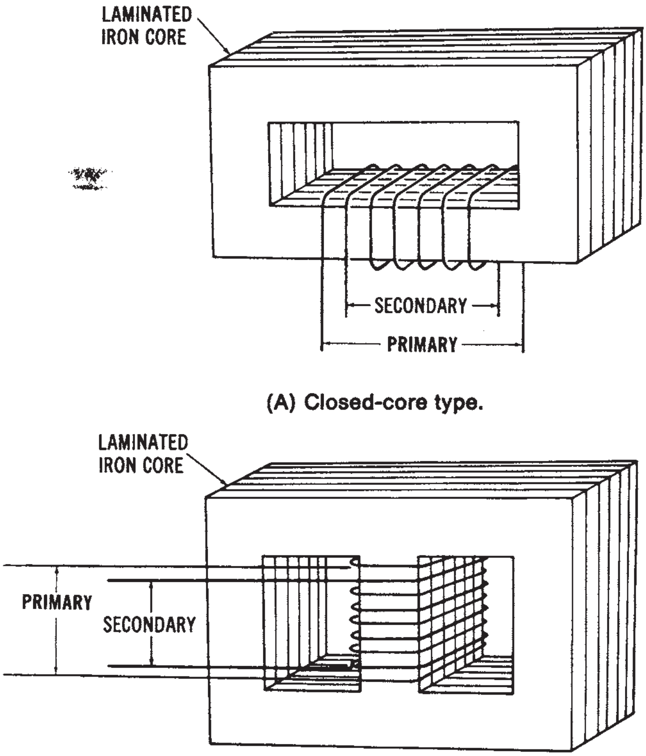

Figure 8-9. Types of iron-core transformers: (A) Closed-core type, (B) Shellcore type

Sample Problem:

Given: a transformer circuit has a power output of 2.5 kW and a power input of 2,550 W.

Find: the efficiency of the transformer.

Solution:

$$\% \text{ Eff} = \frac{2{,}500 \text{ W}}{2{,}550 \text{ W}} \times 100$$

$$\% \text{ Eff} = 98\%$$

The losses that reduce efficiency, in addition to *flux leakage,* are copper and iron losses. *Copper loss* is the I^2R loss of the windings, while *iron* losses are those caused by the metallic core material. The insulated laminations of the iron core help to reduce iron losses.

Figure 8-10. Step-up and step-down transformers

Step-Up and Step-Down Transformers

Transformers are functionally classified as *step-up* or *step-down* types. These types are illustrated in Figure 8-10. The *step-up transformer* in Figure 8-10 has fewer turns of wire on the primary than on the secondary. If the primary winding has 50 turns of wire and the secondary has 500 turns, a turns ratio of 1:10 is developed. Therefore, if 12-volts AC is applied to the primary from the source, 10 times that voltage, or 120 volts ac, will be transferred to the secondary load (assuming no losses).

The example in Figure 8-10B is a *step-down transformer.* The step-down transformer has more turns of wire on the primary than on the secondary. The primary winding of the example has 200 turns, while the secondary winding has 100 turns—or a 2:1 ratio. If 120-volts AC are applied to the primary from the source, then one-half that amount, or 60-volts AC, will be transferred to the secondary load.

Transformer Voltage and Current Relationships

In the preceding examples, a *direct* relationship is shown between the primary and secondary turns and the voltages across each winding. This relationship may be expressed as:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

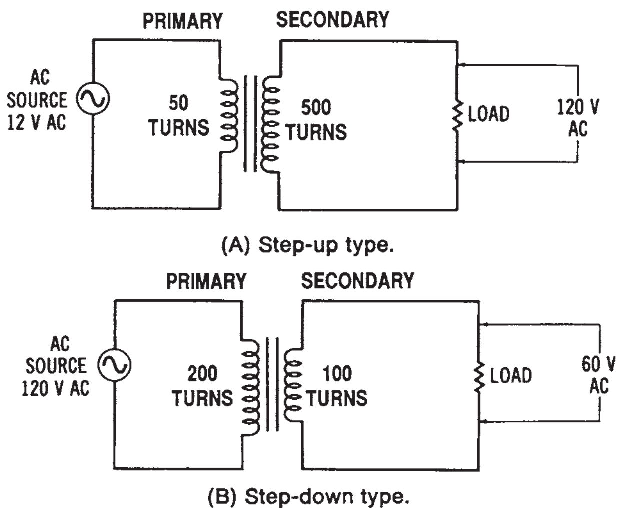

Figure 8-10. Step-up and step-down transformers

where:

V_P = the voltage across the primary winding,
V_S = the voltage across the secondary winding,
N_P = the number of turns in the primary winding, and
N_S = the number of turns in the secondary winding.

Sample Problem:

Given: a transformer circuit has the following values:
V_P = 240 volts
N_P = 1000 turns
V_S = 120 volts

Find: the number of secondary turns of wire required to accomplish this step-down of voltage.

Solution:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

$$\frac{240\text{ V}}{120\text{ V}} = \frac{1000}{N_S}$$

$$N_S = 500\text{ turns}$$

The transformer is a *power-control device;* therefore, the following relationship can be expressed:

$$P_P = P_S + \text{losses}$$

where:

P_P = the primary power, and
P_S = the secondary power.

Sample Problem:

Given: the power output (secondary power) of a transformer is 15 kW, and its losses are as follows:

iron loss -200 W
copper loss -350 W

Find: the power input (primary power) required. Solution:

$$\begin{aligned} P_P &= P_S + \text{losses} \\ &= 15{,}000\text{ W} + (200\text{ W} + 350\text{ W}) \end{aligned}$$

$$P_P = 15{,}550 \text{ watts}$$

The *losses* are those that ordinarily occur in a transformer. In transformer theory, an *ideal* device is usually assumed, and losses are not considered. Thus, since $P_P = P_S$, and $P = V \times I$, then

$$V_P \times I_P = V_S \times I_S$$

where:

I_P = the primary current, and
I_S = the secondary current.

Therefore, if the voltage across the secondary is stepped up to twice the voltage across the primary, then the secondary current will be stepped down to one-half the primary current. The *current relationship* of a transformer is thus expressed as:

$$\frac{I_P}{I_S} = \frac{N_S}{N_P}$$

Note that whereas the voltage-turns ratio is a direct relationship, the current ratio is an *inverse* relationship.

Sample Problem:

Given: an ideal transformer circuit has the following values:
V_P =600V
V_S =2400V
I_S =80A
Find: the primary current drawn by the step-up transformer
Solution:

$$\frac{I_P}{I_S} = \frac{N_S}{N_P}$$

$$\frac{I_P}{80 \text{ A}} = \frac{2400 \text{ V}}{600 \text{ V}}$$

$$I_P = 3{,}200 \text{ A}$$

Multiple Secondary Transformers

It is also possible to construct a transformer that has *multiple secondary windings,* as shown in Figure 8-11. This transformer is connected to a

120-volt AC source, which produces the primary magnetic flux. The secondary has two step-down windings and one step-up winding. Between points 1 and 2, a voltage of 5-volts AC could be supplied. Between point 5 and point 6, 30-volts AC may be obtained, and between points 3 and 4, a voltage of 360-volts AC can be supplied to a load. This type of transformer is used for the power supply of various types of electronic equipment and instruments.

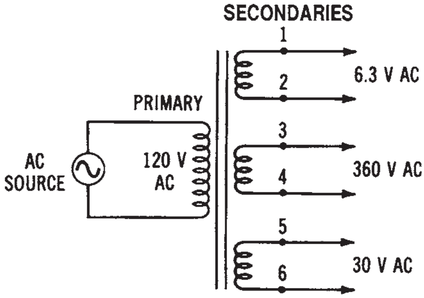

Figure 8-11. Transformer with multiple secondary windings

Autotransformers

Another specialized type of transformer is the *autotransformer,* shown in Figure 8-12. The autotransformer has only *one winding,* with a common connection between the primary and secondary. The principle of operation of the autotransformer is similar to that of other transformers. Both the *step-up* and *step-down* types are shown in Figure 8-12. Another type of control device is a *variable autotransformer,* in which the winding tap may be adjusted along the entire length of the winding to provide a variable AC voltage to a load.

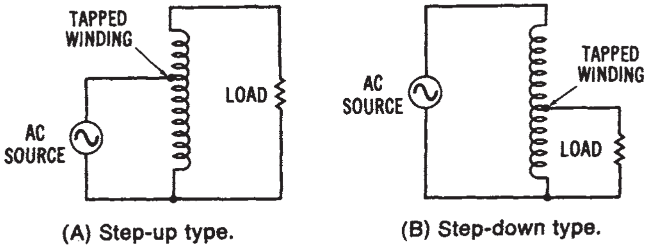

Figure 8-12. Autotransformers: (A) Step-up type, (B) Step-down type

Current Transformers

Current transformers are often used to reduce a large value of line current to a smaller value, for measurement or control purposes. These transformers are used to measure the current magnitude of high-current systems. Since most *metering* systems respond linearly to current changes, the current transformer principle can also be used to measure quantities other than current in high-power systems.

Transformer Polarity and Ratings

Power distribution transformers usually have *polarity markings,* so that their windings may be connected in parallel to increase their current capacity. The standard markings are H_1, H_2, H_3, et cetera, for the high-voltage windings, and X_1, X_2, X_3, et cetera, for the low-voltage windings. Many power transformers have two similar primary windings and two similar secondary windings to make them adaptable to different voltage requirements simply by changing from a series to a parallel connection. The voltage combinations available from this type of transformer are shown in Figure 8-13.

The *ratings* of power transformers are very important. Usually, transformers are rated in *kilovolt-amperes (kVA).* A kilowatt rating is not used, since it would be misleading, because of the various power-factor ratings of industrial loads. Other power transformer ratings usually include *frequency,* rated *voltage* of each winding, and an *impedance* rating.

Power transformers located along a power distribution system operate at very *high temperatures. Cooling equipment* is necessary for large power transformers. The purpose of the cooling equipment is to conduct heat away from the transformer windings. Several power transformers are of the *liquid-immersed* type. The windings and core of the transformer are immersed in an insulating liquid, which is contained in the transformer enclosure. The liquid insulates the windings, and conducts heat away from them as well. One insulating liquid that is used extensively is called *Askarel*. Some transformers, called *dry types,* use forced air or inert gas as coolants. Some locations, particularly indoors, are considered hazardous for the use of liquid-immersed transformers. However, most transformers, rated at over 500 kVA, are liquid filled.

Transformer Malfunctions

Transformer *malfunctions* result when a circuit problem causes the insulation to break down. *Insulation breakdown* permits electrical arcs to

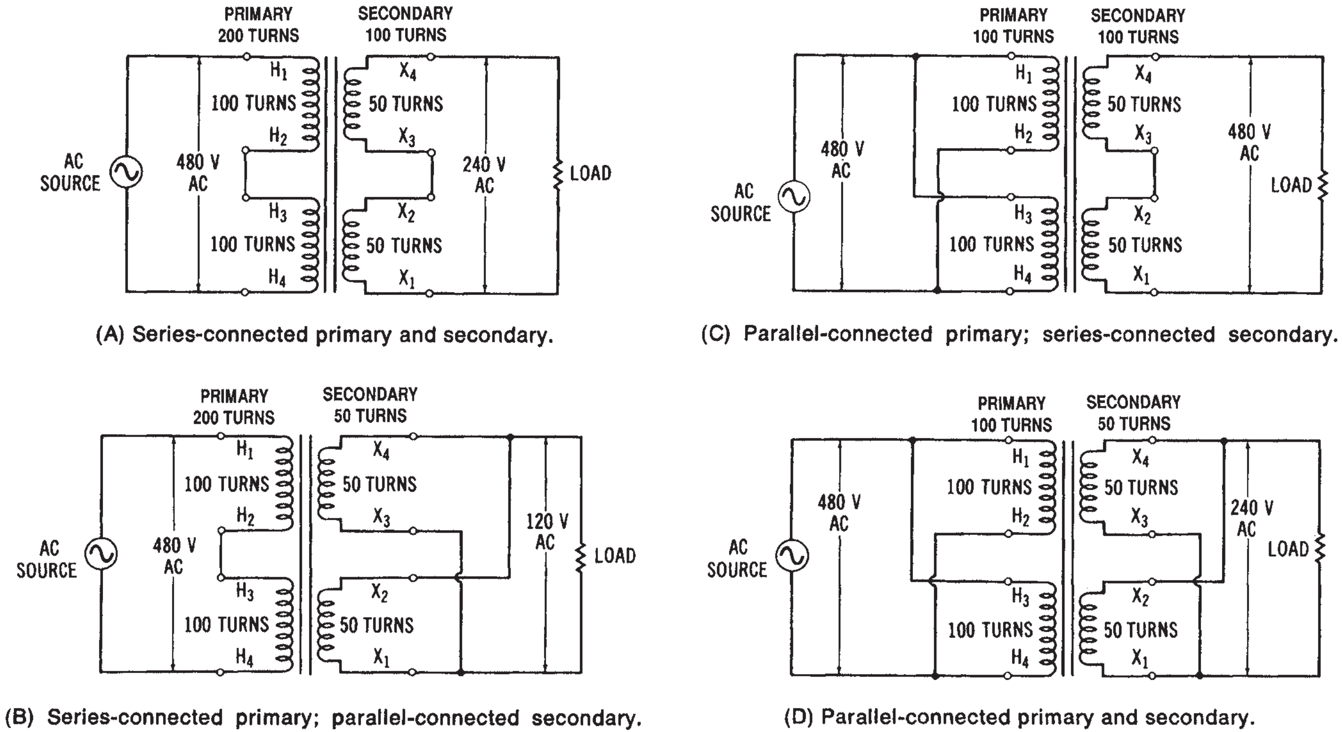

Figure 8-13. Some transformer connection methods for various voltage combinations: (A) Series-connected primary and secondary, (B) Series-connected primary, parallel-connected secondary, (C) Parallel, connected primary, series-connected secondary, (D) Parallel-connected primary and secondary

flow from one winding to an adjacent winding. These *arcs,* which may be developed throughout the transformer, cause a decomposition of the *paper* or *oil* insulation used in the transformer. This can be a particularly hazardous problem for larger power transformers, since the reaction of the electric arc and the insulating material may produce a gas. For this reason, it is very important for circuit protection to be provided for transformers. They should have power removed promptly whenever some type of fault develops. *Current-limiting fuses* may also be used to respond rapidly to any circuit malfunction.

CONDUCTORS IN POWER DISTRIBUTION SYSTEMS

The portions of the electrical distribution system that carry current are known as *conductors.* Conductors may be in the form of *solid* or *stranded* wires, cable assemblies, or large metallic bus-bar systems. A conductor may have insulation, or, in some cases, it may be bare metal.

Conductor Characteristics

Round conductors are measured by using an *American wire gage (AWG)* (see Figure 8-14). The sizes range from No. 36 (smallest) to No. 0000 (largest), with 40 sizes within this range. The *cross-sectional area* of a conductor doubles with each increase of three sizes and the diameter doubles with every six sizes. The area of conductors is measured in *circular mils (cmil).*

Almost all conductors are made of either *copper* or *aluminum.* Both of these metals possess the necessary flexibility, current-carrying ability, and economical cost to act as efficient and practical conductors. *Copper* is a better conductor; however, *aluminum* is 30 percent lighter in weight. Therefore, aluminum conductors are used when weight is a factor in conductor selection. One specialized overhead power line conductor is the *aluminum-conductor, steel-reinforced (ACSR)* type used for long-distance power transmission. This type of conductor has stranded aluminum wires.

Conductor Types

Copper is still the most widely used conductor material, both for *solid* and for *stranded* electrical wire. The availability of a variety of thermosetting and thermoplastic insulating materials offers great flexibility in meeting the requirements for most conductor applications. The *operating temperature* ranges for various types of insulation are given in Table 8-1.

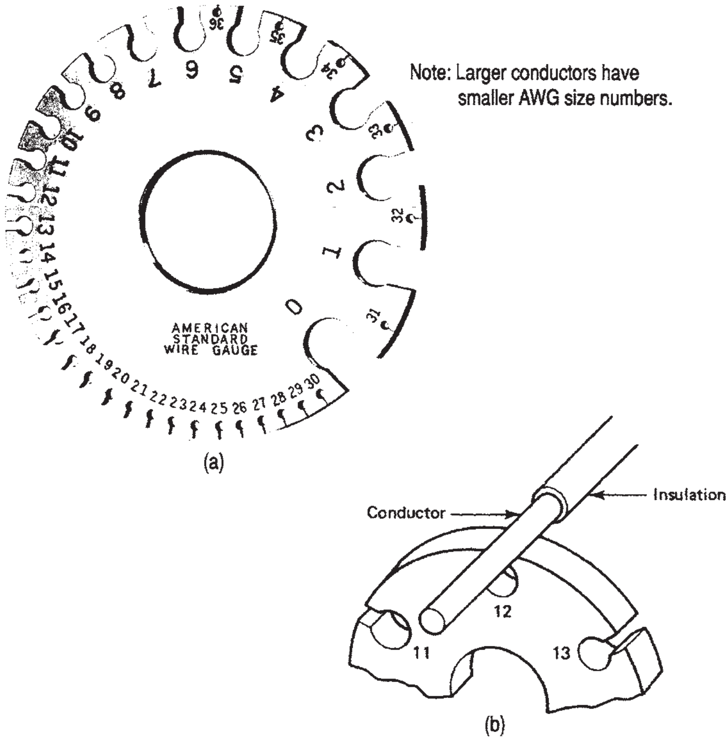

Figure 8-14. Using the AWG: (A) The American wire gage (AWG) (B) Using the AWG to measure conductor size

Table 8-1. Operating Temperature Ranges of Various Types of Insulation

Type of Insulation	*Temperature Range* (ac)
Neoprene®	–30° to 90°
Teflon®	–70° to 200°
Polyethylene	–60° to 80°
Rubber	–40° to 75°
Vinyl	–20° to 80°
Polypropylene	–20° to 105°

Copper has a combination of various properties, such as malleability, strength, and high electrical and thermal conductivity. It is also capable of being alloyed or coated with other metals. *Copper* may be plated with silver to produce a conductor with better solderability and, also, a conductor that has better high-frequency characteristics. This is due to the high conductivity of the silver and the *"skin effect"* present at higher frequencies.

Where little vibration and no flexing are required of a wire or cable, single-strand conductors may be used. The advantage of a *single-strand conductor* is its lower cost compared to that of equivalent types of stranded wire. Wire and cable with solid conductors may be used as interconnection wires for electrical instruments and similar equipment. *Stranded conductors* are used to provide more flexibility. They also have a longer usage life than do solid conductors. If a solid conductor were cut by wire strippers during its installation, it would probably break after being bent a few times. However, stranded wire would not break in this situation. Wires having from 26 to 41 strands may be used where much flexibility is needed, while wires with from 65 to 105 strands may be used for special purposes.

Flat or *round braided conductors* are occasionally used for certain applications where they are better suited than solid or stranded cables. These conductors are seldom insulated, since this would hinder their flexibility.

CONDUCTOR AREA

The unit of measurement for conductors is the *circular mil (cmil)*, since most conductors are round. One mil is equal to 0.001 inch (0.0254 mm); thus, one cmil is equal to a circle whose diameter is 0.001 inch. The *cross-sectional area* of a conductor (in cmils) is equal to its diameter (D), in mils squared, or cmil = D^2. For example, if a conductor is 1/4 inch (6.35 mm) in diameter, its circular mil area can be found as follows. The decimal equivalent of 1/4 inch is 0.250 inch, which equals 250 mils. Inserting this value into the formula for the cross-sectional area of a conductor gives you:

$$\begin{aligned} \text{Area} &= D^2 \text{ (in mils)} \\ &= (250)^2 \\ &= 62{,}500 \text{ cmils} \end{aligned}$$

If the conductor is not round, its area may still be found by applying the following formula:

$$\text{Area (in emils)} = \frac{\text{Area (in square mils)}}{0.7854}$$

This formula allows us to convert the dimensions of a conductor to *square mils,* and then to an equivalent value in cmils. For example, if a conductor is 1/2 inch × 3/4% inch (12.7 mm × 19.05 mm), the cmil area may be found using the following method. Again, convert the fractional inches into decimal values, and then into equivalent mil values. Thus, 1/2 inch equals 0.5 inch, which equals 500 mils, and 3/4 inch is 0.75 inch, which equals 750 mils. Using the formula for *square mils* and substituting, you have:

$$\text{Area} = \frac{\text{Area (in square mils)}}{0.7854}$$

$$= \frac{500 \text{ mils} \times 750 \text{ mils}}{0.7854}$$

$$= \frac{375{,}000 \text{ mils}^2}{0.7854}$$

$$= 477{,}463.7 \text{ cmils}$$

We can also use the *cmil area* of a conductor, which may be found in any standard conductor table, to find the diameter of a conductor. If a table shows that the cmil area of a conductor is equal to 16,510 cmils (a No. 8 AWG conductor), its *diameter* is found by the following method. Since

$$D^2 = \text{cmil}$$

then:

$$D = \sqrt{\text{cmil}}$$

$$= \sqrt{16{,}510 \text{ cmils}}$$

$$= 128.5 \text{ mils}$$

$$= 0.1285 \text{ inch}$$

RESISTANCE OF CONDUCTORS

The *resistance* of a conductor expresses the amount of opposition it will offer to the flow of electrical current. The unit of measurement for resistance is the ohm (Ω). The *resistivity (p)* of a conductor is the resistance for a specified cross-sectional area and length. This measurement is given in *circular mil-feet (cmil-ft).* The resistivity of a conductor changes with the temperature, so resistivity is usually specified at a temperature of 20° Celsius. The *resistivity* for some common types of conductors is listed in Table 8-2.

Table 8-2. Resistivity of Common Conductors

Conductor	*Resistivity in ohms per cmil-ft*
Silver	9.8
Copper	10.4
Aluminum	17.0
Tungsten	33.0
Nickel	50.0
Iron	60.0

We can use Table 8-2 to calculate the *resistance* of any size conductor. We know that resistance increases as the length increases and decreases as the cross-sectional area increases. The following method can be used to find th0e resistance of 500 feet (152.4 meters) of aluminum conductor that is V. inch (6.35 mm) in diameter. According to Table 8-2, aluminum has a *resistivity* of 17 ohms. The *diameter* (D) equals 1/4 inch, which equals 0.250 inch, which is the equivalent of 250 mils. Using the formula and substituting, we have:

$$\text{Resistance} = \frac{\text{Resistivity} \times \text{Length (in feet)}}{\text{Diameter}^2 \text{ (in mils)}}$$

$$= \frac{17 \times 500}{(250)^2}$$

$$= \frac{8{,}500}{62{,}500}$$

$$= 0.136 \text{ ohms}$$

CONDUCTOR SIZES AND TYPES

Table 8-3 lists the sizes of *copper* and *aluminum* electrical conductors. The *American wire gage (AWG)* is the standard used to measure the diameter of conductors. The sizes range from No. 40 A WG, which is the smallest, to No. 0000 A *We.* Sizes larger than No. 0000 AWG are expressed in thousand circular mil (MCM) units.

Note, in Table 8-3, that as the *A* WG *size* number becomes smaller, the conductor becomes larger. Sizes up to No.8 A WG are solid conductors, while larger wires have from 7 to 61 strands. Table 8-3 also lists the DC *resistance* (in ohms per 1000 feet) of the copper and aluminum conductors. These values are used to determine conductor *voltage drop* in power distribution systems.

AMPACITY OF CONDUCTORS

A measure of the ability of a conductor to carry electrical current is called *ampacity.* All metal materials will conduct electrical current to some extent; however, copper and aluminum are the two most desirable types used. *Copper* is used more often than aluminum, since it is the better conductor of the two and is physically stronger. However, aluminum is usually used where weight is a factor, such as for long-distance overhead power lines. The weight of copper is almost three times that of a similar volume of *aluminum;* however, the resistance of aluminum is over 150 percent that of copper. The ampacity of an aluminum conductor is, therefore, less than that of a similar size copper conductor. A wiring design will ordinarily use aluminum conductors that are one size larger than the copper conductors necessary to carry a specific amount of current, to allow for this difference.

The *ampacity* of conductors depends upon several factors, such as the type of material, the cross-sectional area, and the type of area in which the conductors are installed. Conductors in the open, or in *"free air,"* dissipate heat much more rapidly than those that are enclosed in a metal *raceway,* or plastic cable. When several conductors are contained within the same enclosure, heat dissipation is a greater problem.

The National Electric Code (NEC)

The *National Electrical Code (NEC)* is a very important document to understand. All industrial equipment and wiring must conform to the

Table 8-3. Sizes of Copper and Aluminum Conductors

					DC Resistance (Ω/1000 ft) 25°C	
Size (AWG or MCM)		Area (cmil)	Number of Wires	Diameter of Each Wire (in.)	Copper	Aluminum
AWG sizes	18	1,620	1	0.0403	6.51	10.7
	16	2,580	1	0.0508	4.10	6.72
	14	4,110	1	0.0641	2.57	4.22
	12	6,530	1	0.0808	1.62	2.66
	10	10,380	1	0.1019	1.018	1.67
	8	16,510	1	0.1285	0.6404	1.05
	6	26,240	7	0.0612	0.410	0.674
	4	41,740	7	0.0772	0.259	0.424
	3	52,620	7	0.0867	0.205	0.336
	2	66,360	7	0.0974	0.162	0.266
	1	83,690	19	0.0664	0.129	0.211
	0	105,600	19	0.0745	0.102	0.168
	00	133,100	19	0.0837	0.0811	0.133
	000	167,800	19	0.0940	0.0642	0.105
	0000	211,600	19	0.1055	0.0509	0.0836
MCM sizes	250	250.000	37	0.0822	0.0431	0.0708
	300	300,000	37	0.0900	0.0360	0.0590
	350	350,000	37	0.0973	0.0308	0.0505
	400	400,000	37	0.1040	0.0270	0.0442
	500	500,000	37	0.1162	0.0216	0.0354
	600	600,000	61	0.0992	0.0180	0.0295
	700	700,000	61	0.1071	0.0154	0.0253
	750	750,000	61	0.1109	0.0144	0.0236
	800	800,000	61	0.1145	0.0135	0.0221
	900	900,000	61	0.1215	0.0120	0.0197
	1000	1,000,000	61	0.1280	0.0108	0.0177

NEC standards. The NEC is not difficult to use. The user should become familiar with the comprehensive *index* contained in the NEC, and with the organization of the various *sections.* For instance, if you wish to review the standards related to "system grounding," you should look in the index and locate this term. The index will refer you to the sections in the NEC that discuss "system grounding." A *table of contents* for an NEC is shown below. This listing provides an overview of the organization of the NEC. It is important for electrical technicians to learn to use the NEC.

National Electrical Code (NEC)
Table of Contents

354 Underfloor Raceways
356 Cellular Metal Floor Raceways
358 Cellular Concrete Floor Raceways
362 Wireways
363 Flat Cable Assemblies
364 Busways
365 Cablebus
366 Electrical Floor Assemblies
370 Outlet, Switch and Junction Boxes, and Fittings
373 Cabinets and Cutout Boxes
374 Auxiliary Gutters
380 Switches
384 Switchboards and Panelboards

Chapter 4—*Equipment for General Use*
400 Flexible Cords and Cables
402 Fixture Wires
410 Lighting Fixtures, Lampholders, Lamps, Receptacles, and Rosettes
422 Appliances
424 Fixed Electric Space Heating Equipment
426 Fixed Outdoor Electric De-Icing and Snow-Melting Equipment
427 Fixed Electric Heating Equipment for Pipelines and Vessels
430 Motors, Motor Circuits, and Controllers
440 Air-Conditioning and Refrigerating Equipment
445 Generators
450 Transformers and Transformer Vaults
460 Capacitors
470 Resistors and Reactors
480 Storage Batteries

Chapter 5—*Special Occupancies*
500 Hazardous (Classified) Locations
501 Hazardous Locations—Class I Installations
502 Hazardous Locations—Class II Installations
503 Hazardous Locations—Class III Installations
510 Hazardous (Classified) Locations-Specific
511 Commercial Garages, Repair, and Storage
513 Aircraft Hangars
514 Gasoline Dispensing and Service Stations
515 Bulk-Storage Plants
516 Finishing Processes
517 Health Care Facilities
518 Places of Assembly
520 Theaters and Similar Locations
530 Motion Picture and Television Studios and Similar Locations
540 Motion Picture Projectors
545 Manufactured Buildings
547 Agricultural Buildings
550 Mobile Homes and Mobile Home Parks
551 Recreational Vehicles and Recreational Vehicle Parks
555 Marinas and Boatyards

Chapter 6—*Special Equipment*
600 Electric Signs and Outline Lighting
610 Cranes and Hoists
620 Elevators, Dumbwaiters, Escalators, and Moving Walks
630 Electric Welders
640 Sound-Recording and Similar Equipment
645 Data Processing Systems
650 Organs
660 X-ray Equipment
665 Induction and Dielectric Heating Equipment
668 Electrolytic Cells
670 Metal-Working Machine Tools
675 Electrically Driven or Controlled Irrigation Machines
680 Swimming Pools, Fountains, and Similar Installations

Chapter 7—*Special Conditions*
700 Emergency Systems
710 Over 600 Volts, Nominal—General
720 Circuits and Equipment Operating at Less than 50 Volts
725 Class I, Class II, and Class III Remote—Control, Signaling, and Power Limited Circuits
750 Stand-By Power Generation Systems
760 Fire Protective Signaling Systems

Chapter 8—*Communications Systems*
800 Communication Circuits
810 Radio and Television Equipment
820 Community Antenna Television and Radio Distribution Systems

Chapter 9—*Tables and Examples*
Tables
Examples

Index

AMPACITY TABLES

Tables 8-4 through 8-6 are used for *conductor ampacity* calculations for electrical wiring design. These tables are simplified versions of those given in the NEC. Table 8-4 is used to determine conductor ampacity when a single conductor is mounted in *free air.* Table 8-5 is used to find the ampacity of conductors when not more than three are mounted in a *raceway* or cable. These two tables are based on *ambient temperatures* of 30° Celsius (86° Fahrenheit). Table 8-6 lists the *correction factors* that are used for temperatures over 30°C. As an example, we will find the *ampacity* of three No. 10 copper conductors with RHW insulation that are mounted in a raceway. They will be located in a foundry area where temperatures reach 50°C. The ampacity for No. 10 RHW copper wire is 30 A (from Table 8-5). The *correction factor* for an RHW-insulated conductor at 50°C ambient temperature is 0.75 (Table 8-6). Therefore,

$$30 \text{ amperes} \times 0.75 = 22.5 \text{ amperes}$$

Table 8-4. Allowable Ampacities of Single Conductance in Free Air

		Copper		*Aluminum*	
	Wire Size	*With R, T, TW Insulation*	*With RH, RHW TH, THW Insulation*	*With R, T, TW Insulation*	*With RH, RHW, TH THW Insulation*
AWG	14	20	20		
	12	25	25	20	20
	10	40	40	30	30
	8	55	65	45	55
	6	80	95	60	75
	4	105	125	80	100
	3	120	145	95	115
	2	140	170	110	135
	1	165	195	130	155
	0	195	230	150	180
	00	225	265	175	210
	000	260	310	200	240
	0000	300	360	230	280
MCM	250	340	405	265	315
	300	375	445	290	350
	350	420	505	330	395
	400	455	545	355	425
	500	515	620	405	485
	600	575	690	455	545
	700	630	755	500	595
	750	655	785	515	620
	800	680	815	535	645
	900	730	870	580	700
	1000	780	935	625	750

USE OF INSULATION IN POWER DISTRIBUTION SYSTEMS

Synthetic *insulation* for wire and cable is classified into two broad categories—*thermosetting* and *thermoplastic.* The mixtures of materials within each of these categories are so varied as to make the available number of

Table 8-5. Ampacities of Conductors in a Raceway of Cable (3 or less)

		Copper		*Aluminum*	
	Wire Size	*With R, T, TW Insulation*	*With RH, RHW TH, THW Insulation*	*With R, T, TW Insulation*	*With RH, RHW, TH THW Insulation*
AWG	14	15	15		
	12	20	20	15	15
	10	30	30	25	25
	8	40	45	30	40
	6	55	65	40	50
	4	70	85	55	65
	3	80	100	65	75
	2	95	115	75	90
	1	110	130	85	100
	0	125	150	100	120
	00	145	175	115	135
	000	165	200	130	155
	0000	195	230	155	180
MCM	250	215	255	170	205
	300	240	285	190	230
	350	260	310	210	250
	400	280	335	225	270
	500	320	380	260	310
	600	355	420	285	340
	700	385	460	310	375
	750	400	475	320	385
	800	410	490	330	395
	900	435	520	355	425
	1000	455	545	375	445

Table 8-6. Correction Factors for Temperatures about 300°C

Ambient Temperature		*Conductor Correction Factor*	
C°	F°	TW	R, T, RH, *RHW, TH, THW*
40	104	0.82	0.88
45	113	0.71	0.82
50	122	0.58	0.75
55	131	0.41	0.67
60	140	—	0.58
70	158	—	0.35

insulations almost unlimited. Most insulation is composed of compounds made of synthetic rubber polymers (thermosetting) and from synthetic materials (thermoplastics). These synthetic materials are combined to provide specific physical and electrical properties.

Thermosetting materials are characterized by their ability to be stretched, compressed, or deformed within reasonable limits under mechanical strain, and then to return to their original shape when the stress is removed.

Thermoplastic insulation materials are best known for their excellent electrical characteristics and relatively low cost. These materials are popular, since they allow much thinner insulation thicknesses to be used to obtain good electrical properties, particularly at the higher voltages.

There are many types of *insulation* used today for electrical conductors. Some new materials have been developed that will last for exceptionally long periods of time and will withstand very high operating temperatures. The operating conditions where the conductors are used mainly determine the type of insulation required. For instance, system voltage, heat, and moisture affect the type of insulation required. Insulation must be used that will withstand both the heat of the surrounding atmosphere and the heat developed by the current flowing through the conductor. Exceptionally large currents will cause excessive heat to be developed in a conductor. Such heat could cause insulation to melt or burn. This is why overcurrent protection is required as a safety factor to prevent fires. The *ampacity* or current-carrying capacity of a conductor depends upon the type of insulation used. The NEC has developed a system of *abbreviations* for identifying various types of insulation. Some of the abbreviations are shown in Table 8-7.

Table 8-7. Common Abbreviations for Types of Electrical Insulation

Abbreviation	*Type of Insulation*
R	Rubber—140° F
RH	Heat-Resistant Rubber—167° F
RHH	Heat-Resistant Rubber—194° F
RHW	Moisture and Heat-Resistant Rubber—167° F
T	Thermoplastic-140° F
THW	Moisture and Heat-Resistant Thermoplastic—167° F
THWN	Moisture and Heat-Resistant Thermoplastic With Nylon—194° F

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Chapter 9

Power Distribution Equipment

In order to distribute electrical power, it is necessary to use many types of specialized *equipment*. The electrical power system consists of such specialized equipment as power *transformers*, high-voltage *fuses* and *circuit breakers*, *lightning arresters*, power-factor-correcting *capacitors*, and *power-metering* systems. Some types of specialized power distribution equipment will be discussed in this chapter.

IMPORTANT TERMS

In Chapter 9, power distribution equipment is discussed. After studying this chapter, you should have an understanding of the following terms:

Substation
High-Voltage Transmission Line
High-Voltage Fuse
High-Voltage Circuit Breaker
High-Voltage Disconnect Switch
Lightning Arrester
High-Voltage Insulator
High-Voltage Conductor
ACSR Conductor
Voltage Regulator
Plug Fuse
Cartridge Fuse
Time Delay Fuse
Renewable-Element Fuse
Low-Voltage Circuit Breaker

Protective Relay
Fault Current
Bimetallic Overload Relay
Melting Alloy Overload Relay
Undervoltage Protection
Raceway
Feeder Circuit
Branch Circuit
Underground Distribution
Safety Switch
Panelboard
Low-Voltage Switchgear
Load Center
Service Entrances
Grounding Electrode
Ground
Service Entrance Conductors
Uninterruptible Power Supply
Power Line Filter
Power Conditioner
Floor-Mounted Raceway
Conduit Connectors
Wire Connectors
Plastic Conduit and Enclosures
Power Outlet Design
International Power Source

EQUIPMENT USED AT SUBSTATIONS

Substations are very important parts of the electrical power systems. The link between the high-voltage transmission lines and the low-voltage power distribution systems is the substation. The function of a *distribution substation,* such as the one shown in Figure 8-2, is to receive electrical power from a high-voltage system and convert it to voltage levels suitable for industrial, commercial, or residential use. The major functional component of a substation is the transformer, whose basic characteristics were discussed previously. However, there are many other types of specialized equipment required for the operation of a substation.

High-voltage Fuses

Since power lines are frequently short circuited, various protective equipment is used to prevent damage to both the power lines and the equipment. This *protective equipment* must be designed to handle high voltages and currents. Either *fuses* or *circuit breakers* may be used to protect high-voltage power lines. High-voltage fuses (those used for over 600 volts) are made in several ways. An *expulsion-type fuse* has an element that will melt and vaporize when it is overloaded, causing the power line it is connected in series with to open. *Liquid fuses* have a liquid-filled metal enclosure that contains the fuse element. The liquid acts as an arc-suppressing medium. When the fuse element melts from an excessive current in a power line, the element is immersed in the liquid to extinguish the arc. This type of fuse reduces the problem of high-voltage arcing. A *solid-material fuse* is similar to a liquid fuse, except that the arc is extinguished in a chamber filled with solid material.

Ordinarily, *high-voltage fuses* at substations are mounted adjacent to air-break disconnect switches. These switches provide a means of switching power lines and disconnecting them for repair. The fuse and switch enclosure is usually mounted near the overhead power lines at a substation.

High-voltage Circuit Breakers

Circuit breakers that control high voltages are also located at electrical substations. In this type of circuit breaker, the contacts are immersed in an insulating oil contained in a metal enclosure. Another type of high-voltage circuit breaker is the *magnetic air breaker* in which the contacts separate, in the air, when the power line is overloaded. Magnetic blowout coils are used to develop a magnetic field that causes the arc (which is produced when the contacts break) to be concentrated into arc chutes where it is extinguished. A modification of this type of circuit breaker is the compressed-air circuit breaker. In this case, a stream of compressed air is concentrated on the contacts when the power line is opened. The compressed air aids in extinguishing the arc that is developed when the contacts open. It should be pointed out that large arcs are present whenever a high-voltage circuit is interrupted. This problem is not encountered to any great extent in low-voltage protective equipment. There are two major types of *high-voltage circuit breakers—oil filled* and *oilless.*

These circuit breakers are designed to operate on voltages of 1000 volts to over 500,000 volts. *Oil-filled* circuit breakers are used primarily for outdoor substations, except for very high voltages in the range of 500,000 volts and higher. *Oilless* circuit breakers are ordinarily used for indoor operation.

High-voltage Disconnect Switches

High-voltage disconnect switches are used to disconnect electrical equipment from the power lines that supply the equipment. Ordinarily, disconnect switches are not operated when current is flowing through them. A high-voltage arcing problem would occur if disconnect switches were opened while current was flowing through them. They are opened mainly to isolate equipment from power lines for safety purposes. Most disconnect switches are the *"air-break"* type, which is similar in construction to knife switches. These switches are available for indoor or outdoor use in both manual and motor-operated designs.

Lightning Arresters

The purpose of using *lightning arresters* on power lines is to cause the conduction to ground of excessively high voltages that are caused by lightning strikes or other system problems. Without lightning arresters, power lines and associated equipment could become inoperable when struck by lightning. Arresters are designed to operate rapidly and repeatedly, if necessary. Their response time must be more rapid than that of the other protective equipment used on power lines.

Lightning arresters must have a rigid connection to ground on one side. The other side of the arrester is connected to a power line. Sometimes, they are connected to transformers or the insides of switchgear. Lightning is a major cause of power-system failures and equipment damage, so lightning arresters have a very important function. *Lightning arresters* are also used at outdoor substations. The lightning arrester is used to provide a path to ground for lightning strikes or hits. This path eliminates the *flashover* between power lines, which causes short circuits. *Valve-type* lightning arresters are used frequently. They are two-terminal devices in which one terminal is connected to the power line, and the other is connected to ground. The path from line to ground is of such high resistance that it is normally open. However, when lightning, which is a very high voltage, strikes a power line, it causes conduction from line to ground. Thus, voltage surges are conducted to ground before flashover between the lines occurs. After the lightning surge has been conducted to ground, the valve assembly then causes the lightning arrester to become nonconductive once more.

High-voltage Insulators

All power transmission lines must be isolated so as not to become safety hazards. Large strings of *insulators* are used at substations, and at other points along the power distribution system, to isolate the current-carrying conductors from their steel supports or any other ground-mounted equipment. Insulators may be made of *porcelain, rubber,* or a *thermoplastic* material.

Power transmission lines require many *insulators* in order to electrically isolate the power lines from the steel towers and wooden poles that support the lines. Insulators must have enough mechanical strength to support power lines under all weather conditions. They must also have sufficient insulating properties to prevent any arcing between the power lines and their support structures. High-voltage insulators are usually made of *porcelain.* Insulators are constructed in *"strings,"* which are suspended from steel or wooden towers. The design of these insulators is very important, since design affects their capacitance and their ability to withstand weather conditions.

High-voltage Conductors

The *conductors* used for power distribution are, ordinarily, uninsulated *aluminum* wires or *aluminum-conductor steel-reinforced (ACSR)* wires for long-distance transmission, and insulated copper wires for shorter distances.

Voltage Regulators

Voltage regulators are an important part of the power distribution system. They are used to maintain the voltage levels at the proper value, as a constant voltage must be maintained in order for the electrical equipment to function properly. For instance, motors do not operate properly when a reduced or an excessive voltage is applied to them. Transformer *tap-changers,* illustrated in Figure 9-1 may be used as voltage regulators. The secondary tap can be changed, either manually or automatically, to change the voltage output, in order to compensate for changes in the load voltage. As load current increases, line loss ($I \times R$) also increases. Increased line loss causes the secondary voltage (V_s) to decrease. If the secondary tap is initially connected to tap No.4, the secondary voltage can be boosted by reconnecting to either tap No. 3, No. 2, or No. 1. This can be done automatically with a motor-controlled tap changer. There are various other types of automatic voltage regulators that can be used with electrical power distribution systems.

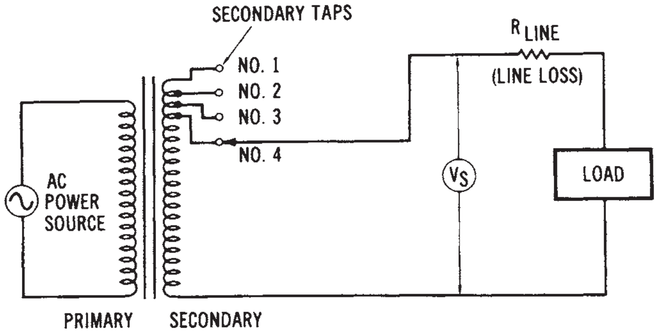


Figure 9-1. Transformer tap-changer voltage regulator

POWER SYSTEM PROTECTIVE EQUIPMENT

There are many devices that are used to *protect* electrical power systems from damage due to abnormal conditions. For instance, *switches, fuses, circuit breakers, lightning arresters,* and *protective relays* are all used for this purpose. Some of these devices automatically disconnect the equipment from power lines before any dam age can occur. Other devices sense variations from the normal operation of the system and make the changes necessary to compensate for abnormal circuit conditions. The most common electrical problem that requires protection is *short circuits.* Other problems include *overvoltage, undervoltage,* and *changes ill frequency.* Generally, more than one method of protection is used to protect electrical circuits from faulty conditions. The purpose of any type of protective device is to cause a current-carrying conductor to become inoperative when an excessive amount of current flows through it.

Types of Fuses

The simplest type of protective device is a *fuse.* Fuses are low-cost items and have a fast operating speed. However, in three-phase systems, since each hot line must be fused, two lines are still operative if only one fuse burns out. Three-phase motors will continue to run with one phase removed. This condition is undesirable, in most instances, since motor torque is greatly reduced, and overheating may result. Another obvious disadvantage of fuses is that replacements are required. All protective devices, including fuses, have an *operating-characteristic time curve,* such as the one shown in Figure 9-2, prevent any possible damage to equipment,

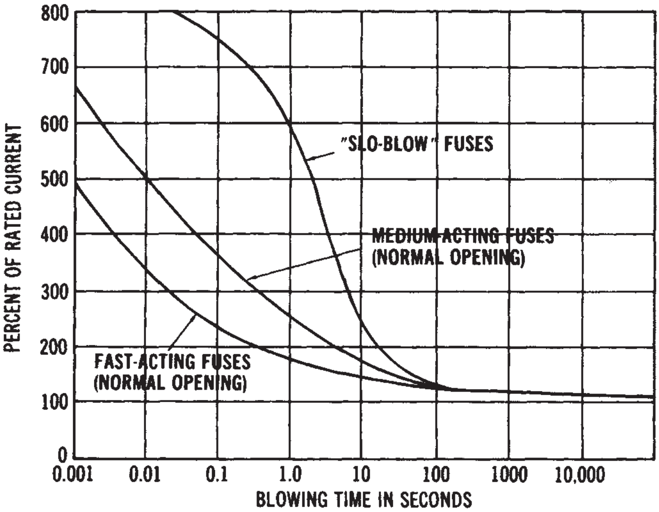


Figure 9-2. Typical operating-characteristic time curves for three different types of fuses *(Courtesy Littelfuse, Inc.)*

circuit protection should be planned utilizing these curves. They show the response time required for a protective device to interrupt a circuit, when an overload occurs.

Plug Fuses—Fuses are used in safety switches and power distribution panels. The *plug fuse* is a common type of fuse. Standard sizes for this fuse are 10, 15, 20, 25, and 30 amperes at voltages of 125 volts or below. These fuses have a zinc or metallic-alloy-fusible element enclosed in a case made of an insulating material. Their most common use is in safety switches and fuse panelboards.

Cartridge Fuses—Cartridge fuses are commonly used in power distribution systems for voltages up to 600 volts. They have a zinc- or alloy-fusible element, which is housed in a round fiber enclosure. One type has a *nonrenewable element,* while another type has a *renewable element.* Cartridge fuses may be used to protect high-current circuits, since they come in sizes of 60,100,200,400,600, and 1000 amperes.

Time Delay Fuses—A modification of the plug or cartridge fuse is called a *time delay fuse.* This type of fuse is used to delay the circuit-interrupting action. It is useful where momentary high currents exist periodically, such as motor-starting currents. The fuse element melts only when an excessive current is sustained over the time-lag period; thus, sufficient circuit protection is still provided.

Time delay fuse are used to limit current on systems including electric motors, which draw higher currents during their start cycle than during normal operation. These devices allow the system to start up at a higher than normal current; they then protect the system during normal operation without disrupting the distribution system.

Fuse Metals—The type of metal used in fuses is ordinarily an *alloy* material or, possibly, *aluminum.* All metals have resistance, so when current flows through metal, heat energy is produced. As the current increases, more heat is produced, causing the temperature of the metal to increase. When the *melting point* of the fuse metal is reached, the fuse will open, causing the circuit to which it is connected to open. Metals that decompose rapidly are used, rather than ones that produce small metallic globules when they melt. This reduces the likelihood of any *arc-over* occurring after the fuse metal has melted. The current rating of fuses depends upon the melting temperature of the fuse metal, as well as its shape, size, and the type of enclosure used.

Low-voltage Circuit Breakers

Circuit breakers are somewhat more sophisticated overload devices than are fuses. Although their function is the same as that of fuses, circuit breakers are much more versatile. In three-phase systems, circuit breakers can open all three hot lines when an *overload* occurs. They may also be activated by remote-control relays. *Relay systems* may cause circuit breakers to open in response to changes in frequency, voltage, current, or other circuit variables. Circuit breakers are used in industrial plants, and are usually of the low-voltage variety (less than 600 volts). They are not nearly as complex as their high-voltage counterparts (which were discussed previously). Most low-voltage circuit breakers are housed in molded-plastic cases that mount in metal power distribution panels. *Circuit breakers* are designed so that they will automatically open when a current occurs that exceeds the rating of the breaker. Ordinarily, the circuit breakers must be reset manually. Most circuit breakers employ either a *thermal tripping* element or a *magnetic trip* element. Ratings of circuit breakers extend into current ranges that are as high as 800 to 2000 amperes.

Protective Relays

Protective relays provide an accurate and sensitive method of protecting electrical equipment from short circuits and other abnormal conditions. Overcurrent relays are used to cause the rapid opening of electrical power lines when the current exceeds a predetermined value. The *response time* of the relays is very important in protecting the equipment from damage. Some common types of faults that relays protect against are *line-to-ground short circuits, line-to-line short circuits, double line-to-ground short circuits, and three-phase line short circuits.* Each of these conditions is caused by faulty circuit conditions that draw abnormally high current from the power lines.

Motor Fault Current Protection

Motor fault currents are excessive currents that occur in motors as the result of some unnatural malfunction. Since motor fault currents cannot be withstood for any duration of time, some type of protection must be provided to disconnect the motor from the power distribution system when a fault condition occurs. Such protection may be provided by *motor starters, circuit breakers,* or *fuses.* The type of protection used is dependent upon several characteristics of the power distribution system and the motor.

Motor Protective Devices

The distribution of electrical power to *motors* is a very important function of industrial and commercial power distribution. Distribution of energy to industrial electric motors is particularly important. Basic *functions* that motors are expected to perform are *starting, stopping, reversing,* and *speed variation.* These functions may be manually or automatically controlled. Various types of *protective devices* are used to provide for the efficient distribution of power to electric motors.

Overload protection is the most important motor protection function. Such protection should serve the motor, its branch circuit, and the associated control equipment. The major cause of motor overload is an excessive mechanical load on the motor, which causes it to draw too much current from the power source. A block diagram of a motor-protection system is shown in Figure 9-3.

Thermal overload relays are often used as protective devices. Thermal relays may be reset either manually or automatically. One type of thermal overload relay uses a *bimetallic heater* element. The bimetallic element bends as it is heated by the current flowing through it. When the current reaches the rating of the element, the relay opens the branch circuit. Another type of element is the *melting alloy* type. This device has contacts

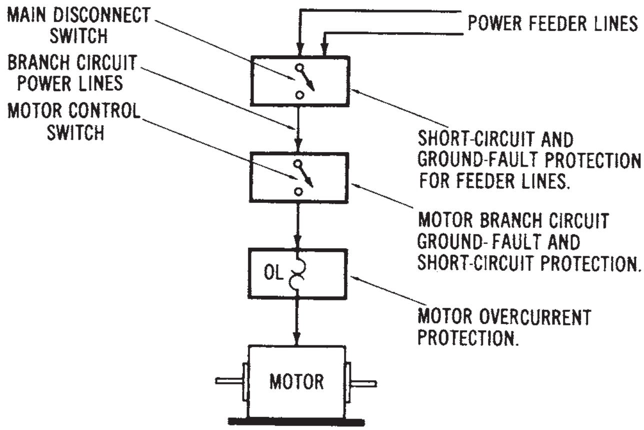


Figure 9-3. Block diagram of a motor-protection circuit

held closed by a ratchet wheel. At the current capacity of the device, the fusible alloy melts, causing the ratchet wheel to turn. A spring then causes the device to open the circuit.

Overheating Protection for Motors

Motors must be protected from excessive *overheating.* This protection is provided by *magnetic* or *thermal* protective devices, which are ordinarily within the motor-starter enclosure. Protective relays or circuit breakers can also perform this function. When an operational problem causes the motor to overheat, the protective device is automatically used to disconnect the motor from its power supply.

Undervoltage Protection

Motors do not operate efficiently when less than their rated voltage is applied, and some types of motors can be destroyed if they are operated continuously at reduced voltages. Magnetic contactors (see Chapter 15) may be used effectively to protect against *undervoltages.* A specific level of voltage is required to cause magnetic contactors to operate. If the voltage is reduced below a specified level, the magnetic contactor will open, thus disconnecting the circuit between the power source and the motor, and stopping the motor before any damage can be done.

POWER DISTRIBUTION INSIDE INDUSTRIAL AND COMMERCIAL BUILDINGS

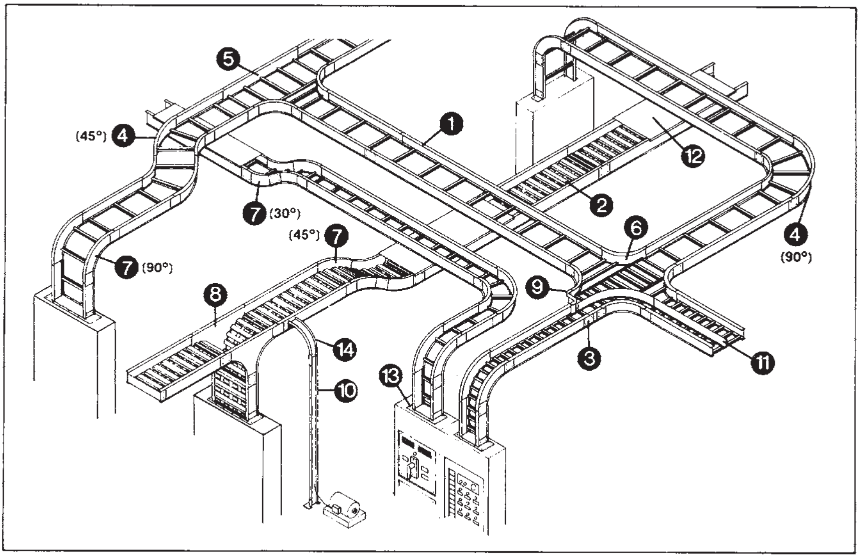
Electrical power is delivered to the location where it is to be used, and then distributed *within a building* by the power distribution system. Various types of circuit breakers and switchgear are employed for power distribution. Another factor involved in power distribution is the distribution of electrical energy to the many types of loads that are connected to the system. This part of the distribution system is concerned with the *conductors, feeder* systems, *branch circuits, grounding* methods, and *protective* and *control* equipment that is used.

Raceways

Most electrical distribution to industrial and commercial loads is through wires and cables contained in *raceways.* These raceways carry the conductors, which carry the power to the various equipment throughout a building. Copper *conductors* are ordinarily used for indoor power distribution. The physical size of each conductor is dependent upon the current rating of the branch circuit. Raceways may be large metal *ducts* or rigid metal *conduits.* These raceways provide a compact and efficient method of routing cables, wires, et cetera, throughout an industrial complex. A *cable tray raceway* design for industrial applications is shown in Figure 9-4.

Feeder Lines and Branch Circuits

The conductors that carry current to the electrical load devices in a building are called *feeders* and *branch circuits.* Feeder lines supply power to branches, which are connected to them. *Primary feeder lines* may be either overhead or underground. Usually, overhead lines are preferred because they permit flexibility for future expansion. *Underground* systems cost more, but they help to maintain a more attractive environment. Secondary feeders are connected to the primary feeder lines, to supply power to individual sections within the building. Either aluminum or copper feeder lines may be used, depending on the specific power requirements. The distribution is from the feeder lines, through individual protective equipment, to *branch circuits,* which supply the various loads. Each branch circuit has various protective devices according to the needs of that particular branch. The overall feeder-branch system may be a very complex network of switching equipment, transformers, conductors, and protective equipment.



1. Ladder tray straight section.
2. Ventilated trough tray.
3. Splice plate-bolted connector.
4. Horizontal bend (30° to 90°).
5. Tee.
6. Cross.
7. Vertical bends (30° to 90°).
   INSIDE VERTICAL =
   transition from level to upward direction.
   OUTSIDE VERTICAL =
   transition from level to downward direction.
8. Vertical tee.
9. Reducer.
10. Channel tray.
11. Barrier.
12. Cover.
13. Tray-to-box connector.
14. Channel-outside bend.

Figure 9-4. Industrial cable tray raceway design (*Courtesy Chalfant Manufacturing Co.*)

Switching Equipment

In addition to circuit protection, power distribution systems must have equipment that can be used to connect or disconnect the entire system or parts of the system. Various types of *switching devices* are used to perform this function. A simple type of switch is the *safety switch.* This type of switch is mounted in a metal enclosure and operated by means of an external handle. Safety switches are used only to turn a circuit off or on; however, fuses are often mounted in the same enclosure with the safety switch.

Distribution Panelboards

Another type of switch is the kind used in conjunction with a circuit breaker *panelboard.* Panelboards are metal cabinets that enclose the main disconnect switch and the branch circuit protective equipment. Distribution panelboards are usually located between the power feed lines within a building and the branch circuits that are connected to it.

Low-voltage Switchgear

Metal-enclosed *low-voltage switchgear* is used in many industrial and commercial buildings as a distribution control center to house the circuit breakers, bus bars, and terminal connections that are part of the power distribution system. Ordinarily, a combination of switchgear and distribution transformers is placed in adjacent metal *enclosures.* This combination is referred to as a *load-center unit substation,* since it is the central control for several loads. The rating of these load centers is usually 15,000 volts or less for the high-voltage section, and 600 volts or less for the low-voltage section. Load centers provide flexibility in the electrical power distribution design of industrial plants and commercial buildings.

Metal-enclosed switchgear, or metal-clad switchgear, is a type of equipment that houses all the necessary control devices for the electrical circuits that are connected to them. The control devices contained inside the switchgear include circuit breakers, disconnect switches, interconnecting cables and buses, transformers, and the necessary measuring instruments. Switchgear is used for indoor and outdoor applications at industrial plants, commercial buildings, and substations. The voltage ratings of switchgear are usually from 13.8 to 138 kV, with 1 to 10 MV A power ratings.

THE ELECTRICAL SERVICE ENTRANCE

Electrical power is brought from the overhead power lines, or from the underground cable, into a building by what is called a *service entrance.* A good working knowledge of the *National Electrical Code* (NEC) specifications and definitions is necessary for an understanding of service entrance equipment. The NEC sets the minimum standards that are necessary for *wiring design* inside a building.

The type of *equipment* used for an electrical service entrance of a building may include high-current *conductors* and *insulators,* disconnect *switches, protective* equipment for each load circuit that will be connected to the main power system, and the meters needed to measure power, voltage, current, and/or frequency. It is also necessary to ground the power system at the service entrance location. This is done by a *grounding electrode,* which is a metal rod driven deep into the ground. The grounding conductor is attached securely to this grounding electrode. Then, the grounding conductor is used to make contact with all neutral conductors and safety grounds of the system.

SERVICE ENTRANCE TERMINOLOGY

There are several terms associated with service entrance equipment. The *service entrance conductors* are a set of conductors brought to a building by the local electrical utility company. These conductors must be capable of carrying all of the electrical current that is to be delivered to the various loads inside the building that are to be supplied with power by the power system. Conductors that extend from the service entrance to a power distribution panel or other type of overcurrent protective equipment, are called *feeders.* Feeders are power lines that supply branch circuits. A *branch circuit* is defined as conductors that extend beyond the last overcurrent protective equipment of the power system. Usually, each branch circuit delivers electrical power to a small percentage of the total load of the main power system.

In commercial and industrial installations, *switchboards* and *panelboards* are used to supply power to various loads throughout the power system. A *switchboard* is a large enclosure that has several overcurrent protective devices (fuses or circuit breakers). Each feeder is connected to the proper type of overcurrent device. Often, switchboards contain metering equipment for the power system. *Panelboards* are smaller than switchboards, but are used for a similar purpose. They are enclosures for overcurrent devices for either branch circuits or feeder circuits. A common example of a panelboard is the main power-distribution panel that houses the circuit breakers used for the branch circuits of a home. For more specific definitions of terms, you should refer to the most recent edition of the NEC.

Power Distribution System Components

Several specialized types of power distribution system components are available today and should be reviewed.

Uninterruptible Power Supply—An uninterruptible power supply (UPS) has computer-controlled diagnostics and monitoring to provide constant on-line power for today's modern equipment. The constant power capability is particularly useful for computer systems used in business and industry.

Power Filters and Conditioners—Power *line filters* ordinarily plug into interior power distribution systems. These filters have power outlets for obtaining filtered AC power. *Power conditioners* are also used to protect power distribution systems from spikes, surges, or other interference that may be damaging to certain types of equipment.

Floor-mounted Raceways—*Floor-mounted raceways*, surface raceways and power outlets, are used in most commercial and industrial facilities.

Conduit Connectors—Several types of *conduit bodies* are used today. These bodies are used to provide a means of connecting conductors, and to allow angular bends in conduit runs throughout a building.

Wire Connectors—Simple but essential components of electrical power distribution systems are *wire end connectors* (sometimes called "wire nuts").

Plastic Components—Flexible *plastic conduit* provides an alternative to *electrical metallic tubing (EMT)* and rigid conduit, in certain distribution systems. Plastic boxes are compatible with flexible conduit and *plastic enclosures* for power distribution systems.

Power Outlets—*Power outlets* have standard configurations that have been established by the National Electrical Manufacturers Association (NEMA). The specific configuration indicates the voltage, current, and phase ratings of the distribution system. *NEMA designs* are shown in Figure 9-5.

International Power Sources—an *international power source* provides a convenient means of converting North American voltage and frequency (120 volt/60 hertz) to international voltages and frequencies. Output power is obtained through the appropriate standard international socket. The system shown has adjustable voltages and frequencies for obtaining power to match that of most countries, and for the use of products purchased in other countries, without modification of power supplies.

Note that the following NEMA configurations are not to scale. Canadian, United Kingdom, European, and other required configurations are also available.

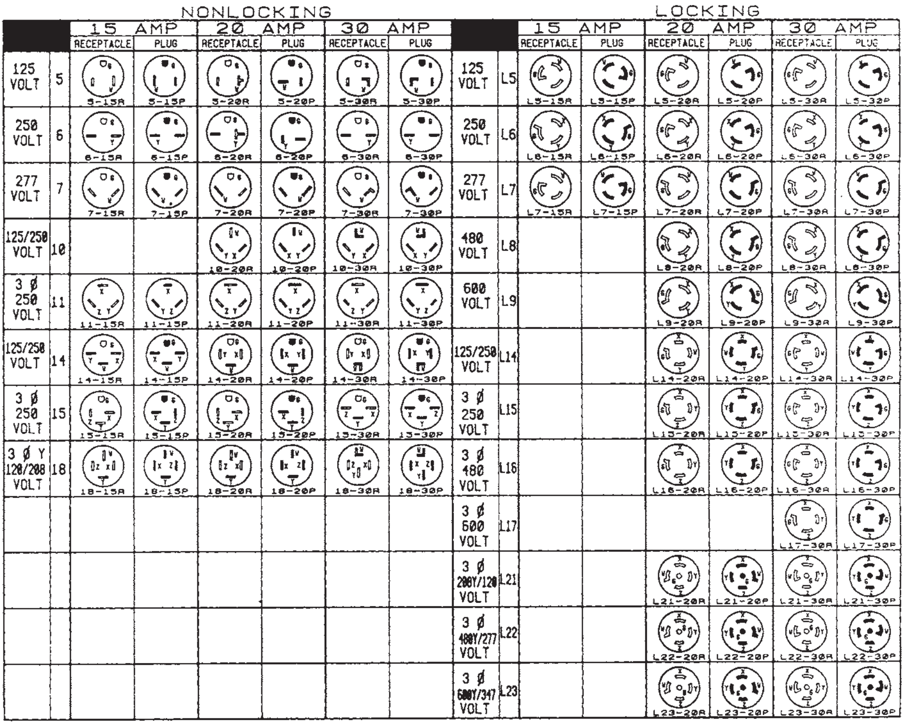


Figure 9-5. Standard NEMA designs for power outlets (*Courtesy Pulizzi Engineering, Inc.*)