ELECTRIC POWER SYSTEM BASICS

For the Nonelectrical Professional

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SYSTEM OVERVIEW, TERMINOLOGY, AND BASIC CONCEPTS

CHAPTER OBJECTIVES

- ☑ *Discuss the history of electricity*
- ☑ *Present a basic overview of today's electric power system*
- ☑ *Discuss general terminology and basic concepts used in the power industry*
- ☑ *Explain the key terms voltage, current, power, and energy*
- ☑ *Discuss the nature of electricity and terminology relationships*
- ☑ *Describe the three types of consumption loads and their characteristics*

HISTORY OF ELECTRIC POWER

Benjamin Franklin is known for his discovery of electricity. Born in 1706, he began studying electricity in the early 1750s. His observations, including his kite experiment, verified the nature of electricity. He knew that lightning was very powerful and dangerous. The famous 1752 kite experiment featured a pointed metal piece on the top of the kite and a metal key at the base

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end of the kite string. The string went through the key and attached to a Leyden jar. (A Leyden jar consists of two metal conductors separated by an insulator.) He held the string with a short section of dry silk as insulation from the lightning energy. He then flew the kite in a thunderstorm. He first noticed that some loose strands of the hemp string stood erect, avoiding one another. (Hemp is a perennial American plant used in rope making by the Indians.) He proceeded to touch the key with his knuckle and received a small electrical shock.

Between 1750 and 1850 there were many great discoveries in the principles of electricity and magnetism by Volta, Coulomb, Gauss, Henry, Faraday, and others. It was found that electric current produces a magnetic field and that a moving magnetic field produces electricity in a wire. This led to many inventions such as the battery (1800), generator (1831), electric motor (1831), telegraph (1837), and telephone (1876), plus many other intriguing inventions.

In 1879, Thomas Edison invented a more efficient lightbulb, similar to those in use today. In 1882, he placed into operation the historic Pearl Street steam–electric plant and the first direct current (dc) distribution system in New York City, powering over 10,000 electric lightbulbs. By the late 1880s, power demand for electric motors required 24-hour service and dramatically raised electricity demand for transportation and other industry needs. By the end of the 1880s, small, centralized areas of electrical power distribution were sprinkled across U.S. cities. Each distribution center was limited to a service range of a few blocks because of the inefficiencies of transmitting direct current. Voltage could not be increased or decreased using direct current systems, and a way to to transport power longer distances was needed.

To solve the problem of transporting electrical power over long distances, George Westinghouse developed a device called the "transformer." The transformer allowed electrical energy to be transported over long distances efficiently. This made it possible to supply electric power to homes and businesses located far from the electric generating plants. The application of transformers required the distribution system to be of the alternating current (ac) type as opposed to direct current (dc) type.

The development of the Niagara Falls hydroelectric power plant in 1896 initiated the practice of placing electric power generating plants far from consumption areas. The Niagara plant provided electricity to Buffalo, New York, more than 20 miles away. With the Niagara plant, Westinghouse convincingly demonstrated the superiority of transporting electric power over long distances using alternating current (ac). Niagara was the first large power system to supply multiple large consumers with only one power line.

Since the early 1900s alternating current power systems began appearing throughout the United States. These power systems became interconnected to form what we know today as the three major power grids in the United States and Canada. The remainder of this chapter discusses the fundamental terms used in today's electric power systems based on this history.

SYSTEM OVERVIEW

Electric power systems are real-time energy delivery systems. Real time means that power is generated, transported, and supplied the moment you turn on the light switch. Electric power systems are not storage systems like water systems and gas systems. Instead, generators produce the energy as the demand calls for it.

Figure 1-1 shows the basic building blocks of an electric power system. The system starts with *generation,* by which electrical energy is produced in the power plant and then transformed in the power station to high-voltage electrical energy that is more suitable for efficient long-distance transportation. The power plants transform other sources of energy in the process of producing electrical energy. For example, heat, mechanical, hydraulic, chemical, solar, wind, geothermal, nuclear, and other energy sources are used in the production of electrical energy. High-voltage (HV) power lines in the *transmission* portion of the electric power system efficiently transport electrical energy over long distances to the consumption locations. Finally, substations transform this HV electrical energy into lower-voltage energy that is transmitted over distribution power lines that are more suitable for the *distribution* of electrical energy to its destination, where it is again transformed for residential, commercial, and industrial consumption.

A full-scale actual interconnected electric power system is much more complex than that shown in Figure 1-1; however the basic principles, concepts, theories, and terminologies are all the same. We will start with the basics and add complexity as we progress through the material.

TERMINOLOGY AND BASIC CONCEPTS

Let us start with building a good understanding of the basic terms and concepts most often used by industry professionals and experts to describe and discuss electrical issues in small-to-large power systems. Please take the time necessary to grasp these basic terms and concepts. We will use them

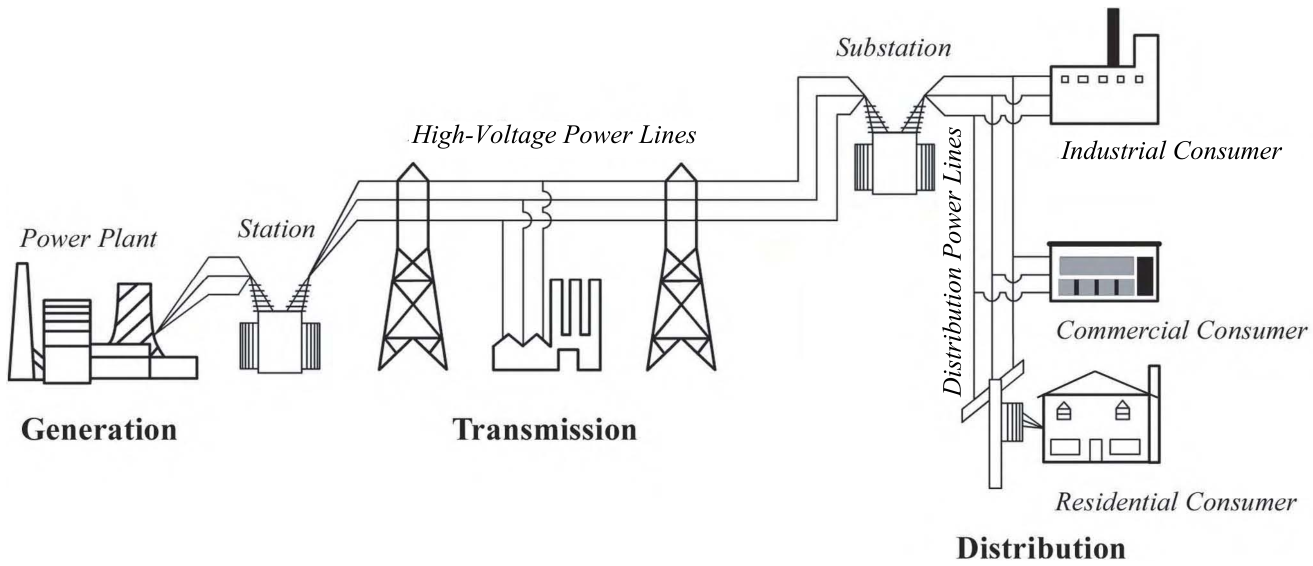

Figure 1-1. System overview.

throughout this book to build a complete working knowledge of electrical power systems.

Voltage

The first term or concept to understand is *voltage.* Voltage is the *potential energy* source in an electrical circuit that makes things happen. It is sometimes called *Electromotive Force* or EMF. The basic unit (measurement) of electromotive force (EMF) is the *volt.* The volt was named in honor of Allessandro Giuseppe Antonio Anastasio Volta (1745–1827), the Italian physicist who also invented the battery. Electrical voltage is identified by the symbol “e” or “E.” (Some references use symbols “v” or “V.”

Voltage is the electric power system’s potential energy source. Voltage does nothing by itself but has the potential to do work. Voltage is a push or a force. Voltage always appears between two points.

Normally, voltage is either constant (i.e., direct) or alternating. Electric power systems are based on alternating voltage applications from low-voltage 120 volt residential systems to ultra high voltage 765,000 volt transmission systems. There are lower and higher voltage applications involved in electric power systems, but this is the range commonly used to cover generation through distribution and consumption.

In water systems, voltage corresponds to the pressure that pushes water through a pipe. The pressure is present even though no water is flowing.

Current

Current is the flow of electrons in a *conductor* (wire). Electrons are pushed and pulled by voltage through an *electrical circuit* or closed-loop path. The electrons flowing in a conductor always return to their voltage source. Current is measured in *amperes*, usually called *amps.* (One amp is equal to 628×10^{16} electrons flowing in the conductor per second.) The number of electrons never decreases in a loop or circuit. The flow of electrons in a conductor produces heat due to the conductor’s *resistance* (i.e., friction).

Voltage always tries to push or pull current. Therefore, when a complete circuit or closed-loop path is provided, voltage will cause current to flow. The resistance in the circuit will reduce the amount of current flow and will cause heat to be provided. The *potential energy* of the voltage source is thereby converted into *kinetic energy* as the electrons flow. The kinetic energy is then utilized by the load (i.e., consumption device) and converted into useful work.

Current flow in a conductor is similar to ping-pong balls lined up in a tube. Referring to Figure 1-2, pressure on one end of the tube (i.e., voltage)

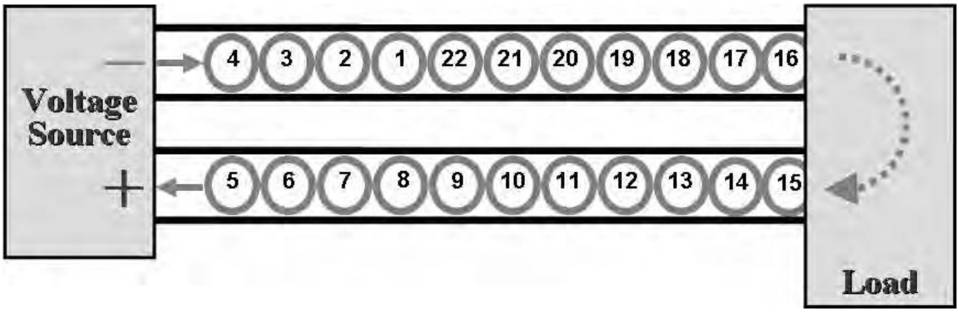

Figure 1-2. Current flow.

pushes the balls through the tube. The pressure source (i.e., battery) collects the balls exiting the tube and returns them to the tube in a circulating manner (closed-loop path). The number of balls traveling through the tube per second is analogous to current. This movement of electrons in a specified direction is called *current*. Electrical current is identified by the symbol "*i*" or "*I*."

Hole Flow Versus Electron Flow

Electron flow occurs when the electron leaves the atom and moves toward the positive side of the voltage source, leaving a hole behind. The holes left behind can be thought of as a current moving toward the negative side of the voltage source. Therefore, as electrons flow in a circuit in one direction, holes are created in the same circuit that flow in the opposite direction. Current is defined as either electron flow or hole flow. *The standard convention used in electric circuits is* ***hole flow****!* One reason for this is that the concept of positive (+) and negative (–) terminals on a battery or voltage source was established long before the electron was discovered. The early experiments simply defined current flow as being from positive to negative, without really knowing what was actually moving.

One important phenomenon of current flowing in a wire that we will discuss in more detail later is the fact that *a current flowing in a conductor produces a magnetic field.* (See Figure 1-3.) This is a physical law, similar to gravity being a physical law. For now, just keep in mind that when electrons are pushed or pulled through a wire by voltage, a magnetic field is produced automatically around the wire. Note: Figure 1-3 is a diagram that corresponds to the direction of conventional or hole flow current according to the "right-hand rule."

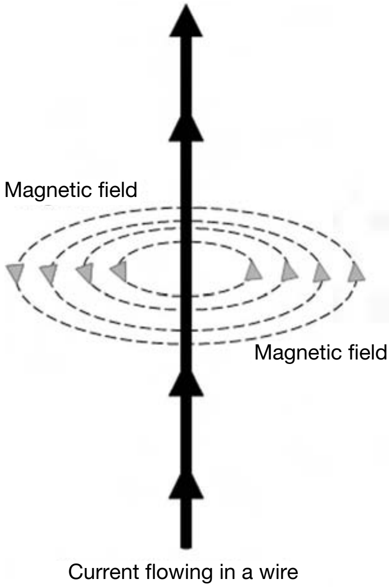

Figure 1-3. Current and magnetic field.

Power

The basic unit (measurement) of *power* is the *watt* (W), named after James Watt (1736–1819), who also invented the steam engine. Voltage by itself does not do any real work. Current by itself does not do any real work. However, voltage and current together can produce real work. The product of voltage times current is power. Power is used to produce real work.

For example, electrical power can be used to create heat, spin motors, light lamps, and so on. The fact that power is part voltage and part current means that power equals zero if either voltage or current are zero. Voltage might appear at a wall outlet in your home and a toaster might be plugged into the outlet, but until someone turns on the toaster, no current flows, and, hence, no power occurs until the switch is turned on and current is flowing through the wires.

Energy

Electrical *energy* is the product of electrical power and time. The amount of time a load is on (i.e., current is flowing) times the amount of power used by the load (i.e., watts) is energy. The measurement for electrical energy is *watt-hours* (Wh). The more common units of energy in electric power systems are kilowatt-hours (kWh, meaning 1,000 watt-hours) for residential applications and megawatt-hours (MWh, meaning 1,000,000 watt-hours) for large industrial applications or the power companies themselves.

dc Voltage and Current

Direct current (dc) is the flow of electrons in a circuit that is always in the same direction. Direct current (i.e., one-direction current) occurs when the voltage is kept constant, as shown in Figure 1-4. A battery, for example, produces dc current when connected to a circuit. The electrons leave the negative terminal of the battery and move through the circuit toward the positive terminal of the battery.

ac Voltage and Current

When the terminals of the potential energy source (i.e., voltage) alternate between positive and negative, the current flowing in the electrical circuit likewise alternates between positive and negative. Thus, alternating current (ac) occurs when the voltage source alternates.

Figure 1-5 shows the voltage increasing from zero to a positive peak value, then decreasing through zero to a negative value, and back through zero again, completing one cycle. In mathematical terms, this describes a *sine wave.* The sine wave can repeat many times in a second, minute, hour, or day. The length of time it takes to complete one cycle in a second is called the *period* of the cycle.

Frequency

Frequency is the term used to describe the number of cycles in a second. The number of cycles per second is also called *hertz,* named after Heinrich

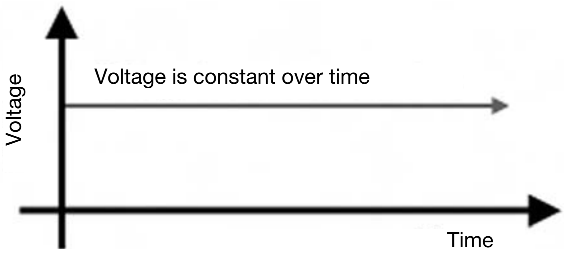

Figure 1-4. Direct current (dc voltage).

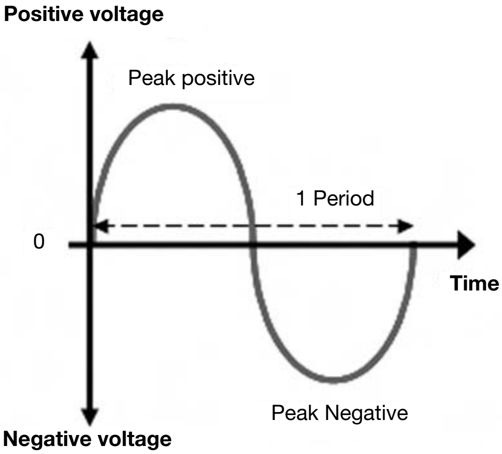

Figure 1-5. Alternating current (ac voltage).

Hertz (1857–1894), a German physicist. Note: direct current (dc) has no frequency; therefore, frequency is a term used only for ac circuits.

For electric power systems in the United States, the standard frequency is 60 cycles/second or 60 hertz. The European countries have adopted 50 hertz as the standard frequency. Countries outside the United States and Europe use 50 and/or 60 hertz. (Note: at one time the United States had 25, 50, and 60 hertz systems. These were later standardized to 60 hertz.)

Comparing ac and dc Voltage and Current

Electrical loads, such as lightbulbs, toasters, and hot water heaters, can be served by either ac or dc voltage and current. However, dc voltage sources continuously supply heat in the load, whereas ac voltage sources cause heat to increase and decrease during the positive part of the cycle, then increase and decrease again in the negative part of the cycle. In ac circuits, there are actually moments of time when the voltage and current are zero and no additional heating occurs.

It is important to note that there is an equivalent ac voltage and current that will produce the same heating effect in an electrical load as if it were a dc voltage and current. The equivalent voltages and currents are referred to as the *root mean squared* values, or *rms* values. The reason this concept is important is that all electric power systems are rated in rms voltages and currents.

For example, the 120 Vac wall outlet is actually the rms value. Theoretically, one could plug a 120 Vac toaster into a 120 Vdc battery source and cook the toast in the same amount of time. The ac rms value has the same heating capability as a dc value.

Optional Supplementary Reading

Appendix A explains how rms is derived.

The Three Types of Electrical Loads

Devices that are connected to the power system are referred to as electrical *loads.* Toasters, refrigerators, bug zappers, and so on are considered electrical loads. There are three types of electrical loads. They vary according to their *leading* or *lagging* time relationship between voltage and current.

The three load types are *resistive, inductive, and capacitive.* Each type has specific characteristics that make them unique. Understanding the differences between these load types will help explain how power systems can operate efficiently. Power system engineers, system operators, maintenance personnel, and others try to maximize system efficiency on a continuous basis by having a good understanding of the three types of loads. They understand how having them work together can minimize system losses, provide additional equipment capacity, and maximize system reliability.

The three different types of load are summarized below. The standard units of measurement are in parentheses and their symbols and abbreviations follow.

Resistive Load (Figure 1-6)

The resistance in a wire (i.e., conductor) causes friction and reduces the amount of current flow if the voltage remains constant. Byproducts of this electrical friction are heat and light. The units (measurement) of resistance are referred to as *ohms.* The units of electrical power associated with resistive load are *watts.* Lightbulbs, toasters, electric hot water heaters, and so on are resistive loads.

Figure 1-6. Resistive loads.

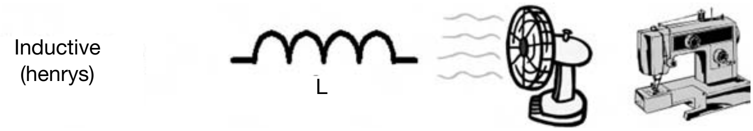

Figure 1-7. Inductive loads.

Inductive Load (Figure 1-7)

Inductive loads require a magnetic field to operate. All electrical loads that have a coil of wire to produce the magnetic field are called inductive loads. Examples of inductive loads are hair dryers, fans, blenders, vacuum cleaners, and many other motorized devices. In essence, all motors are inductive loads. The unique difference between inductive loads and other load types is that the current in an inductive load *lags* the applied voltage. Inductive loads take time to develop their magnetic field when the voltage is applied, so the current is delayed. The units (measurement) of inductance are called *henrys.*

Regarding electrical motors, a load placed on a spinning shaft to perform a work function draws what is referred to as *real* power (i.e., watts) from the electrical energy source. In addition to real power, what is referred to as *reactive* power is also drawn from the electrical energy source to produce the magnetic fields in the motor. The *total power* consumed by the motor is, therefore, the sum of both real and reactive power. The units of electrical power associated with reactive power are called *positive VARs.* (The acronym VAR stands for volts-amps-reactive.)

Capacitive Load (Figure 1-8)

A capacitor is a device made of two metal conductors separated by an insulator called a *dielectric* (i.e., air, paper, glass, and other nonconductive materials). These dielectric materials become charged when voltage is applied to the attached conductors. Capacitors can remain charged long after the

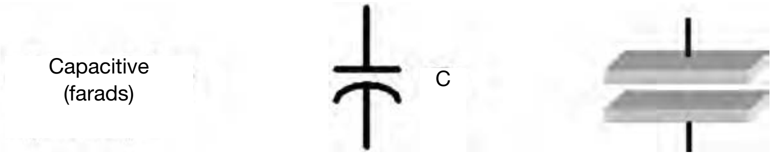

Figure 1-8. Capacitive loads.

voltage source has been removed. Examples of capacitor loads are TV picture tubes, long extension cords, and components used in electronic devices.

Opposite to inductors, the current associated with capacitors *leads* (instead of lags) the voltage because of the time it takes for the dielectric material to charge up to full voltage from the charging current. Therefore, it is said that the current in a capacitor leads the voltage. The units (measurement) of capacitance are called *farads*.

Similar to inductors, the power associated with capacitors is also called reactive power, but has the opposite polarity. Thus, inductors have positive VARs and capacitors have *negative VARs*. Note, the negative VARs of inductors can be cancelled by the positive VARs of capacitors, to leading a net zero reactive power requirement. How capacitors cancel out inductors in electrical circuits and improve system efficiency will be discussed later.

As a general rule, capacitive loads are not items that people purchase at the store in massive quantities like they do resistive and inductive loads. For that reason, power companies must install capacitors on a regular basis to maintain a reactive power balance with the inductive demand.

2

GENERATION

CHAPTER OBJECTIVES

- ☑ *Describe how voltage is produced in a conductor when in the presence of a changing magnetic field*
- ☑ *Explain how three coils of wire in the presence of a changing magnetic field produce three-phase voltage*
- ☑ *Describe how current flowing through a wire produces a magnetic field*
- ☑ *Discuss how generator rotors provide the magnetic field for the generation of electricity*
- ☑ *Describe the three main components of a generator*
- ☑ *Explain what is meant by real-time generation*
- ☑ *Discuss the two different ways to connect three generator windings symmetrically*
- ☑ *Discuss the different types of generation plants (i.e., steam, nuclear, wind, etc.)*
- ☑ *Describe the different power plant prime-mover types*

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- ☑ *Discuss the conversion of mechanical energy to electrical energy*
- ☑ *Discuss how the various energy resources are converted into electrical energy*
- ☑ *Describe the environmental considerations for the different power plant types*

ac VOLTAGE GENERATION

There are basically two physical laws that describe how electric power systems work. (Gravity is an example of a physical law.) One law has to do with generating a voltage from a changing magnetic field and the other has to do with a current flowing through a wire creating a magnetic field. Both physical laws are used throughout the entire electric power system from generation through transmission, distribution, and consumption. The combination of these two laws makes our electric power systems work. Understanding these two physical laws will enable the reader to fully understand and appreciate how electric power systems work.

Physical Law #1

ac voltage is generated in electric power systems by a very fundamental physical law called *Faraday's Law.* Faraday's Law represents the phenomena behind how electric motors turn and how electric generators produce electricity. Faraday's Law is the foundation for electric power systems.

Faraday's Law states, "A voltage is produced on any conductor in a changing magnetic field." It may be difficult to grasp the full meaning of that statement at first. It is, however, easier to understand the meaning and significance of this statement through graphs, pictures, and animations.

In essence, this statement is saying that if one takes a coil of wire and puts it next to a moving or rotating magnet, a measurable voltage will be produced in that coil. Generators, for example, use a spinning magnet (i.e., rotor) next to a coil of wire to produce voltage. This voltage is then distributed throughout the electric power system.

We will now study how a generator works. Keep in mind that virtually all generators in service today have coils of wire mounted on stationary housings, called *stators,* where voltage is produced due to the *magnetic field* provided on the spinning *rotor.* The rotor is sometimes called the *field* because it is responsible for the magnetic field portion of the generator. The rotor's strong magnetic field passes the stator windings (coils), thus producing or generating an alternating voltage (ac) that is based on Faraday's Law. This principle will be shown and described in the following sections.

The amplitude of the generator's output voltage can be changed by changing the strength of rotor's magnetic field. Thus, the generator's output voltage can be lowered by reducing the rotor's magnetic field strength. The means by which the magnetic field in the rotor is actually changed will be discussed later in this book when Physical Law #2 is discussed.

Single-Phase ac Voltage Generation

Placing a coil of wire (i.e., conductor) in the presence of a moving magnetic field produces a voltage, as discovered by Faraday. This principle is graphically presented in Figure 2-1. While reviewing the drawing, note that changing the rotor's speed changes the frequency of the sine wave. Also recognize the fact that increasing the number of turns (loops) of conductor or wire in the coil increases the resulting output voltage.

Three-Phase ac Voltage Generation

When three coils are placed in the presence of a changing magnetic field, three voltages are produced. When the coils are spaced 120 degrees apart in a 360 degree circle, *three-phase* ac voltage is produced. As shown in Figure 2-2, three-phase generation can be viewed as three separate single-phase generators, each of which are displaced by 120 degrees.

THE THREE-PHASE ac GENERATOR

Large and small generators that are connected to the power system have three basic components: stator, rotor, and exciter. This section discusses these three basic components.

The Stator

A three-phase ac generator has three single-phase windings. These three windings are mounted on the stationary part of the generator, called the *stator.* The windings are physically spaced so that the changing magnetic field present on each winding is 120° out of phase with the other wind-

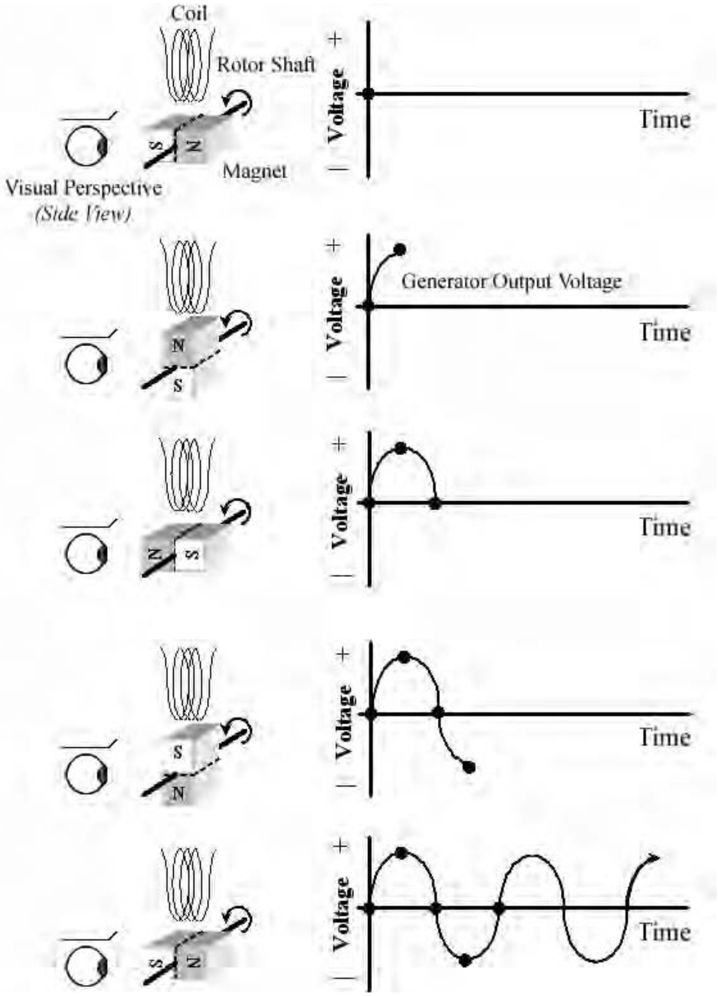


Figure 2-1. Magnetic sine wave.

ings. A simplified drawing of a three-phase generator is shown in Figure 2-3.

The Rotor

The *rotor* is the center component that when turned moves the magnetic field. A rotor could have a permanent magnet or an *electromagnet* and still function as a generator. Large power plant generators use electromagnets so

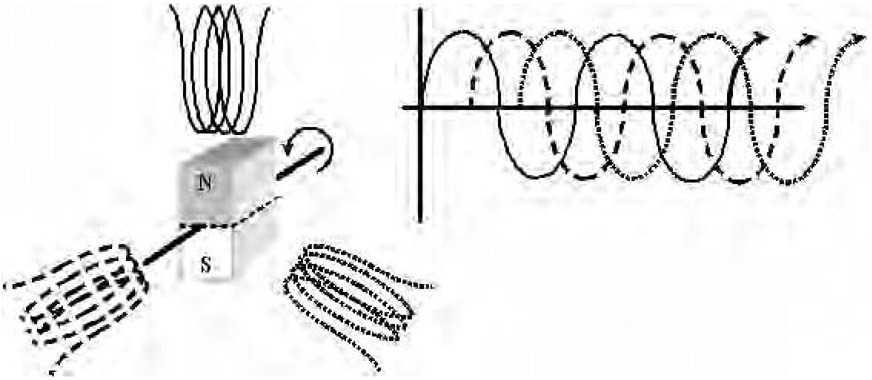


Figure 2-2. Three-phase voltage production.

that the magnetic field can be varied. Varying the magnetic field strength of the rotor enables generation control systems to adjust the output voltage according to load demand and system losses. A drawing of an electromagnet is shown in Figure 2-4.

The operation of electromagnets is described by Physical Law #2.

Ampere's and Lenz's Law (Physical Law #2)

The second basic physical law that explains how electric power systems work is the fact that current flowing in a wire produces a magnetic field. Ampere's and Lenz's law states that "*a current flowing in a wire produces a magnetic field around the wire.*" This law describes the relationship be-

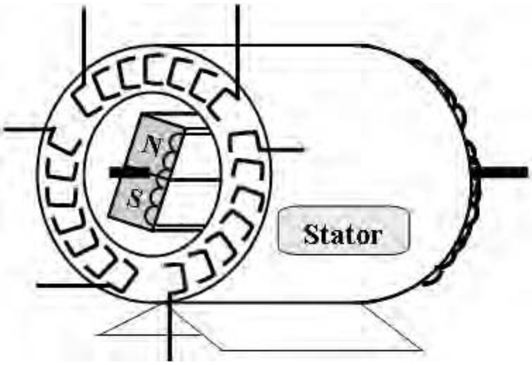


Figure 2-3. Three-phase generator—stator.

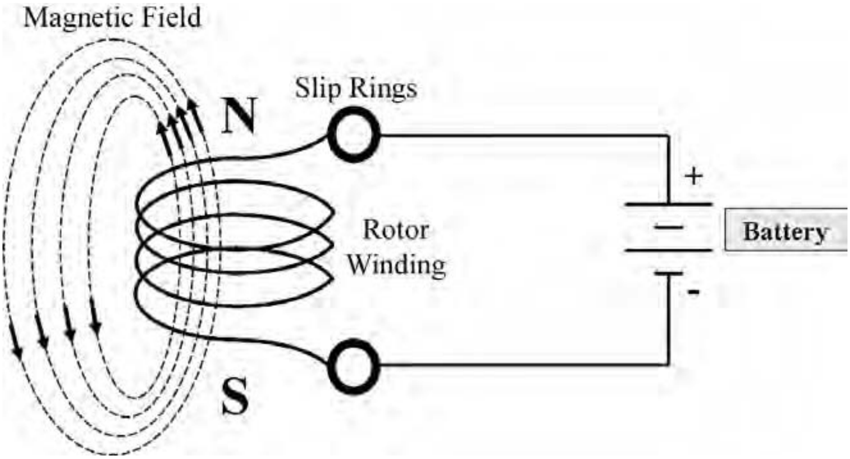


Figure 2-4. Electromagnet and slip rings.

tween the production of magnetic fields and electric current flowing in a wire. In essence, when a current flows through a wire, a magnetic field surrounds the wire.

Electromagnets

Applying a voltage (e.g., battery) to a coil of wire produces a magnetic field. The coil's magnetic field will have a north and a south pole as shown in Figure 2-4. Increasing the voltage or the number of turns in the winding increases the magnetic field. Conversely, decreasing the voltage or number of turns in the winding decreases the magnetic field. *Slip rings* are electrical contacts that are used to connect the stationary battery to the rotating rotor, as shown in Figure 2-4 and Figure 2-5.

The Exciter

The voltage source for the rotor, which eventually creates the rotor's magnetic field, is called the *exciter,* and the coil on the rotor is called the *field.* Figure 2-5 shows the three main components of a three-phase ac generator: the stator, rotor, and exciter.

Most generators use *slip rings* to complete the circuit between the stationary exciter voltage source and the rotating coil on the rotor where the electromagnet produces the north and south poles.

Note: Adding load to a generator's stator windings reduces rotor speed because of the repelling forces between the stator's magnetic field, and the

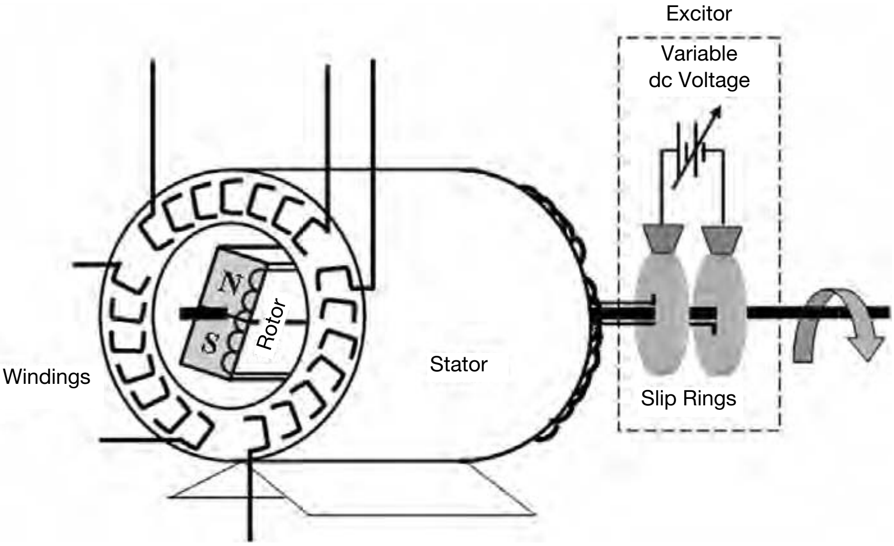


Figure 2-5. Three-phase voltage generator components.

rotor's magnetic field since both windings have electrical current flowing through them. Conversely, removing load from a generator increases rotor speed. Therefore, the mechanical energy of the prime mover that is responsible for spinning the rotor must be adjusted to maintain rotor speed or frequency under varying load conditions.

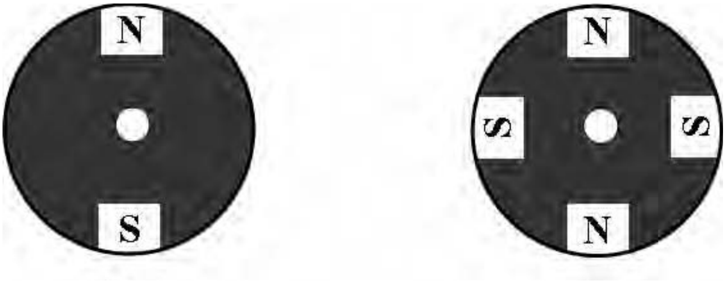
Rotor Poles

Increasing the number of magnetic poles on the rotor enables rotor speeds to be slower and still maintain the same electrical output frequency. Generators that require slower rotor speeds to operate properly use multiple-pole rotors. For example, hydropower plants use generators with multiple-pole rotors because the prime mover (i.e., water) is very dense and harder to control than light-weight steam.

The relationship between the number of poles on the rotor and the speed of the shaft is determined using the following mathematical formula:

$$\text{Revolutions per minute} = \frac{7200}{\text{Number of poles}}$$

Figure 2-6 shows the concept of multiple poles in a generator rotor. Since these poles are derived from electromagnets, having multiple windings on a rotor can provide multiple poles.



Two-pole Four-pole

Figure 2-6. Rotor poles.

Example 1: A two pole rotor would turn at 3600 rpm for 60 hertz.

Example 2: Some of the generators at Hoover Dam near Las Vegas, Nevada, use 40-pole rotors. Therefore, the rotor speed is 180 rpm or three revolutions per second, yet the electrical frequency is 60 cycles/second (or 60 Hz). One can actually see the shaft turning at this relatively slow rotational speed.

REAL-TIME GENERATION

Power plants produce electrical energy on a real-time basis. Electric power systems do not store energy such as most gas or water systems do. For example, when a toaster is switched on and drawing electrical energy from the system, the associated generating plants immediately see this as new load and slightly slow down. As more and more load (i.e., toasters, lights, motors, etc.) are switched on, generation output and prime mover rotational shaft energy must be increased to balance the load demand on the system. Unlike water utility systems that store water in tanks located up high on hills or tall structures to serve real-time demand, electric power systems must control generation to balance load on demand. Water is pumped into the tank when the water level in the tank is low, allowing the pumps to turn off during low and high demand periods. Electrical generation always produces electricity on an "as needed" basis. Note: some generation units can be taken off-line during light load conditions, but there must always be enough generation online to maintain frequency during light and heavy load conditions.

There are electrical energy storage systems such as batteries, but electricity found in interconnected ac power systems is in a real-time energy supply system, not an energy storage system.

GENERATOR CONNECTIONS

There are two ways to connect three windings that have a total of six leads (the ends of the winding wires) symmetrically. The two symmetrical connection configurations of a three-phase generator (or motor) are called *delta* and *wye.* Figure 2-7 shows these two connection types. Generators usually have their stator windings connected internally in either a delta or wye configuration.

The generator *nameplate* specifies which winding configuration is used on the stator.

Delta

Delta configurations have all three windings connected in series, as shown in Figure 2-7. The phase leads are connected to the three common points where windings are joined.

Wye

The wye configuration connects one lead from each winding to form a common point called the *neutral.* The other three phase leads are brought out of the generator separately for external system connections. The neutral is often grounded to the station ground grid for voltage reference and stability. Grounding the neutral is discussed later.

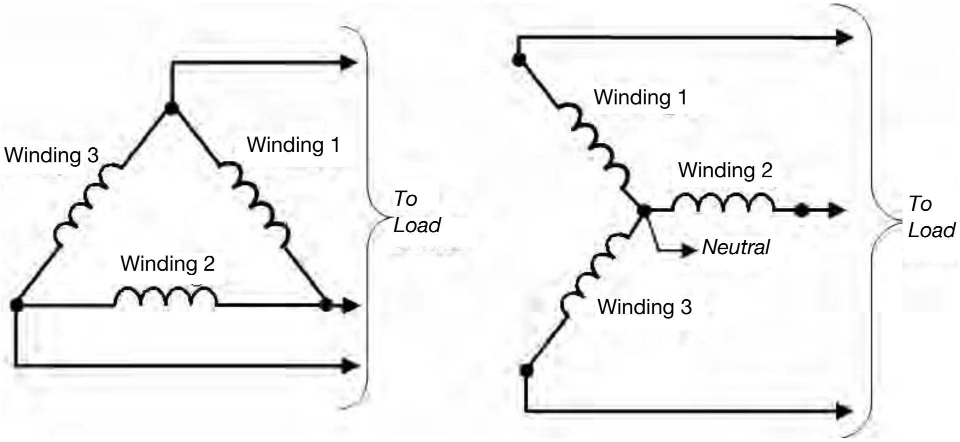


Figure 2-7. Delta and wye configurations.

WYE AND DELTA STATOR CONNECTIONS

Electric power plant generators use either wye or delta connections. The phase leads from the generator are connected to the plant's step-up transformer (not shown yet) where the generator output voltage is increased significantly to transmission voltage levels for the efficient transportation of electrical energy. Step-up transformers are discussed later in this book. Figures 2-8 and 2-9 show both the wye and the delta generator connections.

POWER PLANTS AND PRIME MOVERS

Power generation plants produce the electrical energy that is ultimately delivered to consumers through transmission lines, substations, and distribution lines. Generation plants or power plants consist of three-phase generator(s), the *prime mover,* energy source, control room, and substation. The generator portion has been discussed already. The prime movers and their associated energy sources are the focus of this section.

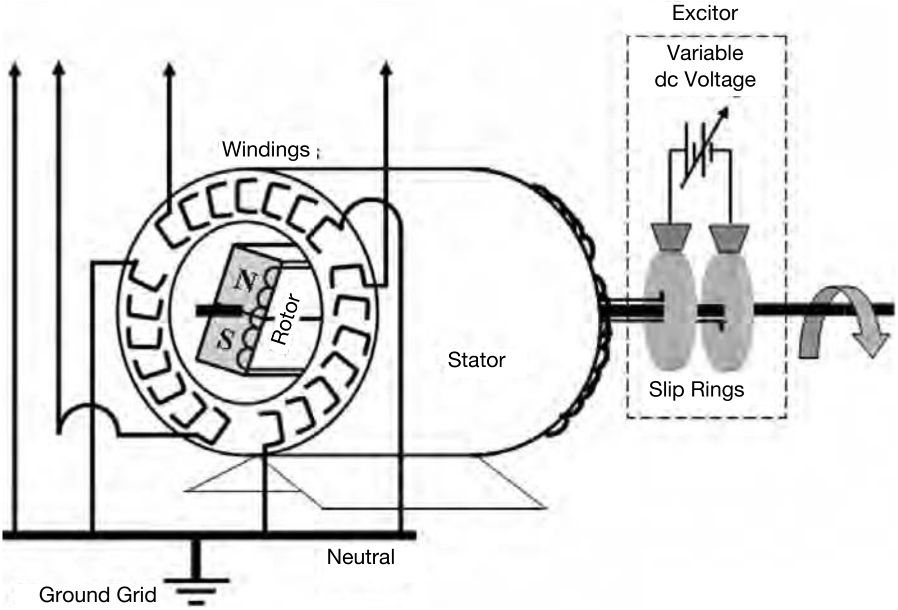


Figure 2-8. Wye connected generator.

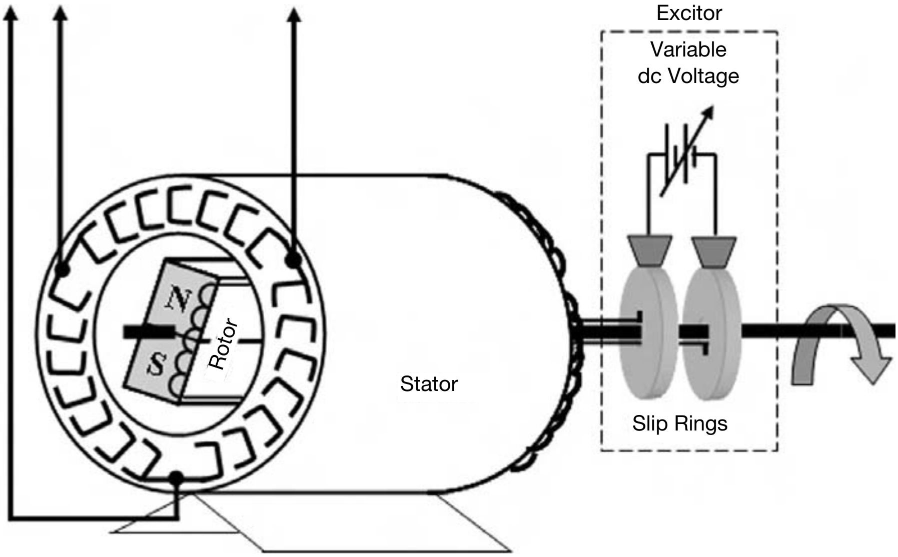


Figure 2-9. Delta-connected generator.

The mechanical means of turning the generator's rotor is called the prime mover. The prime mover's energy sources include the conversion process of raw fuel, such as coal, to the end product—steam—that will turn the turbine. The bulk of electrical energy produced in today's interconnected power systems is normally produced through a conversion process from coal, oil, natural gas, nuclear, and hydro. To a lesser degree, electrical power is produced from wind, solar, geothermal, and biomass energy resources.

The more common types of energy resources used to generate electricity and their associated prime movers that are discussed in this chapter include:

Steam turbines
- Fossil fuels (coal, gas, oil)
- Nuclear
- Geothermal
- Solar-heated steam

Hydro turbines
- Dams and rivers
- Pump storage

Combustion turbines
- Diesel
- Natural gas
- Combined cycle

Wind turbines
Solar direct (photovoltaic)

Steam Turbine Power Plants

High-pressure and high-temperature steam is created in a boiler, furnace, or heat exchanger and moved through a *steam turbine generator* (STG) that converts the steam's energy into rotational energy that turns the generator shaft. The steam turbine's rotating shaft is directly coupled to the generator rotor. The STG shaft speed is tightly controlled for it is directly related to the frequency of the electrical power being produced.

High-temperature, high-pressure steam is used to turn steam turbines that ultimately turn the generator rotors. Temperatures on the order of 1,000°F and pressures on the order of 2,000 pounds per square inch (psi) are commonly used in large steam power plants. Steam at this pressure and temperature is called *superheated steam,* sometimes referred to as *dry steam.*

The steam's pressure and temperature drop significantly after it is applied across the *first stage* turbine blades. Turbine blades make up the fan-shaped rotor to which steam is directed, thus turning the shaft. The superheated steam is reduced in pressure and temperature after it passes through the turbine. The reduced steam can be routed through a *second stage* set of turbine blades where additional steam energy is transferred to the turbine shaft. This second stage equipment is significantly larger than the first stage to allow for additional expansion and energy transformation. In some power plants, the steam following the first stage is redirected back to the boiler where it is reheated and then sent back to the second turbine stage for a more efficient energy transformation.

Once the energy of the steam has been transferred to the turbine shaft, the low-temperature and low-pressure steam has basically exhausted its energy and must be fully *condensed* back to water before it can be recycled. The condensing process of steam back to water is accomplished by a *condenser* and *cooling tower(s).* Once the used steam is condensed back to warm water, the *boiler feed pump* (BFP) pumps the warm water back to the boiler where it is recycled. This is a closed-loop processes. Some water has to be added in the process due to small leaks and evaporation.

The condenser takes cold water from nearby lakes, ponds, rivers, oceans, deep wells, cooling towers, and other water sources and pumps it through pipes in the condenser. The used steam passes through the relatively cold water pipes and causes dripping to occur. The droplets are collected at the base of the condenser (the well) and pumped back to the boiler by the BFP.

The overall steam generation plant efficiency in converting fuel heat energy into mechanical rotation energy and then into electrical energy ranges from 25 to 35%. Although it is a relatively low-efficiency system, steam turbine generation is very reliable and is commonly used as base load generation units in large electric power systems. Most of the inefficiency in steam turbine generation plants comes from the loss of heat into the atmosphere in the boiler process.

Fossil Fuel Power Plants

Steam turbine power plants can use coal, oil, natural gas, or just about any combustible material as the fuel resource. However, each fuel type requires a unique set of accessory equipment to inject fuel into the boiler, control the burning process, vent and exhaust gases, capture unwanted byproducts, and so on.

Some fossil fuel power plants can switch fuels. For example, it is common for an oil plant to convert to natural gas when gas is less expensive than oil. Most of the time, it is not practical to convert a coal burning power plant to oil or gas unless it has been designed for conversion. The processes are usually different enough so that switching will not be cost effective.

Coal is burned in two different ways in coal fired plants. First, in traditional coal fired plants, the coal is placed on metal conveyor belts inside the boiler chamber. The coal is burned while on the belt as the belt slowly traverses the bottom of the boiler. Ash falls through the chain conveyor belt and is collected below where it is sometimes sold as a useful by-product for other industries.

In pulverized coal power plants, the coal is crushed into a fine powder and injected into the furnace where it is burned similar to a gas. Pulverized coal is mixed with air and ignited in the furnace. Combustion by-products include solid residue (ash) that is collected at the bottom of the furnace and gases that include fine ash, NO_2, CO, and SO_2, which are emitted into the atmosphere through the stack. Depending on local environmental regulations, scrubber and baghouse equipment may be required and installed to collect most of these by-products before they reach the atmosphere.

Scrubbers are used to collect the undesirable gases to improve the quality of the stack output emissions. Baghouses are commonly used to help collect fly ash.

Some of the drawbacks that could be encountered with coal fired steam generating power plants are:

- Environmental concerns from burning coal (i.e., acid rain)
- Transportation issues regarding rail systems for coal delivery
- Length of transmission lines to remote power plant locations

Figure 2-10 shows the layout of a typical steam power plant. Notice the steam line used to transfer superheated steam from the boiler to the turbine and then through the condenser where it is returned to a water state and recycled. Notice the steam turbine connected to the generator. The turbine speed is controlled by the amount of steam applied in order to control frequency. When load picks up on the electrical system, the turbine shaft speed slows down and more steam is then placed on the turbine blades to maintain frequency. Notice how coal is delivered to the boiler and burned. Exhaust is vented through the stack. Scrubbers and bags remove the by-products before they enter the atmosphere. Water from a nearby reservoir is pumped to the condenser where it is used to convert steam back into water and recycled.

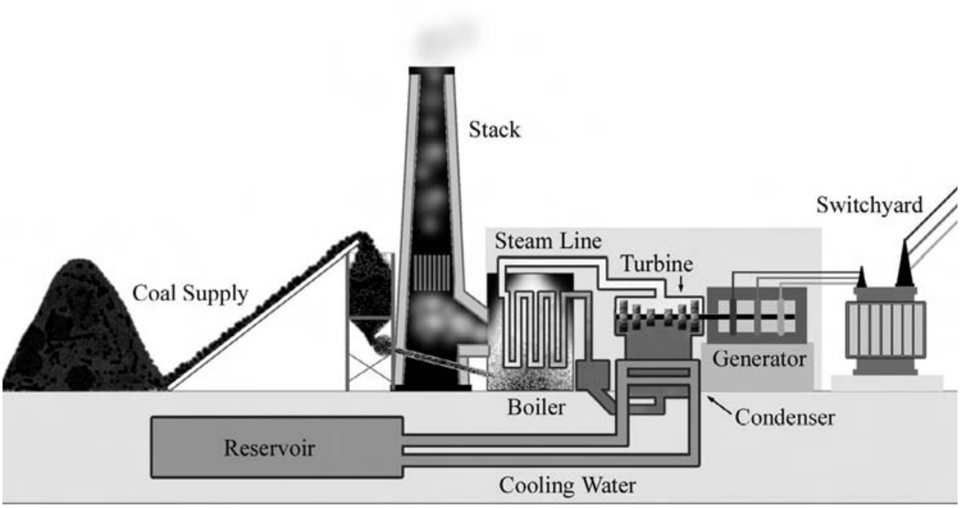


Figure 2-10. Steam power plant.

Figure 2-11 shows a coal fired steam turbine power plant. The ramp in front lifts the coal to the pulverizer where it is crushed before being injected into the boiler and burned. Plant operators must be careful to not allow the spontaneous combustion of coal while it is stored in the yard.

Nuclear Power Plants

In nuclear power plants such as the one shown in Figure 2-12, a controlled nuclear reaction is used to make heat to produce steam needed to drive a steam turbine generator.

All nuclear plants in the United States must conform to the Nuclear Regulatory Commission's rules and regulations. Extensive documentation is required to establish that the proposed design can be operated safely without undue risk to the public. Once the Nuclear Regulatory Commission issues a license, the license holder must maintain the license and the reactor in accordance with strict rules, usually called Tech Specs. Compliance to these rules and regulations in conjunction with site inspections ensures that a safe nuclear power plant is in operation.

Figure 2-11. Coal power plant. *Source:* Fotosearch.

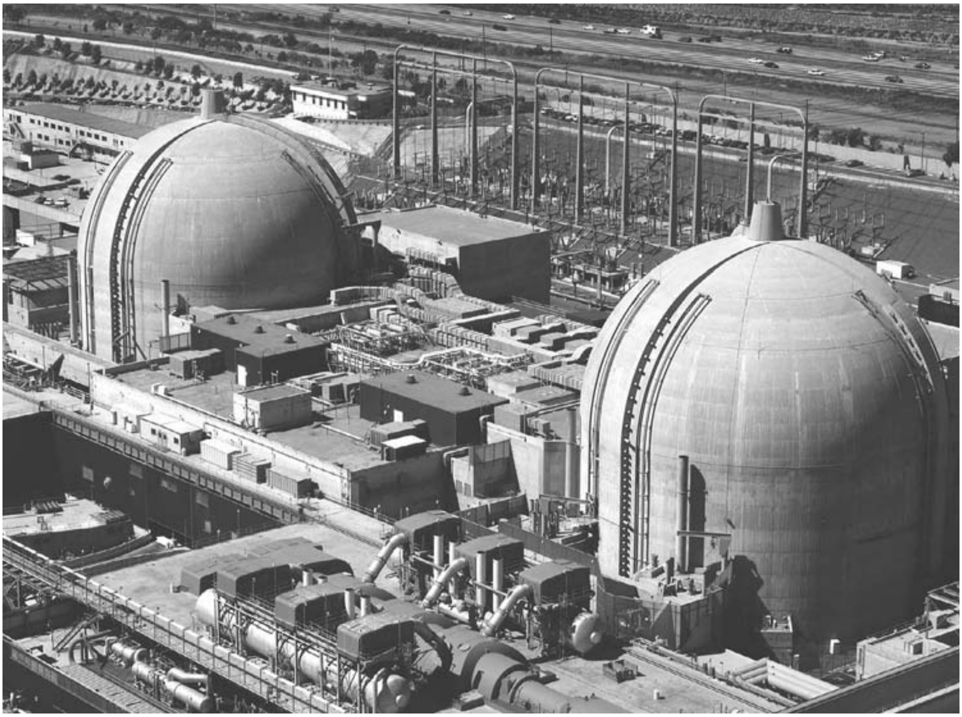


Figure 2-12. Nuclear power plant. *Source:* Fotosearch.

Nuclear Energy

Atoms are the building blocks from which all matter is formed. Everything is made up of atoms. Atoms are made up of a nucleus (with protons and neutrons) and orbiting electrons. The number of atomic particles (i.e., sum of neutrons, protons, and electrons) determines the atomic weight of the atom and type of element in the periodic table. Nuclear energy is contained within the center of atoms (i.e., nucleus) where the atom's protons and neutrons exist. Nature holds the particles within the atom's nucleus together by a very strong force. If a nucleus of a large element (such as uranium 235) is split apart into multiple nuclei of different element compositions, generous amounts of energy are released in the process. The heat emitted during this process (i.e., *nuclear reaction*) is used to produce steam energy to drive a turbine generator. This is the foundation of a nuclear power plant.

There are basically two methods used to produce nuclear energy in order to produce heat to make steam. The first process is called *fission.* Fission is the splitting of large nuclei atoms such as uranium inside a nuclear reactor to release energy in the form of heat to be used to produce steam to drive steam turbine electrical power generators. The second process is called *fusion.* Fusion is the combining of small nuclei atoms into larger ones, resulting in an accompanying release of energy. However, fusion reactors are not yet used to produce electrical power because it is difficult to overcome the natural mutual repulsion force of the positively charged protons in the nuclei of the atoms being combined.

In the fission process, certain heavy elements, such as uranium, are split when a neutron strikes them. When they split, they release energy in the form of *kinetic energy* (heat) and *radiation*. Radiation is subatomic particles or high-energy light waves emitted by unstable nuclei. The process not only produces energy and radiation, it also provides additional neutrons that can be used to fission other uranium nuclei and, in essence, start a chain reaction. The controlled release of this nuclear energy using commercial-grade fuels is the basis of electric power generation. The uncontrolled release of this nuclear energy using more highly enriched fuels is the basis for atomic bombs.

The reactor is contained inside an obvious *containment shell.* It is made up of extremely heavy concrete and dense steel in order to minimize the possibility of a reactor breach due to an accidental. Nuclear power plants also have an emergency backup scheme of injecting *boron* into the reactor coolant. Boron is an element that absorbs neutrons very readily. By absorbing neutrons, the neutrons are not available to continue the nuclear reaction, and the reactor shuts down.

The most widely used design for nuclear reactors consists of a heavy steel pressure vessel surrounding the *reactor core.* The reactor core contains the uranium fuel. The fuel is formed into cylindrical ceramic pellets about one-half inch in diameter, which are sealed in long metal tubes called *fuel tubes.* The tubes are arranged in groups to make a *fuel assembly.* A group of fuel assemblies forms the *reactor core.*

Controlling the heat production in nuclear reactors is accomplished by using materials that absorb neutrons. These control materials or elements are placed among the fuel assemblies. When the control elements, or *control rods* as they are often called, are pulled out of the core, more neutrons are available and the chain reaction increases, producing more heat. When the control rods are inserted into the core, more neutrons are absorbed, and the chain reaction slows down or stops, producing no heat. The *control rod drive system* controls the actual output power of the electric power plant.

Most commercial nuclear reactors use ordinary water to remove the heat created by the fission process. These are called *light water reactors.* The water also serves to slow down or *moderate* the neutrons in the fission process. In this type of reactor, control mechanisms are used such that the chain reaction will not occur without the water to serve as a moderator. In the United States, there are two different types of light-water reactor designs used, the *pressurized water reactor* (PWR) and the *boiling water reactor* (BWR).

PRESSURIZED WATER REACTOR (PWR). The basic design of a pressurized water reactor is shown in Figure 2-13. The reactor and the primary steam generator are housed inside a containment structure. The structure is designed to withstand accidental events such as small airplane crashes. The PWR steam generator separates the radioactive water that exists inside the reactor from the steam that is going to the turbine outside the shell.

In a PWR, the heat is removed from the reactor by water flowing in a closed, pressurized loop. The heat is transferred to a second water loop through a *heat exchanger* (or *steam generator*). The second loop is kept at a lower pressure, allowing the water to boil and create steam, which is used to turn the turbine generator and produce electricity. Afterward, the steam is condensed back into water and returned to the heat exchanger where it is recycled into useable steam.

The normal control of the reactor power output is by means of the control rod system. These control rods are normally inserted and controlled from the top of the reactor. Because the control rods are inserted and controlled from the top of the reactor, the design also includes special springs and re-

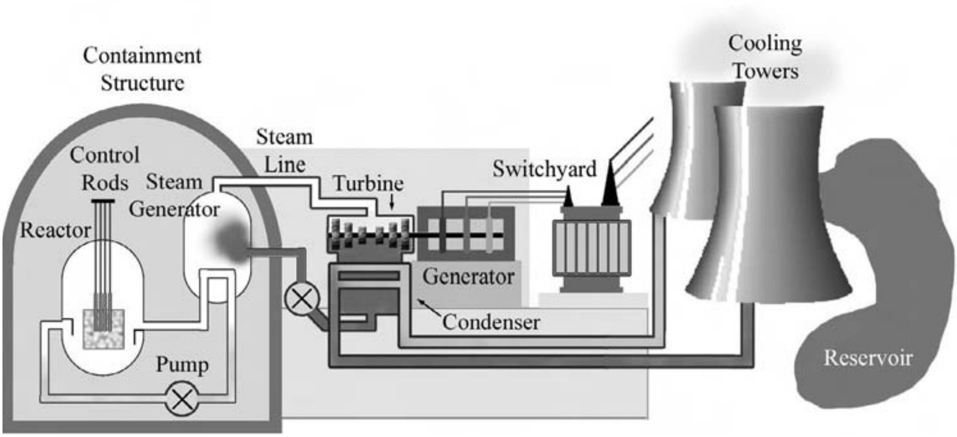


Figure 2-13. Pressurized water reactor.

lease mechanisms so that if all power is lost, the control rod will be dropped into the reactor core by gravity to shut down the reactor.

Advantages and Disadvantages of PWR. As with any design, there are advantages and disadvantages of pressurized water reactors. A major design advantage is the fact that fuel leaks, such as ruptured fuel rods, are isolated in the core and primary loop. That is, radioactive material contained inside the fuel is not allowed to go outside of the containment shell. The pressurized water reactor can be operated at higher temperature/pressure combinations, and this allows an increase in the efficiency of the turbine generator system.

Another advantage is that it is believed that a pressurized water reactor is more stable than other designs. This is because boiling is not allowed to take place inside the reactor vessel and, therefore, the density of the water in the reactor core is more constant. By reducing the variability of the water density, controls are somewhat simplified.

The biggest disadvantage appears to be the fact that the reactor design is more complicated. It is necessary to design for extremely high pressures and temperatures in order to ensure that boiling does not take place inside the reactor core. The use of high-pressure vessels makes the overall reactor somewhat more costly to build. Finally, under certain circumstances, the pressurized water reactor can produce power at a faster rate than the cooling water can remove heat. If this event takes place, there is a high probability of fuel rod damage.

BOILING WATER REACTOR (BWR). Figure 2-14 shows a boiling water reactor (BWR). Again, there is a reactor building or containment shell where the nuclear reactor and some of its complement equipment are located. The reactor housing of the BWR tends to be larger than the PWR and looks almost like an inverted lightbulb.

In a BWR, water boils inside the reactor itself, and the steam goes directly to the turbine generator to produce electricity. Similar to other steam power plants, the steam is condensed and reused. Note that the turbine building is closely coupled to the reactor building, and special constraints exist in entering the turbine building because the water can pick up radioactivity.

Note the *torus* at the bottom of the reactor. If there should be a reactor rupture, the water inside the reactor will flash into steam and create a very high pressure surge in the reactor building. The reactor torus is filled with cold water, which will instantly condense the steam. The torus system en-

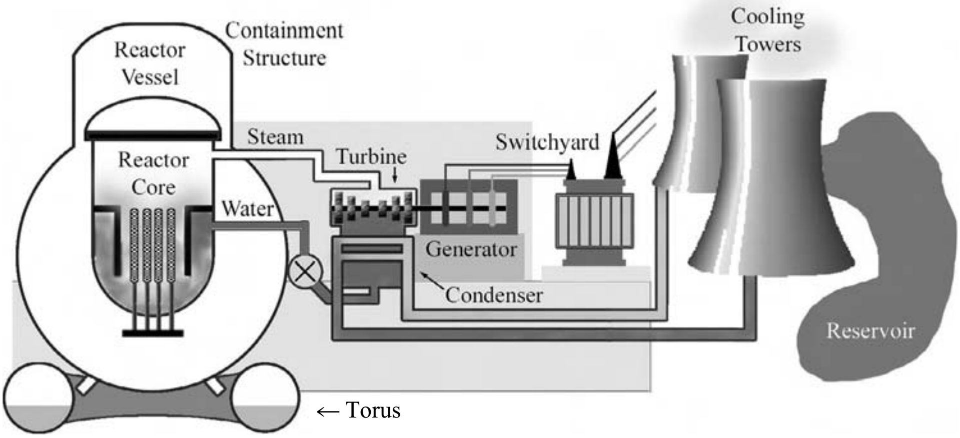


Figure 2-14. Boiling water reactor.

sures that the pressure inside the containment dome never exceeds an acceptable level.

As with the pressurized water reactor, the reactor housing contains the fuel core and water supply flow paths. The reactor recirculation system consists of the pumps and pipes that circulate the water through the reactor. The water circulating through the reactor actually goes into the turbine itself and then condensed water goes back into the reactor. The steam separator in the reactor shell separates the water from the steam and allows the steam to pass to the steam generator. The separated water is returned to the reactor for recirculation.

The boiling water reactor utilizes one cooling loop. Both water and steam exist in the reactor core (i.e., a definition of boiling). Reactor power is controlled by positioning the control rods from start-up to approximately 70% of rated power. From 70% to 100% of rated power, the reactor power is controlled by changing the flow of water through the core. As more water is pumped through the core and more steam generated, more power is produced. In the boiling water reactor, control rods are normally inserted from the bottom. The top of the reactor vessel is used to separate water and steam.

Advantages and Disadvantages of BWR. A major advantage of the BWR is that the overall thermal efficiency is greater than that of a pressurized water reactor because there is no separate steam generator or heat exchanger. Controlling the reactor is a little easier than in a PWR because it is accomplished by controlling the flow of water through the core. Increasing the water flow increases the power generated. Because of the nature of the design, the reactor vessel is subjected to less radiation, and this is considered to be an advantage because some steels become brittle with exposure to excessive radiation.

The greatest disadvantage of the BWR is that the design is much more complex. It requires a larger pressure vessel than the PWR because of the amount of steam that can be released during an accident. This larger pressure vessel also increases the cost of the BWR. Finally, the design does allow a small amount of radioactive contamination to get into the turbine system. This modest radioactivity requires that anybody working on the turbine must wear appropriate protective clothing and use the proper equipment.

Other Related Topics (Optional Supplementary Reading)

The overall function or design of the nonnuclear portion of a nuclear power plant is of the same order of complexity as a fossil fueled power plant. The biggest difference is the degree of documentation that must be maintained and submitted to the regulatory authorities for proof that the design and operation are safe. Roughly speaking, there are about 80 separate systems in a nuclear power plant. The systems that are most critical are those that control the power and/or limit the power output of the plant.

ENVIRONMENTAL. One of the greatest advantages of a nuclear plant, especially with today's concerns about global warming and generation of carbon dioxide due to burning, is the fact that a nuclear plant essentially adds zero emissions to the atmosphere. There is no smoke stack!

SCRAM. A reactor *SCRAM* is an emergency shutdown situation. Basically, all control rods are driven into the reactor core as rapidly as possible to shut down the reactor to stop heat production. A SCRAM occurs when some protective device or sensor signals the control rod drive system. Some typical protective signals that might initiate or trigger a SCRAM include a sudden change in neutron production, a sudden change in temperatures inside the reactor shell, sudden change in pressures, or other potential system malfunctions.

By inserting the control rods into the reactor core, the reactor power is slowed down and/or stopped because the control rod materials absorb neutrons. If the neutrons are absorbed, they cannot cause fission in additional uranium atoms.

Anytime there is a reactor SCRAM, the cause must be fully identified and appropriate remedial actions taken before the reactor can be restarted. Needless to say, a reactor SCRAM usually results in a great deal of paperwork to establish the fact that the reactor can be safely restarted.

There are various theories as to where the term SCRAM came from. One theory says that around the World War II era the original nuclear reactors were controlled manually. As a safety measure, the reactor was designed so that control rods would drop by gravity into the reactor core and absorb the neutrons. The control rods were held up by a rope. In case of emergency, the rope was to be cut to allow the rods to drop. The person responsible for cutting the rope in case of any emergency was called the SCRAM. According to the Nuclear Regulatory Commission, SCRAM stands for "*safety control rod axe man.*" Now, SCRAM stands for any emergency shutdown of the reactor for any reason.

EQUIPMENT VIBRATION. Equipment vibration is probably the biggest single problem in nuclear power plants. Every individual component is monitored by a central computer system for vibration indications. If excessive vibration is detected, the system involved must be quickly shut down. (Note this is also true of regular steam plants. If excessive vibration is detected in the turbine or generator, they will be shut down.)

Nuclear power plants seem to be particularly susceptible to vibration problems, especially on the protective relay panels. Excessive vibration can cause inadvertent relay operations, shutting down a system or the complete plant.

Microprocessor-based protection relay equipment is basically immune to vibration problems, but there is a perception that the solid-state circuits used in such relays may be damaged by radiation. Most nuclear power plants still use electromechanical relays as backup to the microprocessor solid-state relays.

Geothermal Power Plants

Geothermal power plants use hot water and/or steam located underground to produce electrical energy. The hot water and/or steam are brought to the surface where heat exchangers are used to produce clean steam in a secondary system for use with turbines. Clean steam causes no sediment growth inside pipes and other equipment, thereby minimizing maintenance. The clean steam is converted into electrical energy much the same way as in typical fossil fueled steam plants.

Although geothermal energy is considered to be a good renewable source of reliable power, some are concerned that over the long term, the availability of this geothermal resource for power plants may be reduced over time (i.e., it may dry up, become less availabile, or lose pressure). A typical geothermal power plant is shown in Figure 2-15.

Solar Reflective Power

Solar power plants are environmentally friendly as they produce no pollution. Large-scale solar reflective plants require a substantial amount of area as well as specific orientation with the sun to capture the maximum energy possible with high efficiency.

Solar energy is reflected off mirrors and concentrated on a centralized boiler system. The mirrors are parabolic-shaped and motorized to focus the sun's energy toward the receiver tubes in the collector area of the elevated boiler. The receiver tubes contain a heat transfer fluid used in the steam–boiler–turbine system. The collector area housing the receiver tubes absorbs the focused sun energy to gain 30 to 100 times normal solar energy. The fluid in these tubes can reach operating temperatures in excess of 400 degrees Celsius. The steam drives the turbine and then goes through a condenser for conversion back to liquid before being reheated in the boiler system. A typical solar power plant is shown in Figure 2-16.

Hydroelectric Power Plants

Hydroelectric power plants capture the energy of moving water. There are multiple ways hydro energy can be extracted. Falling water such as in a penstock, flume, or waterwheel can be used to drive a hydro turbine. Hydro energy can be extracted from water flowing at the lower section of dams, where the pressure forces water to flow. Hydroelectric power generation is efficient, cost-effective, and environmentally cooperative. Hydro power production is considered to be a renewable energy source because the water cycle is continuous and constantly recharged.

Water flows much slower through a hydro turbine than does steam through a high-pressure steam turbine. Therefore, several rotor magnetic poles are used to reduce the rotational speed requirement of the hydro turbine shaft.

Hydro units have a number of excellent advantages. The hydro unit can be started very quickly and brought up to full load in a matter of minutes. In most cases, little or no start-up power is required. A hydro plant is almost by

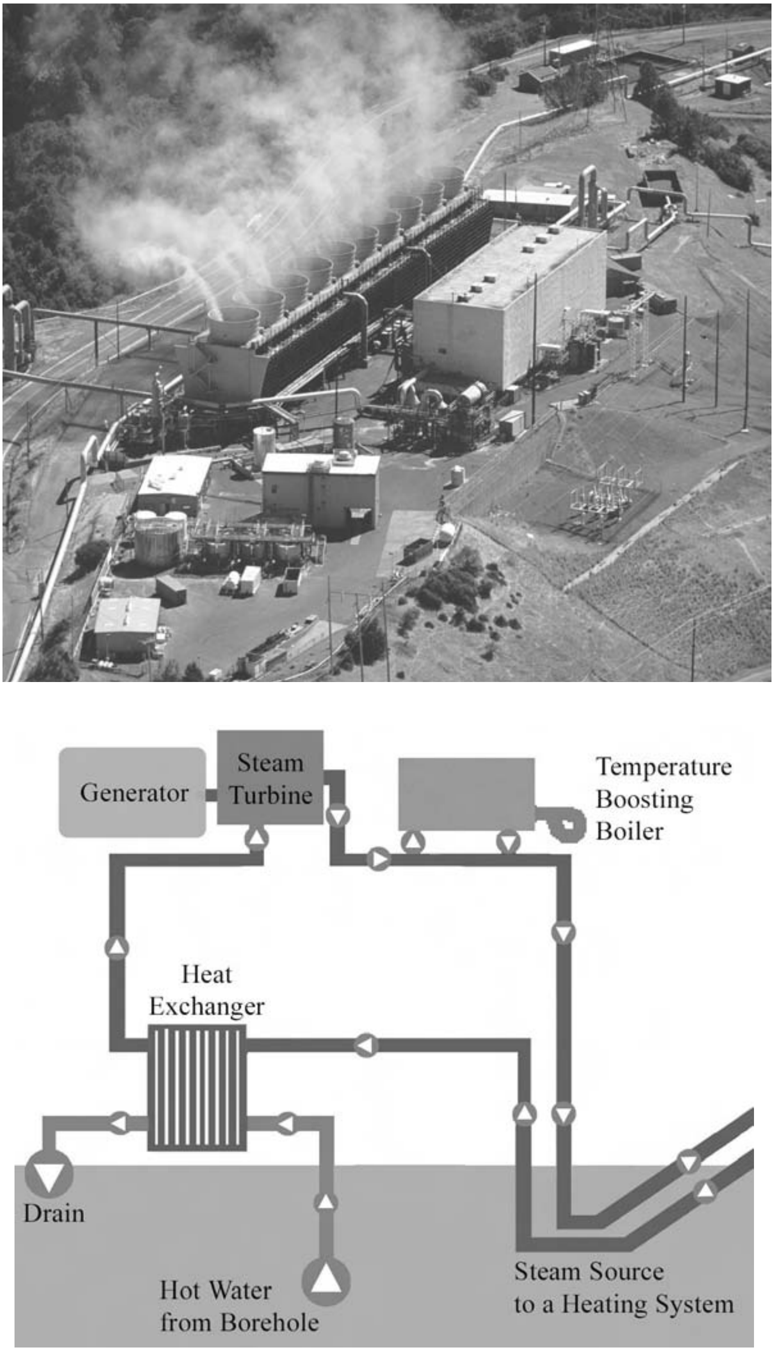


Figure 2-15. A geothermal power plant and schematic. *Source:* Fotosearch.

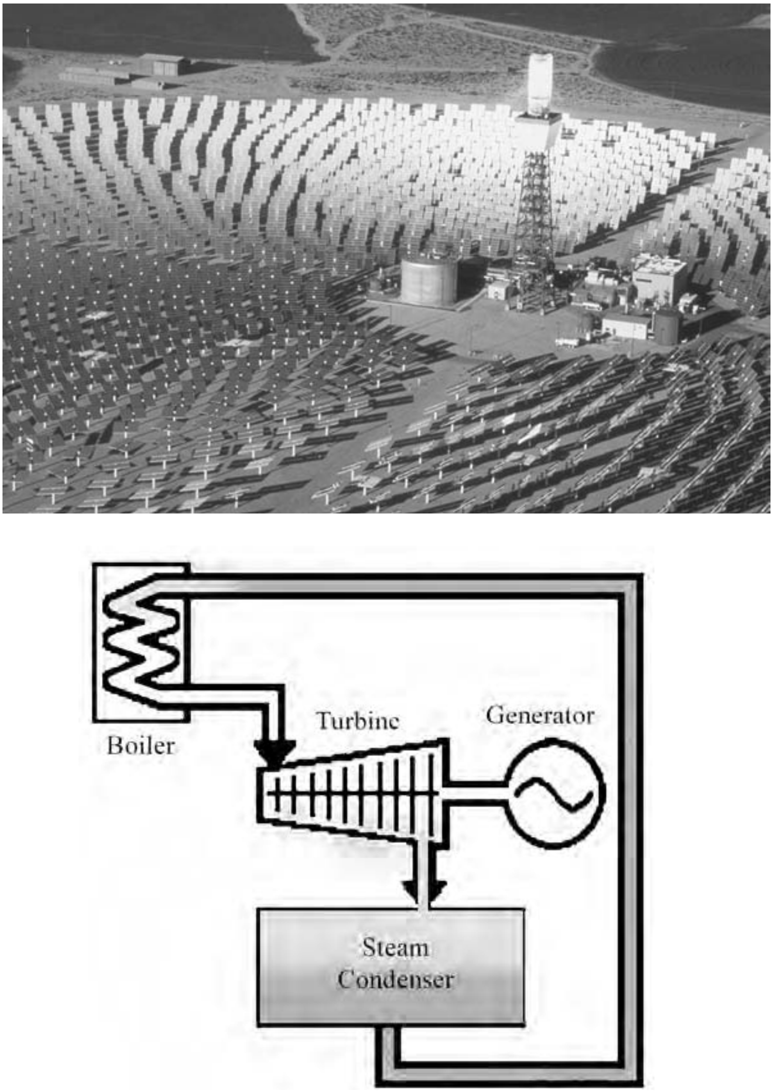


Figure 2-16. Reflective solar power plant and schematic. *Source:* Fotosearch.

definition a *black start* unit. Black start means that electrical power is not needed first in order to start a hydro power plant. Hydro plants have a relatively long life; 50–60 year life spans are common. Some hydroelectric power plants along the Truckee River in California have been in operation for over 100 years. Figure 2-17 shows a typical hydroelectric power plant.

The cross-section of a typical low-head hydro installation is shown in

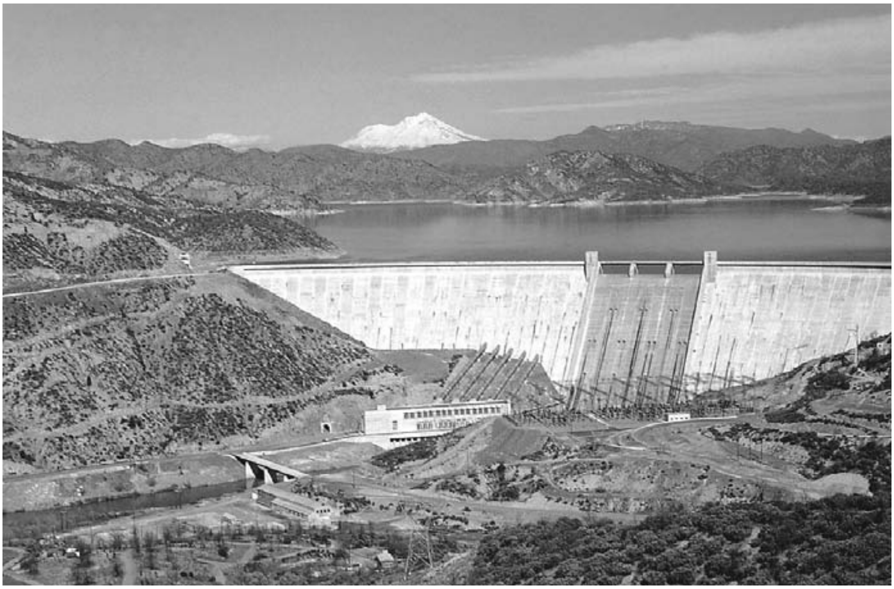


Figure 2-17. Hydroelectric power plant. *Source:* Photovault.

Figure 2-18. Basically, the water behind the dam is transported to the turbine by means of a *penstock.* The turbine causes the generator to rotate, producing electricity, which is then delivered to the load center over long-distance power lines. The water coming out of the turbine goes into the river.

Pumped Storage Hydro Power Plants

Pumped storage hydro power production is a means of actually saving electricity for future use. Power is generated from water falling from a higher lake to a lower lake during peak load periods. The operation is reversed during off-peak conditions by pumping the water from the lower lake back to the upper lake. A power company can obtain high-value power during peak-load generation periods by paying the lower cost to pump the water back during off-peak periods. Basically, the machine at the lower level is reversible; hence, it operates as a hydro-generator unit or a motor–pump unit.

One of the problems associated with pumped storage units is the process of getting the pumping motor started. Starting the pumping motor using the system's power line would usually put a low-voltage sag condition on the power system. The voltage sag or dip could actually cause power quality problems. In some cases, two turbines are used in a pumped storage installation. One of the turbines is used as a generator to start the other turbine that is used as a pump. Once the turbine is turning, the impact on the power system is much less, and the second turbine can then be started as a motor–pump.

Figure 2-19 shows a cross-sectional view of the Tennessee Valley Authority's pumped storage plant at Raccoon Mountain. The main access tunnel was originally used to bring all of the equipment into the powerhouse: the turbine, the pumps, and the auxiliary equipment. Note that the Tennessee Valley Authority installed a visitor center at the top of the mountain so that the installation could be viewed by the general public.

Combustion Turbine Generation Plants

Combustion turbine (CT) power plants burn fuel in a jet engine and use the exhaust gasses to spin a turbine generator. The air is compressed to a very high pressure. Fuel is then injected into the compressed air and ignited, producing high-pressure and high-temperature exhaust gasses. The exhaust is moved though turbine blades much the same way steam is moved through turbine blades in a steam power plant. The exhaust gas movement through the combustion turbine results in the rotation of the generator rotor, thus producing electricity. The exhaust from the CT remains at a very high temperature and pressure after leaving the turbine. Figure 2-20 shows a combustion turbine generator.

One of the advantages of combustion turbines is that they can actually be designed to be remotely controlled for unmanned sites. They offer fast start-up times and fast installation times. In some cases, the purchase of the combustion turbine generator system can be "turnkey," that is, the owner simply contracts for a complete installation and takes over when the plant is finished and ready to operate. In most cases, the combustion turbine generator package is a completely self-contained unit. In fact, some of the smaller-capacity systems are actually built on trailers so that they can be moved quickly to sites requiring emergency generation.

Combustion turbines can be extremely responsive to power system changes. They can go from no load to full load and vice versa in a matter of seconds or in a matter of minutes.

The disadvantages are limited fuel options (i.e., diesel fuel, jet fuel, or natural gas) and inefficient use of exhaust heat.

There are several environmental issues related to the use of combustion turbines. Without appropriate treatment, the exhaust emissions can be very high in undesirable gases. The high temperatures in the combustion cham-

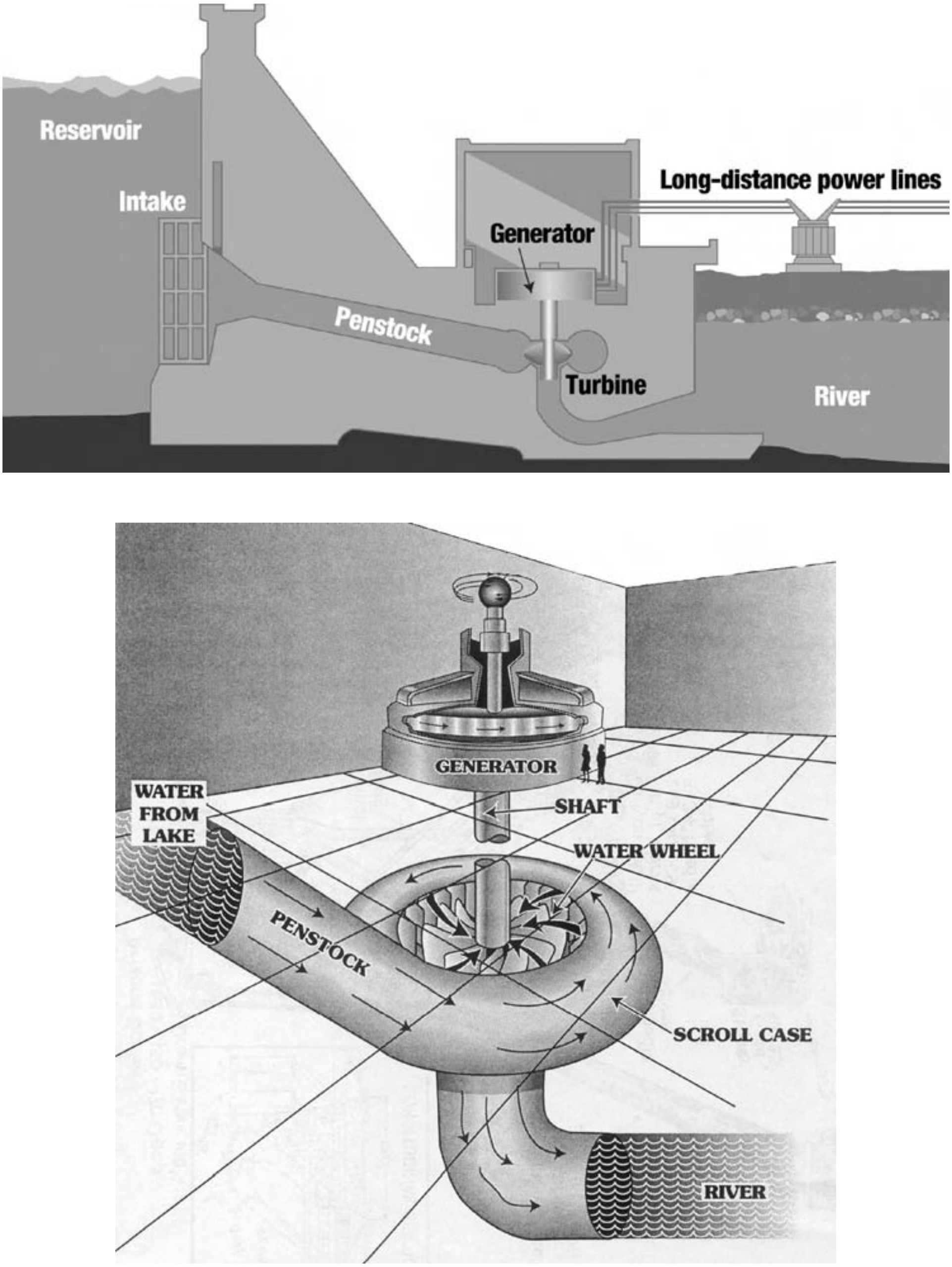


Figure 2-18. Hydroelectric power plant.

Figure 2-18. *Continued*

ber will increase the production of nitric oxide gases and their emissions. Depending on the fuel used, there can be particulate emissions problems. That is, particles or other materials tend to increase the opacity (i.e., smoke) of the gases. Sound levels around combustion turbine installations can be very high. Special sound reduction systems are available and used. (Note: combustion turbines are typically jet engines, very similar to those heard at airports.)

The heat rate or efficiency of a simple-cycle combustion turbine is not very good. The efficiencies are somewhere in the range of 20 to 40% maximum.

One effective way to overcome some of the cost is to incorporate a heat

Figure 2-19. Pumped storage power plant.

Figure 2-20. Combustion turbine power plant.

exchanger so the exhaust gases can be used to generate steam that will drive a secondary steam turbine. Many CTs are used as combined-cycle power plants.

Combined-Cycle Power Plants (Combustion and Steam)

The combined-cycle power plant consists of two means of generation: combustion turbine and steam turbine. The combustion turbine is similar to a jet engine whose high-temperature and high-pressure exhaust spins a turbine whose shaft is connected to a generator. The hot exhaust is then coupled through a *heat recovery steam generator* (HRSG) that is used to heat water, thus producing steam to drive a secondary steam turbine generator. The combustion turbine typically uses natural gas as the fuel to drive the turbine blades.

The advantage of a combined-cycle (CC) system is that in addition to the electrical energy produced by the fuel combustion engine, the exhaust from the engine also produces electrical energy. Another potential benefit of CC plants is that the end user can have steam made available to assist in other functions such as building heat and hot water and production processes that require steam (such as paper mills). Therefore, from one source of fuel (i.e., natural gas), many energy services are provided (electrical energy, steam, hot water, and building heat). Some CCs can reach efficiencies near 90%. Figure 2-21 shows a combined-cycle power plant.

Wind Turbine Generators

Wind generation has increased in popularity and the technology has improved tremendously over the last decade. In the year 2006, the total installed capacity of U.S. wind generation was about 11,000 MW. Wind turbine generators are continuing to be installed worldwide. The total installed capacity worldwide is about 74,000 MW. Figure 2-22 shows typical wind generators.

Wind turbine generators tend to have a high cost per kWh produced. There is also a concern about the availability of wind on a constant basis. Most power companies do not consider wind generators to be *base load* units. Base load implies that units are readily available and that they are part of a 24 hour generation production schedule. They are brought online when available.

Basically, the concept of wind power is that the wind energy is converted into electrical energy by means of modern windmills. One interesting characteristic of wind power is the fact that power produced is proportional to

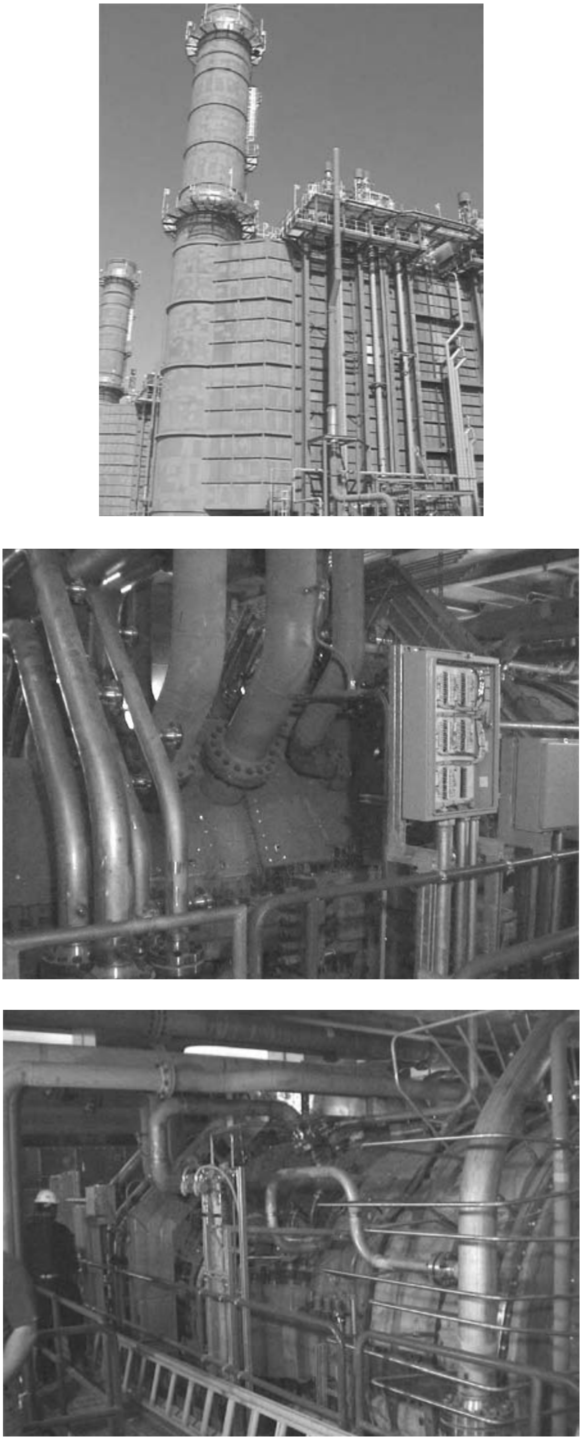


Figure 2-21. Combined-cycle power plant.

Figure 2-22. Wind power. *Source:* Fotosearch.

the cube of the wind speed. In other words, if the wind speed is doubled, the power produced is tripled or increased by a factor of eight. Thus, what might appear to humans as modest changes in breezes severely impact wind power production.

Installation of wind power generators requires selecting sites that are relatively unrestricted to wind flow, preferably at high elevations, and within close proximity to suitable powerlines. Obviously, the site selected should have a fairly constant wind speed.

Wind power is accepted as free energy with no fuel costs. Wind power is also considered renewable energy, since wind really never goes away.

Solar Direct Generation (Photovoltaic)

The *photovoltaic* (sometimes called "voltaic" for short) type of solar power plant converts the sun's energy directly into electrical energy. A photovoltaic array is shown in Figure 2-23. This type of production uses various types of films or special materials that convert sunlight into direct current (dc) electrical energy systems. Panels are then connected in series and parallel to obtain the desired output voltage and current ratings. Some systems use an

Figure 2-23. Direct Solar Photovoltaic. *Source:* Fotosearch.

energy storage device (i.e., battery) to provide electrical power during off-sun-peak periods. This dc energy is converted to utility ac energy by means of a device called an *inverter.*

Larger-scale voltaic solar power systems are typically made of 1.5 Vdc solar cells capable of producing approximately 20 ma of electrical current each. A typical solar photovoltaic panel measuring 4 feet by 1 foot would produce approximately 50–60 watts of electrical power. Therefore, a 4 foot panel would supply power for a 60 watt lightbulb during daylight hours. Given today's technology and the space that is needed, direct solar voltaic systems are not practical for large-scale electric power production.

Solar plants are environmentally friendly as they produce no pollution. The main drawback to these plants is the cost of the panels and conversion equipment. Technology has produced more efficient panels at lower cost, and direct solar systems will eventually be more cost-effective. They are currently used commercially to power small devices in remote areas. There remain several tax incentives to promote use of solar power by residential and small business consumers.

3

TRANSMISSION LINES

CHAPTER OBJECTIVES

- ☑ *Explain why high-voltage transmission lines are used*
- ☑ *Explain the different conductor types, sizes, materials, and configurations*
- ☑ *Discuss the different types of insulation used for overhead and underground conductors*
- ☑ *Identify the common electric power system transmission voltage classes*
- ☑ *Discuss the different transmission line electrical design characteristics (insulation, air gaps, lightning performance, etc.)*
- ☑ *Explain the differences between ac and dc transmission line design, reliability, applications, and benefits*
- ☑ *Discuss overhead and underground transmission systems*

TRANSMISSION LINES

Why use high-voltage transmission lines? The best answer to that question is that high-voltage transmission lines transport power over long distances

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much more efficiently than lower-voltage distribution lines for two main reasons. First, high-voltage transmission lines take advantage of the power equation, that is, power is equal to the voltage times current. Therefore, increasing the voltage allows one to decrease the current for the same amount of power. Second, since transport losses are a function of the square of the current flowing in the conductors, increasing the voltage to lower the current drastically reduces transportation losses. Plus, reducing the current allows one to use smaller conductor sizes.

Figure 3-1 shows a three-phase 500 kV transmission line with two conductors per phase. The two-conductors-per-phase option is called *bundling.* Power companies bundle multiple conductors—double, triple, or more—to increase the power transport capability of a power line. The type of insulation used in this line is referred to as *V-string* insulation. V-string insulation, compared to *I-string* insulation, provides stability in wind conditions. This line also has two *static wires* on the very top to shield itself from lightning. The static wires in this case do not have insulators; instead, they are directly connected to the metal towers so that lightning strikes are immediately grounded to earth. Hopefully, this shielding will keep the main power conductors from experiencing a direct lightning strike.

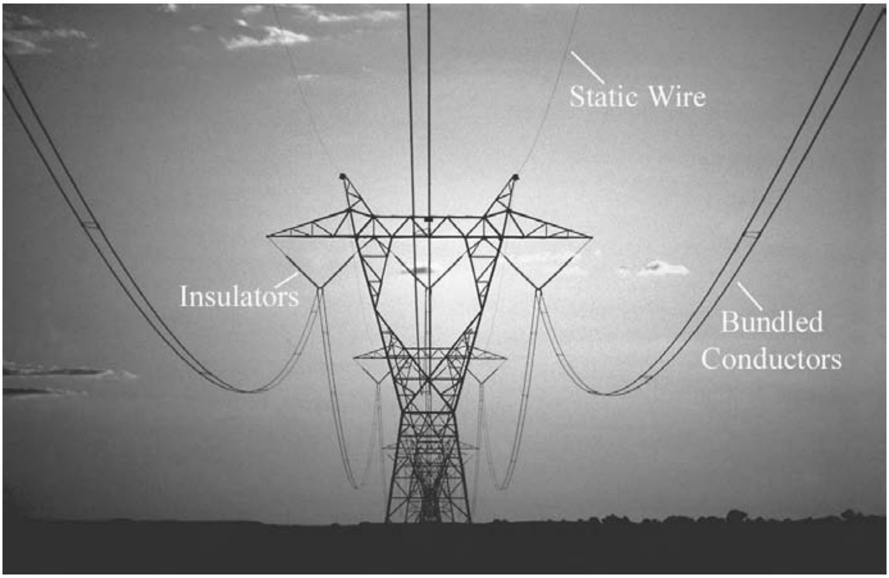

Figure 3-1. High-voltage transmission line. Source: Photovault.

Raising Voltage to Reduce Current

Raising the voltage to reduce current reduces conductor size and increases insulation requirements. Let us look at the power equation again:

$$Power = Voltage \times Current$$

$$Voltage_{\mathrm{In}} \times Current_{\mathrm{In}} = Voltage_{\mathrm{Out}} \times Current_{\mathrm{Out}}$$

From the power equation above, raising the voltage means that the current can be reduced for the same amount of power. The purpose of step-up transformers at power plants, for example, is to increase the voltage to lower the current for power transport over long distances. Then at the receiving end of the transmission line, step-down transformers are used to reduce the voltage for easier distribution.

For example, the amount of current needed to transport 100 MW of power at 230 kV is half the amount of current needed to transport 100 MW of power at 115 kV. In other words, doubling the voltage cuts the required current in half.

The higher-voltage transmission lines require larger structures with longer insulator strings in order to have greater air gaps and needed insulation. However, it is usually much cheaper to build larger structures and wider right of ways for high-voltage transmission lines than it is to pay the continuous cost of high losses associated with lower-voltage power lines. Also, to transport a given amount of power from point “a” to point “b,” a higher-voltage line can require much less right of way land than multiple lower-voltage lines that are side by side.

Raising Voltage to Reduce Losses

The cost due to losses decreases dramatically when the current is lowered. The power losses in conductors are calculated by the formula I^2R. If the current (I) is doubled, the power losses quadruple for the same amount of conductor resistance (R)! Again, it is much more cost effective to transport large quantities of electrical power over long distances using high-voltage transmission lines because the current is less and the losses are much less.

Bundled Conductors

Bundling conductors significantly increases the power transfer capability of the line. The extra relatively small cost when building a transmission line to add bundled conductors is easily justified since bundling the conductors actually doubles, triples, quadruples, and so on the power transfer capability of the line. For example, assume that a right of way for a particular new transmission line has been secured. Designing transmission lines to have multiple conductors per phase significantly increases the power transport capability of that line for a minimal extra overall cost.

CONDUCTORS

Conductor material (all wires), type, size, and current rating are key factors in determining the power handling capability of transmission lines, distribution lines, transformers, service wires, and so on. A conductor heats up when current flows through it due to its resistance. The resistance per mile is constant for a conductor. The larger the diameter of the conductor, the less resistance there is to current flow.

Conductors are rated by how much current causes them to heat up to a predetermined amount of degrees above ambient temperature. The amount of temperature rise above ambient (i.e., when no current flows) determines the current rating of a conductor. For example, when a conductor reaches 70°C above ambient, the conductor is said to be at full load rating. The power company selects the temperature rise above ambient to determine acceptable conductor ratings. The power company might adopt a different current rating (i.e., temperature rating) for emergency conditions.

The amount of current that causes the temperature to rise depends on the conductor material and size. The conductor type determines its strength and application in electric power systems.

Conductor Material

Utility companies use different conductor materials for different applications. Copper, aluminum, and steel are the primary types of conductor materials used in electrical power systems. Other types of conductors, such as silver and gold, are actually better conductors of electricity; however, cost prohibits wide use of these materials.

Copper

Copper is an excellent conductor and is very popular. Copper is very durable and is not affected significantly by weather.

Aluminum

Aluminum is a good conductor but not as good or as durable as copper. However, aluminum costs less. Aluminum is rust resistant and weighs much less than copper.

Steel

Steel is a poor conductor when compared to copper and aluminum; however, it is very strong. Steel strands are often used as the core in aluminum conductors to increase the tensile strength of the conductor.

Conductor Types

Power line conductors are either solid or stranded. Rigid conductors such as hollow aluminum tubes are used as conductors in substations because of the added strength against sag in low-profile substations when the conductor is only supported at both ends. Rigid copper bus bars are commonly used in low-voltage switch gear because of their high current rating and relatively short lengths.

The most common power line conductor types are shown below:

Solid. *Solid* conductors (Figure 3-2) are typically smaller and stronger than stranded conductors. Solid conductors are usually more difficult to bend and are easily damaged.

Stranded. As shown in Figure 3-3, *stranded* conductors have three or more strands of conductor material twisted together to form a single conductor. Stranded conductors can carry high currents and are usually more flexible than solid conductors.

Aluminum Conductor, Steel-Reinforced (ACSR). To add strength to aluminum conductors, Figure 3-4 shows steel strands that are used as the core of aluminum stranded conductors. These high-strength conductors are normally used on long span distances, for minimum sag applications.

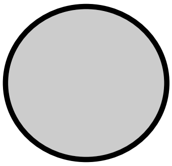

Figure 3-2. Solid conductor.

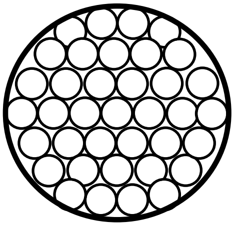

Figure 3-3. Stranded conductor.

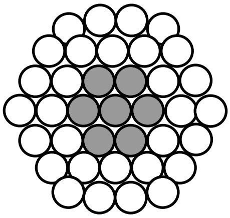

Figure 3-4. ACSR conductor.

Conductor Size

There are two conductor size standards used in electrical systems. One is for smaller conductor sizes (American Wire Gauge) and the other is for larger conductor sizes (circular mils). Table 3-1 compares conductor sizes and standards.

American Standard Wire Gauge (AWG)

The American Standard Wire Gauge is an old standard that is used for relatively small conductor sizes. The scale is in reverse order; in other words, the numbers get smaller as the conductors get larger. The circular mils standard of measurement is used for large conductor sizes.

Circular Mils

Conductors greater than AWG 4/0 are measured in circular mils (cmills). One circular mil is equal to the area of a circle having a 0.001 inch (1 mil) diameter. For example, the magnified conductor in the Figure 3-5 has 55 circular mils. In actual size, a conductor of 55 circular mils is about four times smaller than the period at the end of this sentence. Therefore, conductors sized in circular mils are usually stated in thousands of circular mils (i.e., kcm).

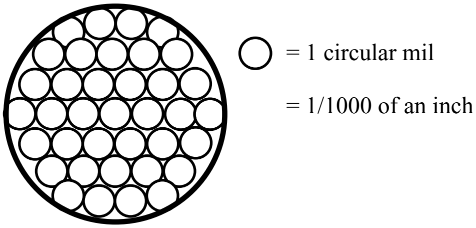

Figure 3-5. Circular mils.

Table 3-1 shows typical conductor sizes and associated current ratings for outdoor bare ACSR conductors having a current rating of 75°C rise above ambient. The table also shows the equivalent copper size conductor.

Insulation and Outer Covers

Metal wire current-carrying conductors can be insulated or noninsulated when in use. Noninsulated conductors (i.e., bare wires) normally use what are called "*insulators*" as the means for separating the bare wires from the grounded structures, making air their insulation. Insulated conductors use plastic, rubber, or other jacketing materials for electrical isolation. High-voltage insulat-

Table 3-1. Typical ACSR conductor sizes

Cross section (inches)	Size, (AWG or cmils)	Size, copper equivalent	Ratio (Al to steel)	Diameter (inches)	Current (amps), (75°C rise)
0.250	4	6	7/1	0.250	140
0.325	2	4	6/1	0.316	180
0.398	1/0	2	6/1	0.398	230
0.447	2/0	1	6/1	0.447	270
0.502	3/0	1/0	6/1	0.502	300
0.563	4/0	2/0	6/1	0.563	340
0.642	266,000	3/0	18/1	0.609	460
0.783	397,000	250,000	26/7	0.783	590
1.092	795,000	500,000	26/7	1.093	900
1.345	1,272,000	800,000	54/19	1.382	1,200

ed conductors are normally used in underground systems. Insulated low-voltage service wires are often used for residential overhead and underground lines.

In the 1800s, Ronalds, Cooke, Wheatstone, Morse, and Edison made the first insulated cables. The insulation materials available at that time were natural substances such as cotton, jute, burlap, wood, and oil-impregnated paper. With the development of rubber compounds and the invention of plastic, insulation for underground cables have become much more reliable and efficient.

Voltage Classes

Table 3-2 shows the various transmission and subtransmission system voltages used in North America. This table is not absolute; some power companies designate their system voltages a little differently. Note: it is quite common to use subtransmission voltages to transport power over medium distances (i.e., across large populated areas) or to transport power over long distances if the total current requirement is low, such as for serving less populated areas that are far away.

The higher transmission system voltages tend to be more standardized compared to the lower distribution voltages. There are many more subtle variations in distribution voltages than transmission voltages.

Voltage class is the term often used by equipment manufacturers and power companies to identify the voltage that the equipment will be connected to. A manufacturer might use the voltage class to identify the intended system operating voltage for their equipment. A power company might use the voltage class as a reference to the system discussed in a conversation. A

Table 3-2. Transmission voltages

Voltage class	Voltage category	System voltage
69,000		Subtransmission
115,000		
138,000		
161,000		Transmission
230,000	Extra high voltage (EHV)	
345,000		
500,000		
765,000		
Above 1,000,000	Ultra high voltage (UHV)	

voltage class might include several *nominal* operating voltages. Nominal voltages are the everyday normal, actual voltages. For example, a circuit breaker might be a 125 kV voltage class piece of equipment that is operating at a nominal 115 kV voltage.

Voltage category is often used to identify a group of voltage classes. For example, "extra high voltage" (or EHV) is a term used to state whether an equipment manufacturer builds transmission equipment or distribution equipment, which would be categorized as "high-voltage equipment" (or HV).

System voltage is a term used to identify whether distribution, transmission, or secondary is referenced. For example, power companies normally distinguish between distribution and transmission departments. A typical power company might distinguish between distribution line crews, transmission line crews, and so on. Secondary system voltage usually refers to customer service voltages.

TRANSMISSION LINE DESIGN PARAMETERS (OPTIONAL SUPPLEMENTARY READING)

This section discusses in more detail the design parameters for high-voltage transmission lines.

Insulation

The minimum insulation requirements for a transmission line are determined by first evaluating individually the minimum requirements for each of the following factors.

Any of the insulation criteria listed below could dictate the minimum spacing and insulation requirements for the transmission line.

Air Gaps for 60 Hertz Power Frequency Voltage

Open air has a flashover voltage rating. A rule of thumb is one foot of air gap for every 100 kV of voltage. Detailed reference charts are available to determine the proper air gap requirements based on operating voltage, elevation, and exposure conditions.

Contamination Levels

Transmission lines located near oceans, alkali salt flats, cement factories, and so on require extra insulation for lines to perform properly in contamination prone environments. Salt mixed with moisture, for example, can cause leakage currents and possible undesirable insulation flashovers to occur. Extra insulation is often required for these contamination prone environments. This extra insulation could increase the minimum air gap clearance.

Expected Switching Surge Overvoltage Conditions

When power system circuit breakers operate, or large motors start, or disturbances happen on the power grid, transient voltages could occur that can flashover the insulation or air gap. The design engineer studies all possible switching transient conditions to make sure adequate insulation is provided on the line at all times.

Safe Working Space

The National Electrical Safety Code (NESC) specifies the minimum phase-to-ground and phase-to-phase air-gap clearances for all power lines and substation equipment. These NESC clearances are based on safe working space requirements. In some cases, the minimum electrical air-gap clearance is increased to meet NESC requirements.

Lightning Performance

Transmission lines frequently use shield wires to improve the line's operating performance under lightning conditions. These *shield wires* (sometimes called *static wires* or *earth wires*) serve as a high-elevation ground wires to attract lightning. When lightning strikes the shield wire, surge current flows through the wires, through the towers, through ground rods, and into the earth, where the energy is dissipated. Sometimes extra air-gap clearance is needed in towers to overcome the possibility of the tower flashing back over to the power conductors when lightning energy is being dissipated. This condition is mitigated by good tower grounding practices.

Audible Noise

Audible noise can also play a role in designing high-voltage power lines. Audible noise can be the result of foul weather, electrical stress, or corona discharge, and the low-frequency hum can become troublesome if not evaluated during the design process. There are ways to minimize audio noise, most of which tend to increase conductor size and/or air-gap spacing.

UNDERGROUND TRANSMISSION (OPTIONAL SUPPLEMENTARY READING)

Underground transmission is usually three to ten times more costly than overhead transmission due to right of way requirements, obstacles, and material costs. It is normally used in urban areas or near airports where overhead transmission is not an option. Cables are made of solid dielectric polyethylene materials and can have ratings on the order of 400 kV. Figure 3-6 shows a 230 kV underground transmission line.

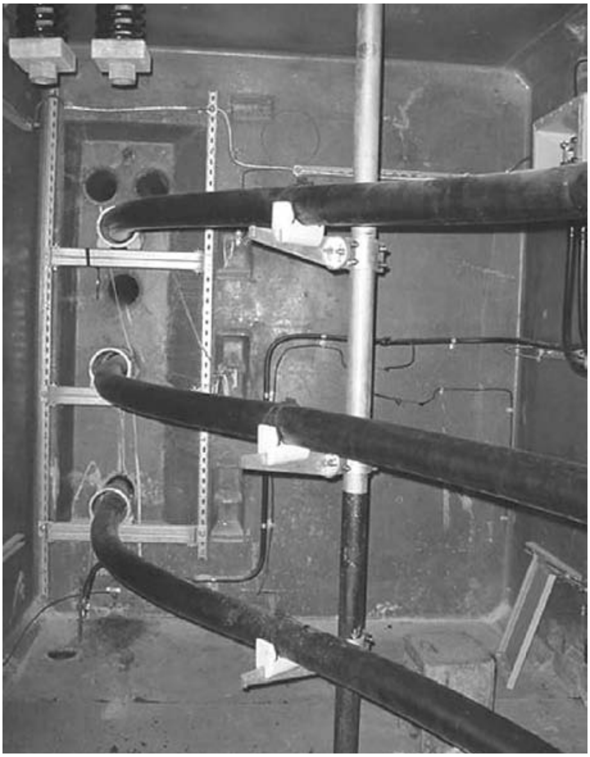

Figure 3-6. Underground transmission line.

4

SUBSTATIONS

CHAPTER OBJECTIVES

- ☑ *Identify all major equipment used in substations*
- ☑ *Describe the purpose and operation of each major equipment type*
- ☑ *Discuss the different types of transformers*
- ☑ *Explain the operation of voltage regulators and tap changers*
- ☑ *Understand the advantages and disadvantages of oil and gas equipment*
- ☑ *Discuss the different types of circuit breakers and how they are used*
- ☑ *Explain the purpose of capacitors, reactors, and static VAR compensators used in electric power systems*
- ☑ *Discuss the equipment found in control buildings*
- ☑ *Discuss the effective preventative maintenance programs used for substation equipment*

SUBSTATION EQUIPMENT

The major types of equipment found in most transmission and distribution substations are discussed in this chapter. The purpose, function, design

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characteristics, and key properties are all explained. After the equipment is discussed, planned and essential predictive maintenance techniques are discussed. The reader should get a good fundamental understanding of all the important aspects of the major equipment found in substations and how they are used and operated.

The substation equipment discussed in this chapter includes:

- Transformers
- Regulators
- Circuit breakers and reclosers
- Air disconnect switches
- Lightning arresters
- Electrical buses
- Capacitor banks
- Reactors
- Static VAR compensators
- Control building
- Preventative maintenance

TRANSFORMERS

Transformers are essential components in electric power systems. They come in all shapes and sizes. Power transformers are used to convert high-voltage power to low-voltage power and vice versa. Power can flow in both directions: from the high-voltage side to the low-voltage side or from the low-voltage side to the high-voltage side. Generation plants use large *step-up* transformers to raise the voltage of the generated power for efficient transport of power over long distances. Then *step-down* transformers convert the power to subtransmission, as in Figure 4-1, or distribution voltages, as in Figure 4-2, for further transport or consumption. *Distribution transformers* are used on distribution lines to further convert distribution voltages down to voltages suitable for residential, commercial, and industrial consumption (see Figure 4-3).

There are many types of transformers used in electric power systems. *Instrument transformers* are used to connect high-power equipment to low-power electronic instruments for monitoring system voltages and currents at convenient levels. Instrument transformers include *CTs* and *PTs* (i.e., current transformers and potential transformers). These instrument transform-

Figure 4-1. Step-down transformer.

ers connect to metering equipment, protective relaying equipment, and telecommunications equipment. *Regulating transformers* are used to maintain proper distribution voltages so that consumers have stable wall outlet voltage. *Phase shifting* transformers are used to control power flow between tie lines.

Transformers can be single phase, three phase, or *banked* together to operate as a single unit. Figure 4-3 shows a three phase transformer bank.

Transformer Fundamentals

Transformers work by combining the two physical laws that were discussed earlier in Chapter 2. Physical law #1 states that a voltage is produced on any conductor in a changing magnetic field. Physical law #2 states that a current flowing in a wire produces a magnetic field. Transformers combine these

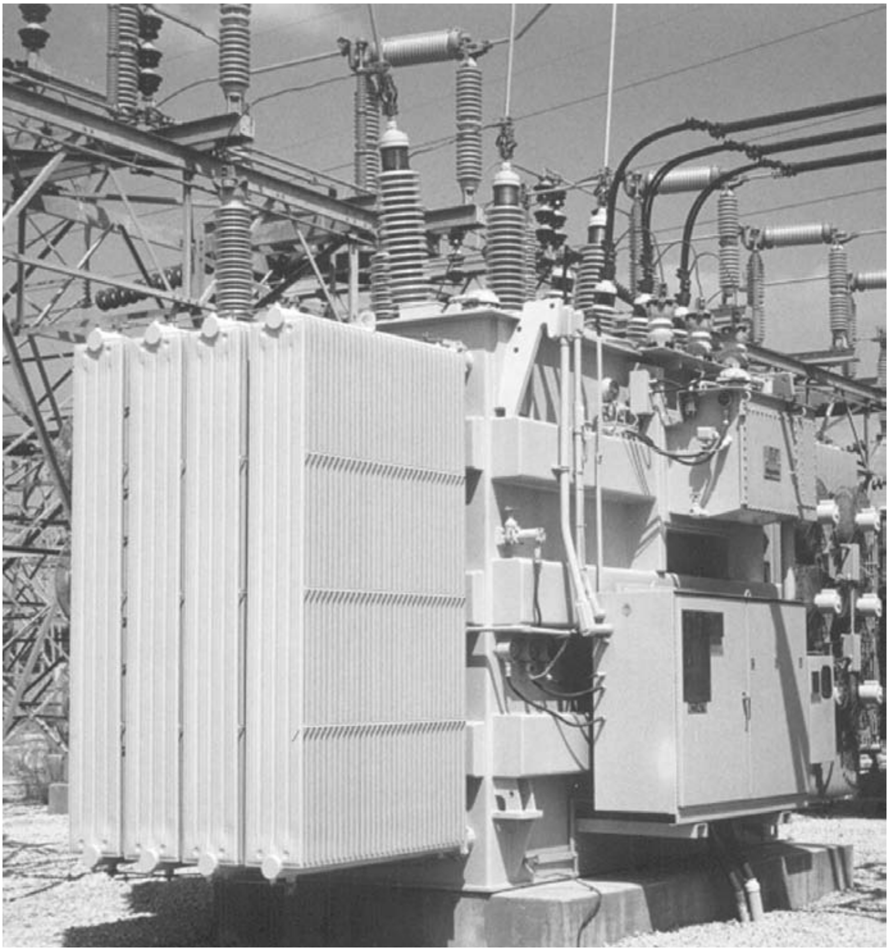

Figure 4-2. Distribution power transformer.

principles by using two coils of wire and a changing voltage source. The current flowing in the coil on one side of the transformer induces a voltage in the coil on the other side. (Hence, the two coils are coupled by the magnetic field.)

This is a very important concept because the entire electric power system depends on these relationships. Looking at them closely; the voltage on the opposite side of a transformer is proportional to the turns ratio of the transformer, and the current on the other side of the transformer is inversely proportional to the turns ratio of the transformer. For example, the transformer in Figure 4-4 has a turns ratio of 2:1.

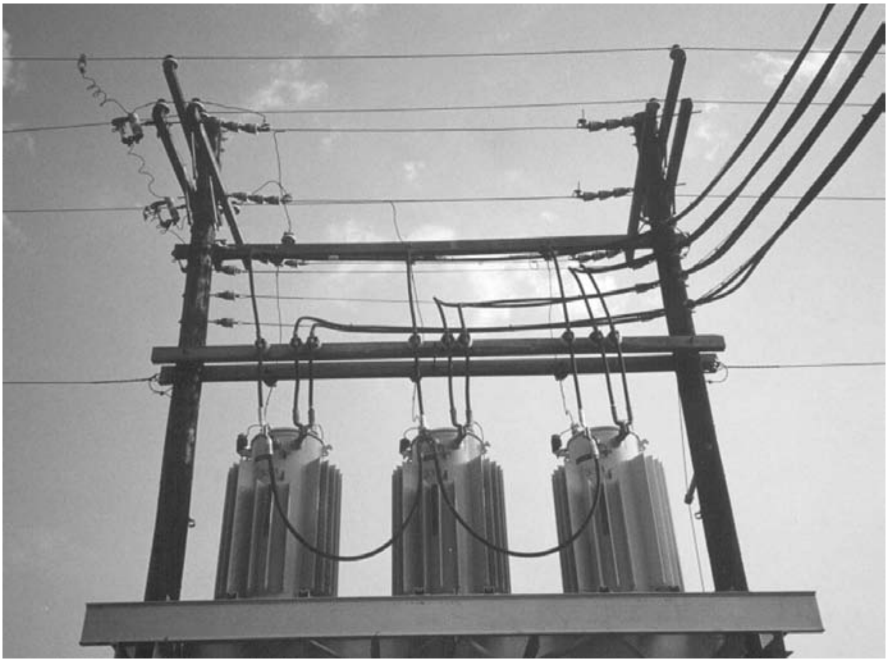

Figure 4-3. Transformer bank.

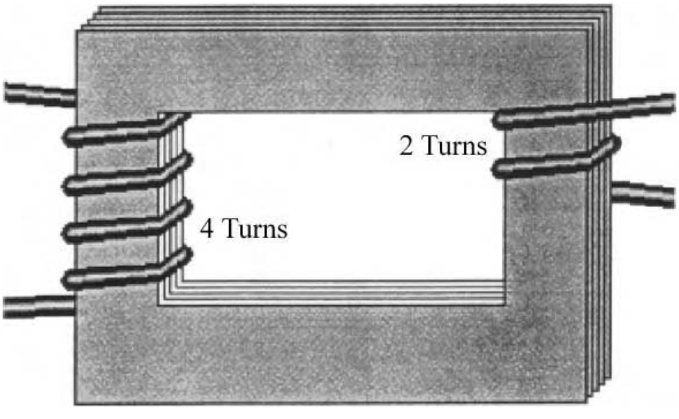

Figure 4-4. Transformer windings. Courtesy of Alliant Energy.

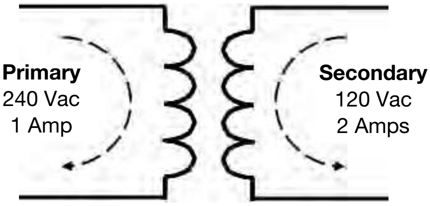

Figure 4-5. Transformer turn ratio.

If the 2:1 turns ratio transformer in Figure 4-4 has 240 Vac at 1 amp applied on its primary winding (left side), it will produce 120 Vac at 2 amps on its secondary winding (right side), as seen in Figure 4-5. Note: power equals 240 watts on either side (i.e., voltage × current). As discussed earlier, raising the voltage (i.e., like on transmission lines) lowers the current and thus significantly lowers system losses.

Power Transformers

Figure 4-6 shows the inside of a large power transformer. Power transformers consist of two or more windings for each phase and these windings are usually wound around an *iron core.* The iron core improves the efficiency of the transformer by concentrating the magnetic field and reduces transformer losses. The high-voltage and low-voltage windings have a unique number of coil turns. The turns ratio between the coils dictates the voltage and current relationships between the high- and low-voltage sides.

Bushings

Bushings are used on transformers, circuit breakers, and many other types of electric power equipment as connection points. Bushings connect outside conductors to conductors inside equipment. Bushings provide insulation between the energized conductor and the grounded metal tank surrounding the conductor. The conductors inside the bushings are normally solid copper rods surrounded by porcelain insulation. Usually an insulation dielectric such as oil or gas is added inside the bushing between the copper conductor and the porcelain housing to improve its insulation properties. Mineral oil and sulfur hexafluoride (SF_6) gas are common dielectric materials used to increase insulation.

Note: transformers have large bushings on the high-voltage side of the unit and small bushings on the low-voltage side. In comparison, circuit breakers (discussed later) have the same size bushings on both sides of the unit.

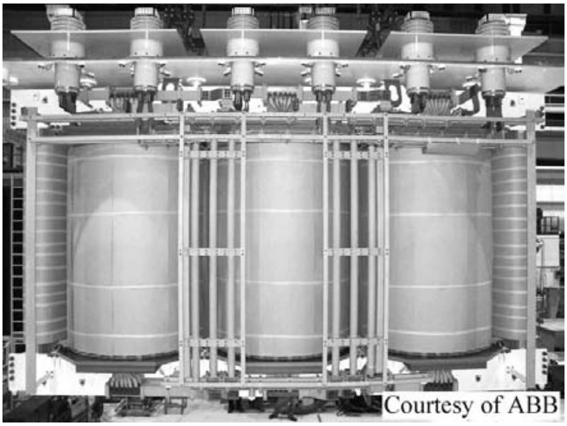

Figure 4-6. Transformer core and coils.

Figures 4-7 and 4-8 are examples of typical transformer bushings. Notice the oil level visible through the glass portion at the top of the bushing. Sometimes, oil level gauges are used for oil level inspections.

The part of the bushing that is exposed to the outside atmosphere generally has *skirts* to reduce unwanted leakage currents. The purpose of the skirts is to increase the leakage current distance in order to decrease the leakage current.

Figure 4-7. Bushing oil level gauge.

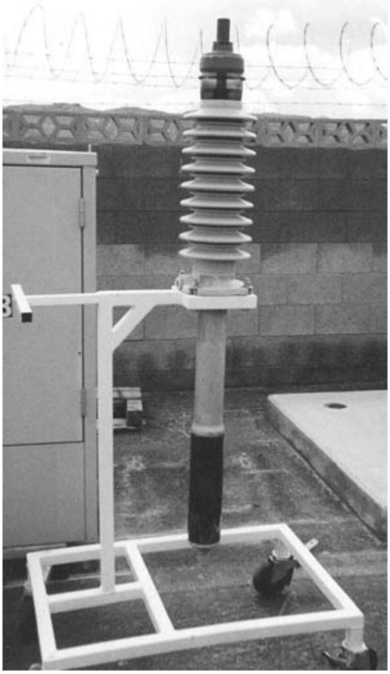

Figure 4-8. Transformer bushing.

Cleanliness of the outside porcelain is also important. Contaminated or dirty bushings can cause arcing that can result in flashovers, especially during light rain or fog conditions.

Instrument Transformers

The term *instrument transformer* refers to current and voltage transformers that are used to scale down actual power system quantities for metering, protective relaying, and/or system monitoring equipment. The application of both current and potential transformers also provides scaled-down quantities for power and energy information.

Current Transformers

Current transformers or *CTs* are used to scale down the high magnitude of current flowing in high-voltage conductors to a level much easier to work with safely. For example, it is much easier to work with 5 amperes of current in the CT's secondary circuit than it is to work with 1,000 amperes of current in the CT's primary circuit.

Figure 4-9 shows a typical CT connection diagram. Using the CT's turn ratio as a *scale factor* provides the current level required for the monitoring instrument. Yet, the current located in the high-voltage conductors is actually being measured.

Taps (or connection points to the coil) are used to allow options for various turns ratio scale factors to best match the operating current to the instrument's current requirements.

Most CTs are located on transformer and circuit breaker bushings, as shown in Figure 4-10. Figure 4-11 shows a stand-alone high-voltage CT.

Potential Transformers

Similarly, *potential transformers* (*PTs*) are used to scale down very high voltages to levels that are safer to work with. For example, it is much easier to work with 115 Vac than 69 kVac. Figure 4-12 shows how a PT is connected. The 600:1 scale factor is taken into account in the calculations of actual voltage. PTs are also used for metering, protective relaying, and system monitoring equipment. The instruments connected to the secondary side of the PT are programmed to account for the turns ratio scale factor.

Like most transformers, taps are used to allow options for various turns ratios to best match the operating voltage with the instrument's voltage-lev-

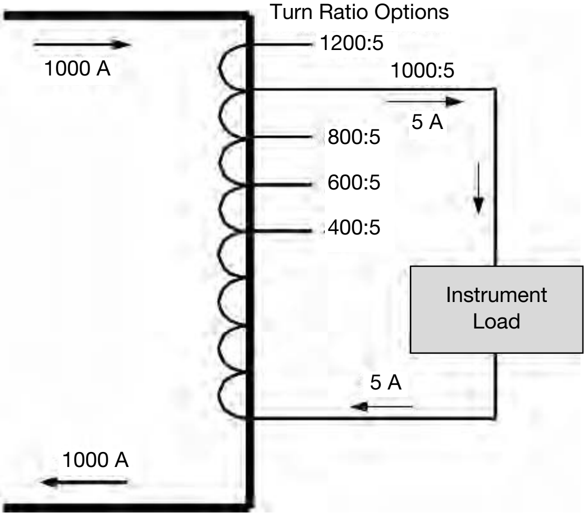

Figure 4-9. CT connections.

Figure 4-10. Bushing CT.

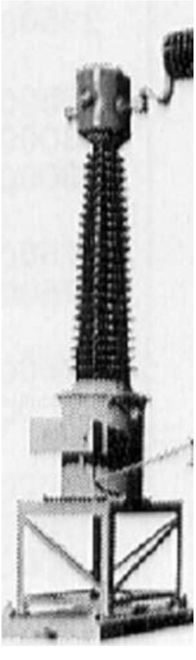

Figure 4-11. External high-voltage CT.

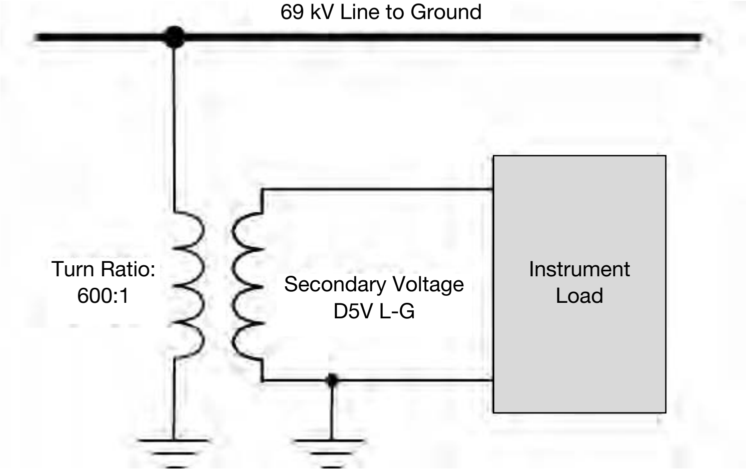

Figure 4-12. PT Connections.

el requirements. An example of a low-voltage PT is shown in Figure 4-13 and a high-voltage PT in Figure 4-14.

Figure 4-13. Low-voltage PT. Courtesy Alliant Energy.