1

System Overview, Terminology, and Basic Concepts

Chapter Objectives

After completing this chapter, the reader will be able to:

☑ *Discuss the history of electricity*
☑ *Describe key components in the system overview*
☑ *Explain the differences between voltage, current, power, and energy*
☑ *Describe how electricity is generated using nature's physical laws*
☑ *Discuss the three main components of a generator*
☑ *Explain the differences between delta and wye connection configurations*
☑ *Describe the three types of load (electrical consumption) 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 famous kite experiment, verified the nature of electricity. He knew that lightning is very powerful and dangerous. The 1752 kite experiment used a pointed metal object at the top end of hemp kite string and a metal key at the string's base end. (Hemp is a perennial American plant used in rope making by native Americans.) The string passed 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 lightning energy. He then flew the kite into a thunderstorm. He first noticed some loose strands of hemp string stood erect, avoiding one another. He touched the key with his knuckle and received a small electrical shock.

Later, many great discoveries in electricity and magnetism principles occurred by Volta, Coulomb, Gauss, Henry, Faraday, Tesla, and others between 1750 and

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1850. It was found that electric current in a wire produces a magnetic field. And it was found that a moving magnetic field near a wire produces electricity. These discoveries led to many inventions such as the battery (1800), generator (1831), motor (1831), telegraph (1837), telephone (1876), and many other intriguing inventions.

In 1879, Thomas Edison invented a relatively efficient light bulb, like today's incandescent bulbs. In 1882, he placed into operation the historic Pearl Street steam-electric power plant and first direct current (dc) distribution system in New York City, powering over 10,000 electric light bulbs. By the late 1880s, power for electric motors brought in 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 centers sprinkled U.S. cities. Each distribution center was limited to a few blocks because of transmission inefficiencies using dc. Voltage could not be increased or decreased using dc systems and the need to transport power longer distances was in order.

To solve the problem of transporting electrical power long distances, George Westinghouse developed a device called "***transformer***." Transformers allow electrical energy to be transported long distances efficiently by raising voltage to reduce losses. This made it possible to supply electric power to homes and businesses located far from electric power generating plants. The application of transformers required electric power systems to be of the alternating current (ac) type opposed to dc type.

The development of Niagara Falls hydroelectric power plant in 1896 started the practice of placing electric power-generating plants far from consumption areas. The Niagara plant produced electricity to Buffalo, NY, over 20 miles away. Westinghouse used technology developed by Nicolas Tesla, who convincingly proved the superiority of transporting electric power long distances using ac instead of dc. Niagara was the first large power system to supply multiple large consumers with only one power line across a long distance.

Since the early 1900s, ac power systems began appearing throughout the United States. These power systems became interconnected to form what we know today as four major power grids in the United States and Canada.

It is interesting to note how dc systems are coming back. For example, rooftop solar, dc transmission lines, offshore wind farms, and other dc generation and load facilities are growing at a significant rate. Furthermore, most electrical devices used as residential load operate on dc. Power converters, such as plug-in ac/dc power supplies, are used to power computers, monitors, and Wi-Fi electronic equipment. Internal ac/dc power converters are used in televisions, radios, home theater equipment, and other digitally based appliances and devices. More on this subject is provided later in this book, including the all-dc electric home.

The remainder of this chapter discusses fundamental terms and concepts used in today's electric power systems based on this impressive history.

System Overview

Electric power systems are real-time energy delivery systems. Real-time, meaning power is generated, transported, and supplied the moment you turn on a light switch. Electric power systems are not storage systems like water and gas systems. Instead, generators produce energy as demand calls for it! Energy is transported almost at the speed of light.

Figure 1-1 shows the basic building blocks of an electric power system. Starting with ***generation***, electrical energy is produced and then transformed into high-voltage (HV) electrical energy, more suitable for long-distance transportation, which occurs at power plants and their associated ***transmission substations***. Power plants transform other sources of energy into producing electrical energy. For example, heat, wind, solar, mechanical, hydraulic, chemical, geothermal, nuclear, biofuel, and other energy sources are used to produce electrical energy. HV ***transmission power lines*** efficiently transport this electrical energy long distances to consumption locations. Remote ***distribution substations*** transform HV transmission electrical energy into more suitable lower HV power lines called "***primary feeders***" for delivery to consumers. The distribution part of the electric power system starts with the lower voltage side of substation transformers, and all distribution primary voltage feeders, and service runs to consumers. Services to consumers require electrical energy on

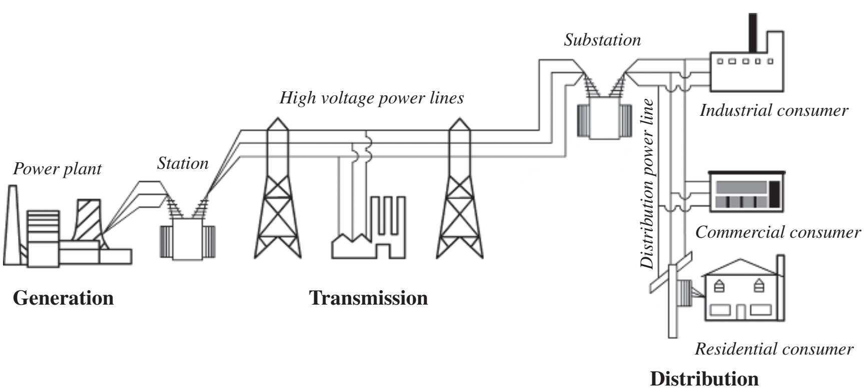


Figure 1-1 System overview.

the primary feeders to be transformed again into an even lower service voltage called ***secondary.*** Secondary voltage services are more suitable for connecting residential, commercial, and industrial equipment.

A full-scale actual interconnected electric power system, often referred to as "***bulk electric power***" system or "BES," is much more complex than that shown; 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, eventually covering the design and operational nature of the entire BES.

Terminology

Let us start with building a strong understanding of basic terms and concepts most often used by industry professionals 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 throughout this book to build a complete working knowledge of how electrical power systems work.

Voltage

The first term or concept to understand is ***voltage***. Voltage is the ***potential energy*** source in an electrical circuit to make things happen. It is sometimes called ***electro-motive force*** or EMF. The unit of voltage is the ***Volt***. The Volt was named in honor of Alessandro 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. In other words, voltage has the potential to do work but does nothing by itself. Voltage is a push or pull force. Voltage is what pushes and pulls electrons through wires. Voltage always appears between two points in an electrical circuit.

Normally, voltage is either constant (i.e., direct) or alternating (i.e., changing). Electric power systems are based on alternating voltage applications from low voltage 120 Volt residential systems to ultra-HV 765,000 Volt transmission systems. There are lower and higher voltage applications involved in electric power systems; however, this voltage range is commonly used in the North American electric power systems.

In water systems, voltage corresponds to pressure pushing water through pipes. Like voltage, water pressure is present in pipes even though no water is flowing (i.e., valve shut), thus a potential energy source!

Current

Current is the flow of electrons in a ***conductor*** (wire). Electrons are pushed or pulled by voltage through an ***electrical circuit*** or closed-loop path. The electrons flowing in a conductor always return to their voltage source (hence "closed-loop path"). The unit of current is ***ampere*** (also called ***amps***), named after Andre-Marie Ampere, a French physicist. (One amp is equal to 628×10^{16} electrons flowing in the conductor per second.) The number of electrons never decreases in a closed-loop path or circuit. The flow of electrons in a conductor produces heat from the conductor's ***resistance*** (i.e., electrical friction).

Voltage always tries to push or pull current. Therefore, voltage causes current to flow in a circuit or closed-loop path. Circuit resistance reduces current flow and produces heat in the process. As electrons flow in a circuit, ***potential energy*** is converted into ***kinetic energy***. Finally, ***load*** converts the kinetic energy into useful work.

Current flow in a conductor is like ping-pong balls lined up in a tube. Referring to Figure 1-2, a pressure on one end of the tube (e.g., voltage) pushes the balls through the tube. The pressure source (e.g., battery) collects the balls exiting the tube and re-enters them into the tube in a circulating manner (hence, a closed-loop path). The number of balls traveling through the tube per second is analogous to current. ***Current*** is the movement of electrons in a specified direction. Electrical current is identified by the symbol "***i***" or "***I***." (The use of "I" for current originated from "intensity").

Hole Flow vs. Electron Flow

Electron flow occurs when electrons leave the negative terminal of a voltage source, then travel from atom to atom toward the positive terminal of the voltage source. Holes or vacancies occur in atoms when electrons leave to enter adjacent atoms. Holes left behind constitute a current of vacancies moving in the opposite direction to electron flow or from the positive side of the voltage source toward the

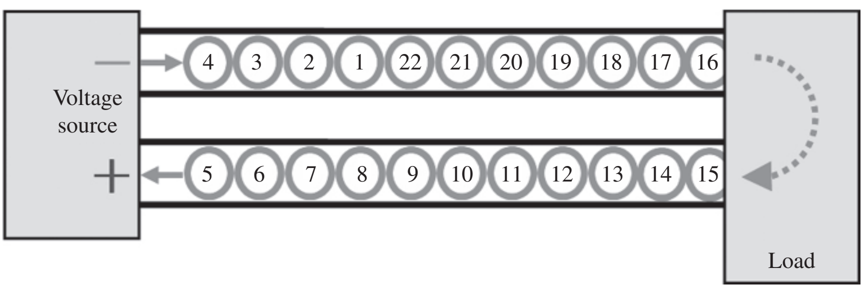


Figure 1-2 Current flow.

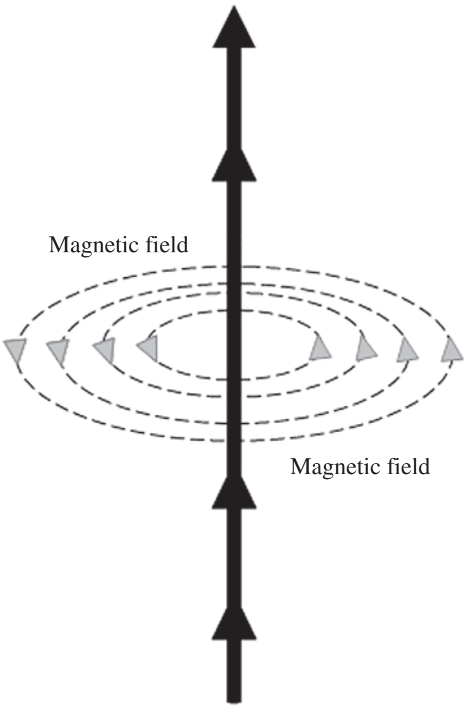


Figure 1-3 Current and magnetic field.

negative side of the voltage source. Therefore, as electrons flow in a circuit in one direction, holes in the same circuit flow in the opposite direction. Current flow is both electron flow or hole flow. *The standard convention used in low-voltage dc electric circuits is* ***hole flow****!* (One reason for this standard convention is early experiments simply defined current flow as being from positive to negative; without really knowing what was moving!) Since current flows both directions in *ac* circuits, the notion of electron flow versus hole flow is minimized.

One especially important phenomenon about current flowing in a conductor is "*current flowing in a conductor produces a magnetic field*"! See Figure 1-3. This is a physical law, like gravity being a physical law. For now, just keep in mind that magnetic fields occur automatically around wires when voltage pushes or pulls electrons. Note: Figure 1-3 shows a diagram that corresponds to the direction of conventional or hole flow current according to the "right-hand rule."

Power

The unit of ***power*** is the ***Watt***, named after James Watt (1736–1819), who is also the inventor of steam engines. Voltage by itself does not do real work, but serves only as a potential energy source. Current does not exist without voltage and therefore current by itself does not do real work. However, voltage and current together can produce real work. Thus, power, the combination of voltage and current, produces real work. Power is the mathematical product of voltage x (times) current.

Electrical power can create heat, spin motors, light lamps, etc. Power is part voltage and part current. Power equals zero if either voltage or current is zero. Voltage appears at a wall outlet in your home as a potential energy source. However, a toaster plugged into an outlet does not consume power until someone switches on the toaster. Switching on the toaster enables current to flow through high-resistive wires, creating heat, thus allowing both voltage and current to be present.

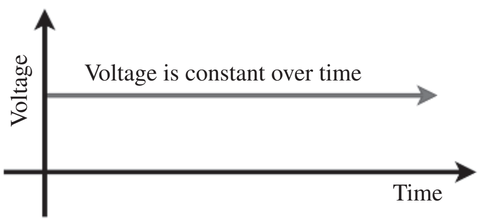
Energy

Electrical ***energy*** is the mathematical product of electrical power and time. The amount of time a load is on (i.e., current flowing) times the amount of power used by the load (i.e., watts) is energy. The measurement for electrical energy is ***watt-hours***. The more common units of electrical energy for residential applications are kilo-watt-hours (kWh, meaning 1,000 watt-hours) and for large industrial applications are mega-watt-hours (MWh, meaning 1,000,000 watt-hours), and power companies might use giga-watt-hours (GWh, meaning 1,000,000,000 watt-hours) as a measurement of substantial amounts of electrical energy produced or consumed.

DC Voltage and Current

Direct Current is the flow of electrons in a circuit and always in the same direction. dc (i.e., one direction current) occurs when voltage is constant, as shown in Figure 1-4. A battery, for example, produces dc current when connected to a circuit because the voltage source is constant. Electrons leaving the negative terminal of a battery move through the circuit toward the positive terminal of the battery. Holes, however, flow in the opposite direction.

Figure 1-4 Direct (i.e., dc voltage).



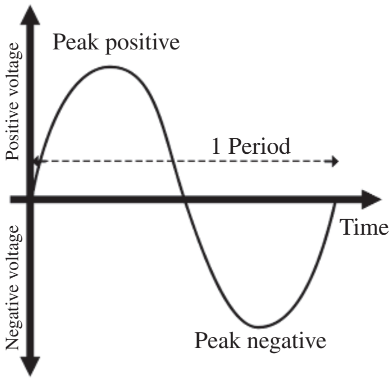


Figure 1-5 Alternating (i.e., ac voltage).

AC Voltage and Current

When the potential energy source terminals (i.e., voltage) alternate positive and negative, current flow in the electrical circuit likewise alternates (clockwise and counterclockwise). Thus, ac occurs when the voltage source terminals alternate.

Figure 1-5 shows the voltage increasing from zero to a positive peak value, then decreasing through zero to a negative peak 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 cycle's ***period*** is the length of time it takes to complete one sine wave cycle. The number of cycles occurring in one second is called "***frequency.***"

Comparing AC and DC Voltage and Current

Electrical load such as incandescent light bulbs, toasters, and hot water heaters. can be served by either ac or dc voltage and current. However, dc voltage sources continuously supply heat in load while 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 moments when voltage and current are both zero and no additive heating occurs.

It is important to note that there are equivalent ac voltage and current that will produce the same heating effect in electrical load as if the sources were dc voltage and current. The equivalent ac voltages and currents that produce the same heating effect as dc are referred to as ***root mean squared*** values or ***rms***. The reason this concept is important to understand is that all electric power system equipment (including HV power lines, substation equipment, etc.) are assessed using rms values of voltages and currents.

For example, the 120-Vac wall outlet in the house is the rms value. Theoretically, one could plug a 120-Vac rms toaster into a 120-Vdc battery source and cook toast in the same amount of time. The ac rms value has the same heating effect as its equivalent dc value. Another example is that a 500-kV HV transmission line is the rms value.

(Optional Supplementary Reading)

Appendix A explains how rms is derived.

Frequency

Frequency is the term used to describe the number of sine wave cycles occurring in a second. The number of cycles per second is also called ***Hertz***. Hertz was named after Heinrich Hertz (1857–1894), a German physicist. Note: dc has no frequency; therefore, frequency is a term used only for ac circuits.

The standard frequency for electric power systems in the United States is 60 cycles/second or 60 Hertz. European countries adopted 50 Hertz as their 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 frequencies were later standardized to 60 Hertz.)

Phase Angle

In ac power systems, voltage and current might have the same frequency but not cross the zero axis simultaneously, resulting in phase angles. The ***phase angle*** between voltage and current is shown in Figure 1-6. Note in this figure, the current wave crosses the horizontal axis after the voltage wave and therefore said, current lags voltage. Load devices, such as motors, make current lag or lead voltage. Load devices that cause current to lag voltage are considered ***inductive***. Load devices that cause current to lead voltage are considered ***capacitive*** (more on this later).

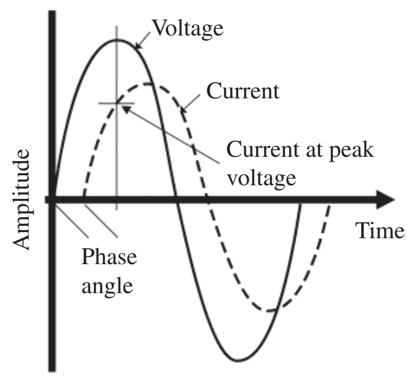


Figure 1-6 Phase angle between voltage and current.

Note that the amplitude of current at the time the voltage peaks is less than peak current. The amplitude of current at the same time of voltage corresponds to *real power* or actual work getting done. Although current amplitude can be greater in lead or lagging circuits, this difference in current magnitude has great significance toward power losses and system ***efficiency***. In other words, *reducing the phase angle between voltage and current reduces the amount of total current needed to get the same amount of real work done*. For instance, adding capacitors (i.e., a leading device) to an inductive motor load ac circuit (i.e., a lagging device) reduces phase angle, reduces peak current, and reduces the amount of current needed from the generation source. Reducing current in this manner still serves the motor load; however, the motor load is now served more efficiently because losses in wires are reduced by current reduction.

AC Voltage Generation

There are two physical laws that describe how electric power systems work. (Gravity is an example of a physical law.) One physical law corresponds to generating a voltage on a coil of wire from a changing magnetic field and the other physical law corresponds to current flowing through a wire that produces a magnetic field. Both physical laws occur continuously throughout the entire electric power system from generation through transmission, distribution, and consumption. The combination of these two physical laws makes our electric power systems work. Understanding these two physical laws enables the reader to fully appreciate and understand the fundamental concepts behind electric power systems.

Physical Law #1

AC voltage is generated in electric power systems by a very fundamental physical law called ***Faraday's law***. Faraday's law is the phenomenon behind 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 this statement at first; however, its meaning and significance are hereby demonstrated through graphs, pictures, and animations.

This statement says, if a person takes a coil of wire and places it near a changing magnetic field (i.e., spinning magnet), a measurable voltage is produced in that coil of wire. Generators, for example, use spinning magnets (i.e., rotors) next to coils of wire (i.e., mounted in the stationary housing) to produce voltage at the generator's terminals.

We will now analyze how a spinning generator works. Keep in mind, virtually all spinning rotor generators in service today use coils of wire mounted on stationary housings, called the ***stator***, where voltage is produced due to changing ***magnetic fields*** provided by spinning ***rotors***. The rotor is sometimes called the "***field"*** because it is responsible for producing the generator's magnetic field. The rotor's strong magnetic field passes through the stator windings to produce alternating voltage (ac) at the stator winding terminals, based on the Faraday's law. This principle is shown and described in the following sections.

Note that the amplitude of a generator's output voltage can be adjusted higher or lower by changing the strength of rotor's magnetic field. The means by which magnetic fields in rotors are changed are discussed later in this chapter.

Single-Phase AC Voltage Generation

Placing a coil of wire in the presence of a changing magnetic field produces voltage, as discovered by Faraday. This principle is graphically presented in Figure 1-7. While reviewing the drawing, note that how changing rotor speed changes frequency and, increasing the number of turns (loops of wire) in the coil increases output voltage.

Three-Phase AC Voltage Generation

When *three* coils of wire are placed in the presence of a changing magnetic field, three independent 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 1-8, three-phase voltage generation can be viewed as three separate single-phase generators, each of which displaced 120 degrees in time, and all of which share the same rotor's magnetic field. As shown, each sine wave is displaced 120 degrees or one-third of a cycle's period.

Three-Phase AC Generator

Large and small generators connected to the power grid 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 generator's stationary section, called ***stator***. The windings are physically spaced 120 degree out of phase to produce three-phase voltage. A simplified drawing of a three-phase generator is shown in Figure 1-9.

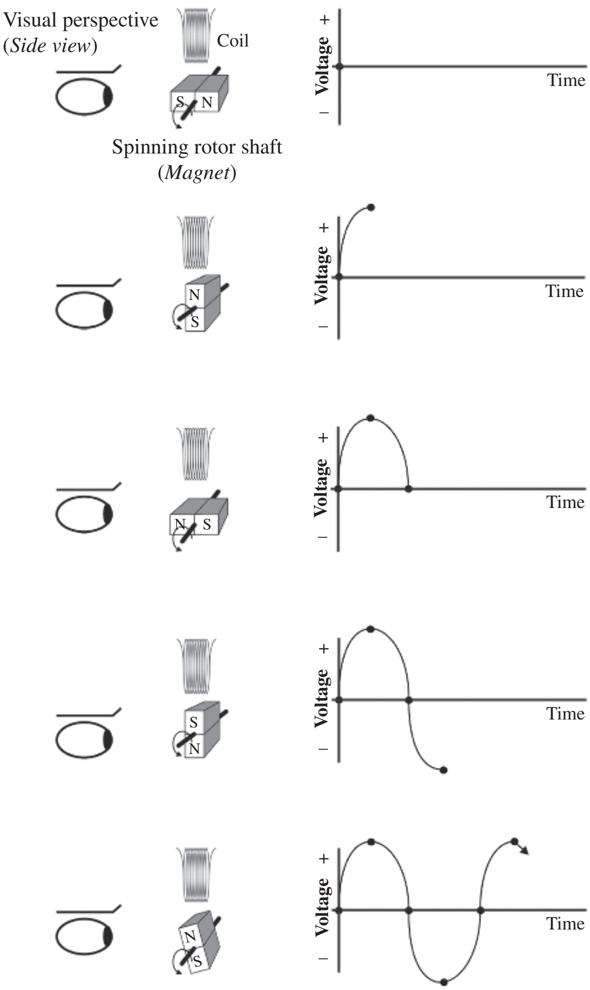


Figure 1-7 Magnetic sine wave.

The Rotor

Rotors, when turned by the shaft's ***prime mover***, provide the changing magnetic field used by stator windings to produce voltage. To function as a generator, rotors consist of either a ***permanent magnet*** or an ***electromagnet***. A permanent magnet rotor produces a fixed strength magnetic field and thus produces a fixed generator output voltage. Large power plant generators use electromagnet rotors to enable variable magnetic field strength and thus adjustable output voltage. The ability to vary rotor magnetic field strength enables generator control operators or automatic systems to adjust generator output voltage to meet load demand, system voltage

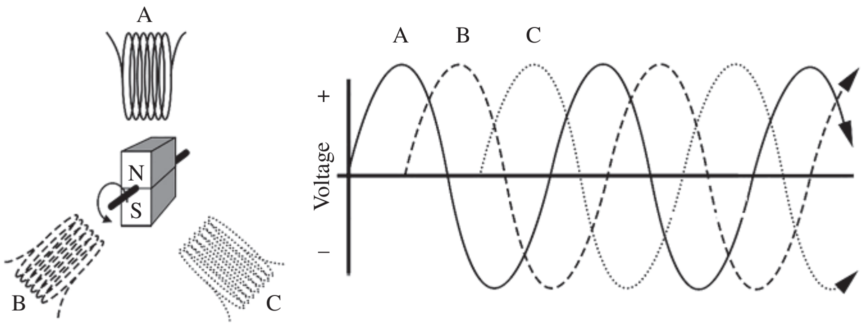
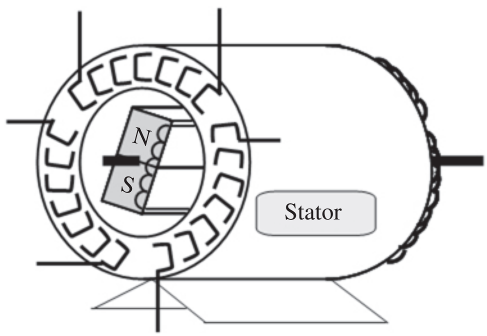


Figure 1-8 Three-phase voltage production.

Figure 1-9 Three-phase generator – stator.



constraints, and power output requirements. A drawing of an electromagnet rotor electrical circuit is shown in Figure 1-10.

The theory of operation behind electromagnet rotors is described by Physical Law #2.

Ampere's Law and Lenz's Law (Physical Law #2) The second basic physical law used to explain how electric power systems work is current flowing in a wire that produces a magnetic field. Ampere's and Lenz's laws state "***a current flowing in a wire produces a magnetic field around the wire***." These laws describe the relationship between electric current flowing in a wire and the production of magnetic fields. When current flows through a wire, a magnetic field surrounds the wire. Therefore, increasing current in the generator's rotor (hence, field current) increases the rotor's magnetic field strength, and vice versa.

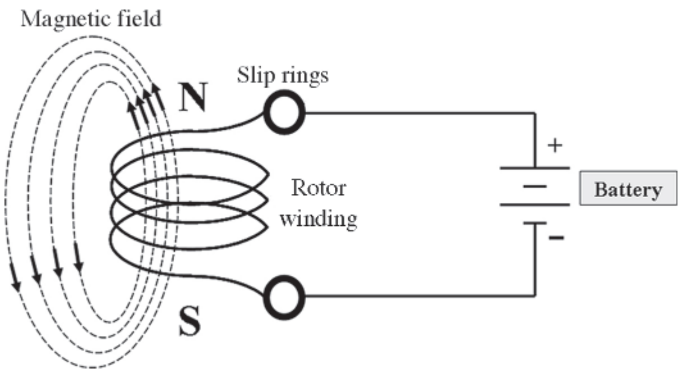


Figure 1-10 Electromagnet and slip rings.

Electromagnets Applying a voltage source to a coil of wire causes current to flow through the coil of wire resulting in a magnetic field about the coil (hence "electromagnet"). A coil's magnetic field is the sum of individual magnetic fields of each loop of wire. In other words, increasing the number of coil turns increases the strength of the magnetic field. The coil's magnetic field has both ***North*** and ***South poles***, as shown in Figure 1-10.

Slip rings are used as electrical contacts to connect the stationary battery to the spinning rotor winding. Increasing applied voltage to the slip rings increases the magnetic field strength. Conversely, decreasing applied voltage decreases the magnetic field strength. Therefore, adjusting the dc voltage applied to the slip rings controls field current and magnetic field strength of the rotor and consequently the generator's output voltage.

Rotor Poles Increasing the number of magnetic poles on the rotor decreases required shaft speed while keeping output frequency constant. Generators that require slower rotor shaft speeds to work, such as hydroelectric and large wind turbines, use multiple pole rotors. Thus, increasing the number of North and South poles on a rotor means less shaft rotation is needed for a North pole to reach a stator phase. For example, hydropower plants use generators with multiple pole rotors because their prime mover (e.g., water) is very dense and moves relatively slow compared to high-pressure steam turbines.

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

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

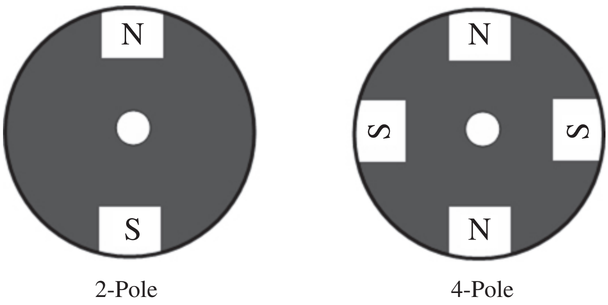


Figure 1-11 Rotor poles.

Figure 1-11 shows the concept of multiple poles in a generator rotor. Since these poles are derived from electromagnets, multiple poles are provided by connecting multiple rotor coils in series.

Example 1: According to the formula, a two-pole rotor (one North and one South) would turn 3,600 rpm for 60 Hertz and a four-pole rotor would turn 1,800 rpm for 60 Hertz.

Example 2: Some generators at Hoover Dam near Las Vegas, Nevada, use 40 pole rotors (20 North and 20 South). Therefore, the rotor speed is 180 rpm or 3 revolutions per second, yet electrical frequency remains 60 cycles/second (or 60 Hz). One can see the shaft turning at this relatively slow rotational speed.

The Exciter

The rotor's controllable voltage source system used to create the rotor's magnetic field is called the "***exciter.***" Figure 1-12 shows the three main components of a three-phase ac generator: stator, rotor, and exciter.

Figure 1-12 shows how ***slip rings*** are used to connect the stationary exciter voltage source to the spinning coil.

From an operational perspective, adding electrical load to the generator's stator windings reduce shaft speed due to the repelling magnetic forces created by load current in the stator. As stator load increases, stronger repelling forces occur against the spinning rotor, thus slowing down shaft speed. Conversely, removing load from a generator reduces stator current, thus reducing repelling forces and therefore increase rotor speed. Thus, regulating the prime mover's ***mechanical energy*** source (i.e., steam for a steam turbine) controls generator rotor speed and system frequency. Varying load conditions require steam throttling to maintain frequency.

Furthermore, as load is added to the generator and rotor speed increased by the prime mover, generator terminal voltage must also be increased by the exciter to help compensate for transmission voltage drop and losses with increased load.

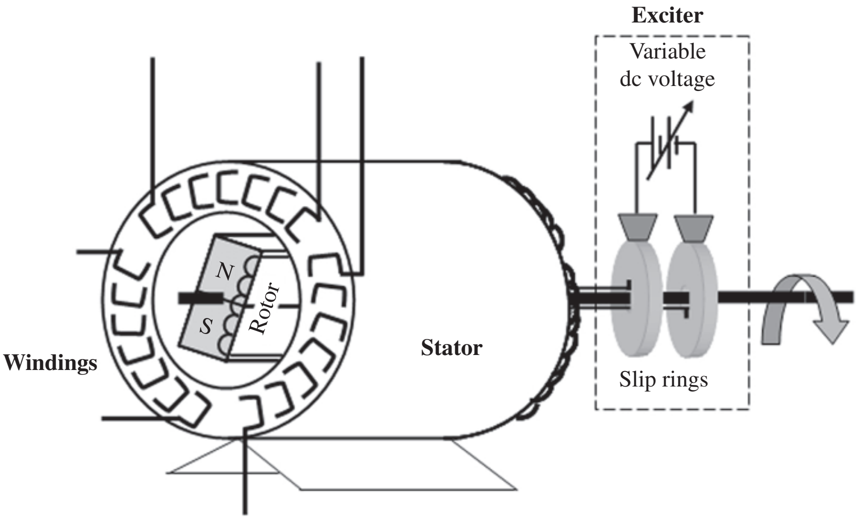


Figure 1-12 Three-phase voltage generator components.

AC Connections

There are two ways to connect three stator windings symmetrically. The two symmetrical connection configurations of a three-phase generator, motor, or transformer are called ***delta*** and ***wye***. Figure 1-13 shows these two connection types.

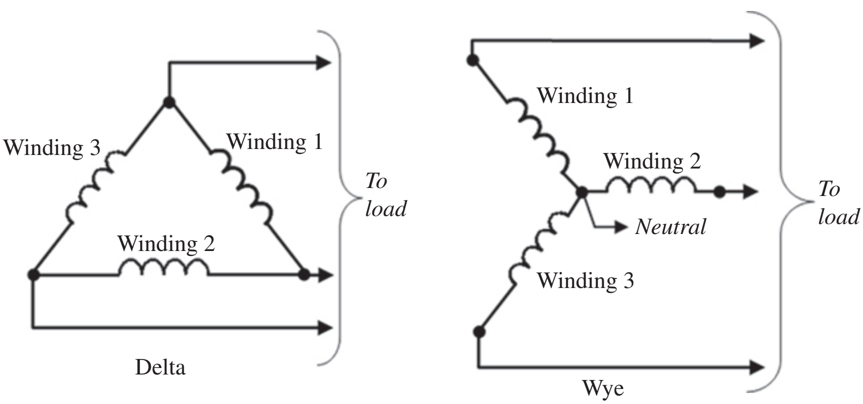


Figure 1-13 Delta and wye connections.

Delta

Delta configurations have all three windings connected in series as shown in Figure 1-13. The three generator terminal leads are connected to the three common points where windings are joined.

Wye

Wye configurations connect one lead from each winding to form a common connection point called "***neutral.***" The other three generator winding leads are brought out separately, creating a four-wire connection. The neutral is often "***grounded***" to the station ground grid for voltage reference, stability, and safety purposes. (Grounded neutrals are discussed later in more detail.)

Wye and Delta Stator Connections

Electric power plant generators use either wye or delta stator connections. The generator's output leads connect to the plant's ***step-up transformer*** (not shown yet). Step-up transformers are used to increase generator output voltage significantly (usually transmission voltage levels), to lower transmission line current for efficient transportation of electrical energy over long distances. (Step-up

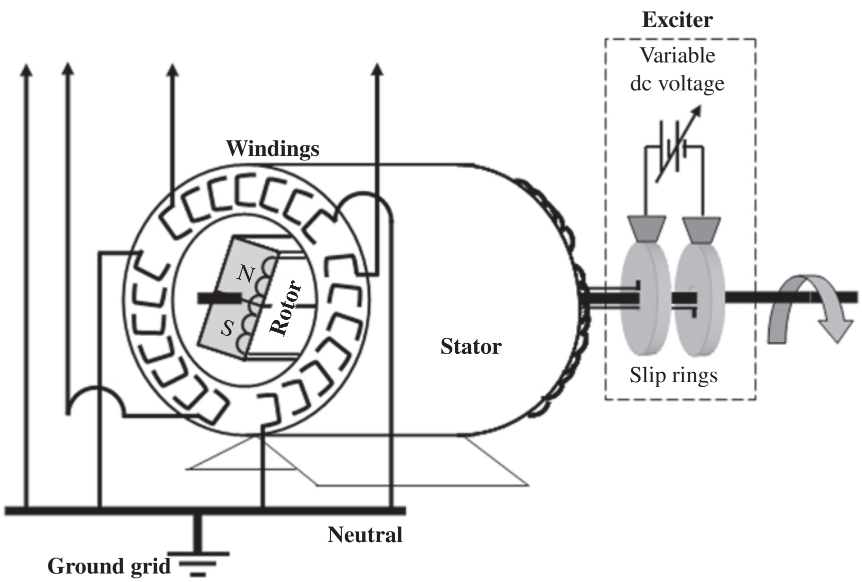


Figure 1-14 Wye-connected generator.

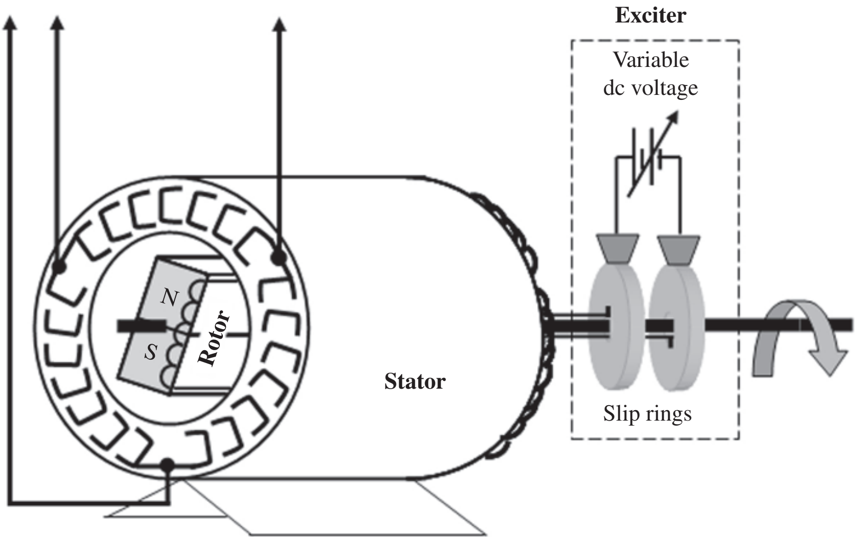


Figure 1-15 Delta-connected generator.

transformers are discussed later in Chapter 3, Substations.) Figures 1-14 and 1-15 show both wye and delta generator connections.

Three Types of Electrical Load

Electrical devices connected to power systems to perform work are referred to as ***load***. A toaster, refrigerator, bug zapper, lighting, and motors are all considered electrical load. There are three types of electrical load, categorized according to their ***leading, lagging, or in-phase*** relationship between voltage and current.

The three load types are ***resistive, inductive, and capacitive***. Each load type has specific characteristics, making them unique from each other. Understanding the differences between the three types of load helps explain how power systems can operate efficiently. Power system engineers, system operators, maintenance personnel, and others try to maximize system efficiency by applying good sense guidance founded by a good understanding of the various characteristics associated with each load type. They understand how load types can work together efficiently to reduce system losses, increase available capacity, and improve system reliability.

The three different load types, their standard units of measurement, respective symbols, and abbreviations are discussed below.

Figure 1-16 Resistive loads.

Figure 1-17 Inductive loads.

Resistive Load

Conductor resistance causes friction (heat) and reduces current flow if the applied voltage remains constant. By-products of electrical friction are heat and light. The unit of resistance is ***Ohm***, named after George Ohm, a German mathematician and physicist. The units of electrical power associated with resistive load are ***watts***. Examples of resistive load are shown in Figure 1-16; light bulbs, toasters, and electric hot water heaters, are all resistive loads. The identifying characteristic of resistive load is current that is ***in-phase*** with applied voltage (hence, the phase angle is zero).

Inductive Load

Inductive loads require a magnetic field to work. Examples of inductive loads are shown in Figure 1-17: hair dryers, fans, blenders, vacuum cleaners, drills, and many other motorized devices. All motors are inductive loads. The unique difference between inductive load, as compared to the other load types, is current ***lags*** applied voltage. Inductive loads take time to develop their magnetic fields when voltage is applied, thus current is delayed (lagging). The unit of inductance is ***henry***, named after Joseph Henry, a U.S. physicist.

Regarding electrical motors, load placed on their spinning shafts to perform work draws ***active*** power (i.e., watts) from the electrical energy source. In addition to active power, ***reactive*** power (i.e., Volts-Amps reactive (VARs)) is also drawn from the electrical energy source and used to produce the magnetic fields required of the motor. The ***total power*** consumed by a motor is the algebraic sum of both active and reactive powers (explained in more detail later). The units of electrical power associated with reactive power are called **VARs**.

Capacitive Load

A capacitor, see Figure 1-18, is a device made of two conductors separated by a ***dielectric*** (e.g., insulator). Dielectrics are insulating materials made of air, paper,

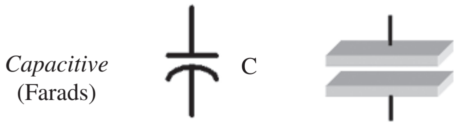


Figure 1-18 Capacitive loads.

glass, and other nonconductive materials. These dielectric materials become charged when voltage is applied to their attached conductors. Capacitors can remain charged long after the voltage source has been removed. Examples of capacitor loads are old TV picture tubes, long extension cords, discrete components used in electronic devices, bug zappers (two metal screens separated by air), and many other objects having two energized conductors separated by a dielectric.

Opposite to inductors, current associated with capacitors ***leads*** (instead of lags) the applied voltage. Time is needed for the dielectric material to charge up to full voltage from the charging current. Therefore, the current in a capacitor leads voltage. The unit of capacitance is called ***farad***, named after Michael Faraday, a British physicist.

Similar to inductors, power associated with capacitors is also called ***reactive power*** but opposite polarity to inductors (hence, −VARs). Inductive load requires positive reactive power (+VARs) to operate, and capacitive load requires negative reactive power (−VARs) to operate. Note, an inductor's positive VAR requirement can be fulfilled by a capacitor's negative VAR requirement, (i.e., cancellation), creating a combined net reactive power requirement.

A key point to understand regarding these reactive loads is *when the same amount of capacitive or leading VARs are added to a lagging VAR load, reactive power cancels fully, leaving total power being real power only!* Thus, peak current aligns with peak voltage. (How capacitors are used by utilities to help cancel inductive load to improve system efficiency is discussed in more detail later in Chapter 6, Consumption.)

Generally, capacitive loads are not items people purchase at the store in massive quantities like resistive and inductive loads. For this reason, power companies install capacitors on their systems to help cancel out reactive power requirements, thus reducing losses and improving efficiently. Power system demand is typically highly resistive and inductive. Capacitors are typically added to distribution feeders or installed in substations. (More on this later.)

Note that it is helpful to understand how these three load types (i.e., resistors, inductors, and capacitors) interact in power systems because their relationships influence system load, system losses, available equipment capacity, bottom line revenue, and reliability. Applications of these load types and associated power requirements are referenced throughout this book.