



THE LAWS THAT CONTROL AND EXPLAIN ELECTRICITY

This chapter will cover the dominate type of electrical power used in commercial and industrial facilities, alternating current (AC).

Electricity is the movement of electrons too small to be seen by the human eye; it cannot be heard with our ears, or smelled by the nose. Yet if it is touched, it can result in injury or death. The most basic and important facts about electricity have been covered. Now let us consider the rest of the electrical story.

A pressure in an electrical system called voltage causes the unseen electrons to move and is measured in units called volts. As the AC voltage and current is always changing in value, it was determined that if the peak AC voltage was multiplied by .707 it would be about the same as a DC (direct current) voltage. While a meter displays 120 volts AC, the peak voltage (PV) is about 169 volts AC.

$$\begin{aligned}PV \times .707 &= \text{RMS} & 169 \times .707 &= 120 \text{ volts} \\ \text{RMS} \times 1.414 &= PV\end{aligned}$$

The root mean square (RMS), and not the average, is used with a continuous time waveform such as an alternating current. Since AC voltage changes polarity either 50 or 60 times (called the *frequency*, or Hertz) each second, it would be impossible to read the meter's fast-moving display with it changing 50 or 60 times each second.

Buffers built into meters slow the speed at which the meter's display changes allowing it to be read. Better quality meters display RMS values.

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The quantity of those unseen electrons moving in an electrical circuit are measured in a unit called *amperes*, or amps, abbreviated with the letters A and I for current.

One ampere contains 6,250,000,000,000,000,000 electrons (or 6.242 times 10 to the 18th power). One volt is defined as the electromotive force (EMF) (pressure) that will move one ampere (quantity) of electrons through a resistance (opposition or friction measured in units of ohms) of one ohm. That is, one volt will move one amp of electrons through a resistance of one ohm.

The three main variables of interest are voltage, amperes, and resistance. Two units of work measurement are watts and horsepower. To obtain watts the voltage is multiplied times the current.

$$\text{Watts} = \text{Volts} \times \text{Amps} \text{ or } W = V \times A$$

Seven-hundred and forty-six watts are equal to one horsepower. Watts are measured in thousandths of watts (KW). Electrical power is sold by kilowatt-hours (KWH).

Electrical power systems have what is called a nominal voltage rating such as 120, 240, or 480. The actual voltage an electrical load (such as a motor) is supplied with may only be 118, or 223, or 456 volts. That is, electrical systems and components have a nominal, rated, and an actual operating voltage. For example, an electrical system would have a nominal voltage of 240 VAC, while a motor would be rated for 230 VAC, and the actual RMS voltage displayed by a voltmeter with the motor operating at the end of a wire, say, 1,000 feet long, may be 223 VAC.

The difference in the nominal voltage and the actual system voltage is mostly the result of pressure-voltage drop caused by the resistance of the wires of perhaps only 3 to 5 percent. Electrical systems are composed of at least one source, a protective device, a controlling device, path, and a load (such as an appliance) that does useful work. All of these components must be sized to safely do their job in an efficient manner.

Protective devices open the circuit when either the amperage or voltage deviates from normal. Insulated electrical wires provide the path for electron flow to the load. No power conversion and transmission system is 100 percent efficient; some amount of energy is lost. Most of

the energy lost in electrical circuits is converted to thermal energy, which heats up the electrical wires, switches, and loads in the system.

This heat does not provide any useful work. As the amperage (A), also called *current* (I), flow increases, the amount of thermal energy lost also increases. When a current flows over, through an electrical conductor, its temperature increases. Human eyes cannot see an effect of electrical energy flow, which is the magnetic force field, the lines of flux radiating from the electrical components wires, switches, and loads.

To keep the electrons flowing only over the correct path, it is necessary that they be electrically insulated with material(s) that tend to keep the electrons on the wire (the path). A perfect electrical conductor or insulator does not exist; all types offer some amount of resistance, and all insulating materials leak some small amount of electrons.

Conductors have low resistances, and insulators offer high resistance to electron flow. While conductors move electrons and insulators tend to keep the electrons on the correct path, the magnetic field still radiates from a conductor even with the best electrical insulation. While we cannot see this magnetic field with our eyes, test instruments have been developed to measure it.

A clamp-on ammeter (or amp-meter) is placed around a single wire to measure the strength of the magnetic field and display its intensity in units of amps. A voltmeter's test leads can be touched to uninsulated electrical parts and display the electrical pressure in volts. The resistance to the flow of electrons is measured in units called ohms (shown using the Greek letter omega, Ω). Additional details about test instruments are provided in Chapter 15, Electrical Test Instruments. In summation, while electricity cannot be seen, heard, or smelled, its variables, voltage, current, and resistance can be measured using electrical test instruments.

POWER FACTOR

The term “power factor” (PF) is an expression of the relationship of the peak voltage to the peak current. Stated differently, power factor is an expression of how far out of phase the voltage and current are to each other. Figure 1–1 shows both voltage and current peaks occurring at the same time in a circuit that has a PF of one.

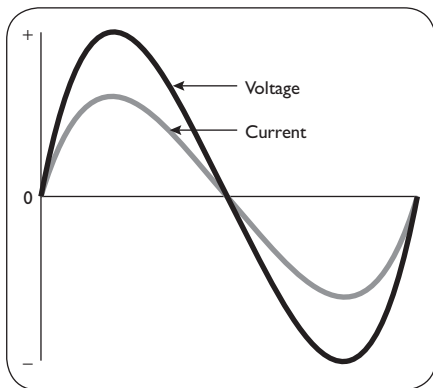


Figure 1-1 Resistive Circuit

When the voltage and current values peak at the same time, the power factor is one. When they do not, the power factor is less than one.

Many facilities have a lagging power factor of around 0.87. When the voltage changes, the current flowing in the system also changes, and the electrical system reacts to this change by creating a kind of resistance called *reactance* (X). Figure 1-2 shows the voltage and current peaks out of phase with each other. The voltage lags the current peak.

The two types of reactance are inductive reactance (X_L) and capacitive reactance (X_C). Their effect upon the power factor of a circuit is opposite to one another. Inductive reactance results in a lagging power factor. Most commercial and industrial facilities have a lagging power factor. Inductive reactance moves current flow after the flow of voltage, and capacitance moves the flow of current ahead of the flow of the voltage.

When a circuit has only resistor-type loads, such as an electrical space heater without a fan motor, the power factor of the circuit is one. When the circuit has only inductor-type loads, such as transformers and motors, the current flow peaks after the voltage peaks. That is, the system has a lagging power factor.

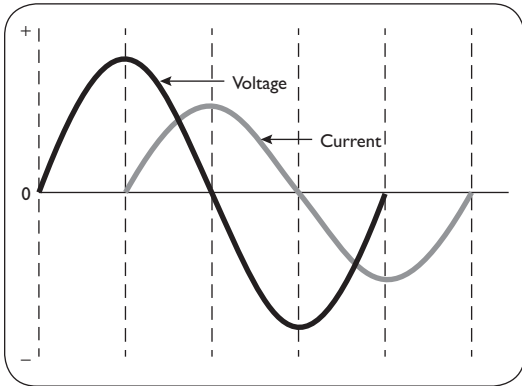


Figure 1-2 Reactive Circuit

When the circuit has only capacitors, the current flow moves ahead of the flow of the voltage, resulting in the system having a leading power factor. Figure 1-3 shows the current peak lagging behind the voltage peak in a capacitive circuit.

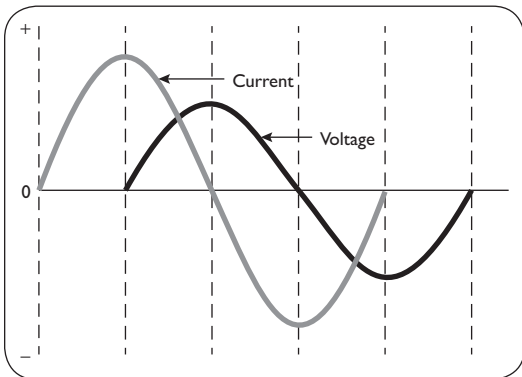


Figure 1-3 Capacitive Circuit

The amount of inductive and capacitive reactance varies from system to system. Typically a facility will have a mixture of resistance-, capacitance-, or inductive-type of loads referred to as *impedance*.

While all electrical systems (like all the roads in a town) and the smaller parts, called feeder and branch circuits (side streets), have some amount of capacitance, it is primarily the amount of inductive reactance in the circuit that determines the system's power factor.

It is possible to mix the correct amount of capacitors with the correct amount of inductors so that the circuits' power factor is one. When the facility's load has a power factor of less than one, the electrical utility must generate, transmit, and distribute more power than is used by the facility.

Facilities pull or demand two types of power from the supply, but only one does useful work. Total power is composed of true power (that does useful work) and reactive, or apparent, power (that does not do useful work—produces only heat). Clamp-on amp-meters do not measure true power, but rather they measure apparent power.

To determine the total power or true power, the installed system's power factor must be included. The result of nonproductive reactive power is that current carrying components (conductors and switchgear) must be sized larger to carry both true and reactive power.

Most of the time the primary variables of voltage, (E for AC, and V for DC) amperage (abbreviated as either A or I), and the resistance (R or Ω) are the ones that affect the operation of electrical systems and equipment.

Figure 1-4, Ohm's Law Wheel, lists all 12 of the variations of Ohm's law.

The main law, known as Ohm's law, is E (AC system) = $I \times Z$. Where E is volts, I is current, and Z = impedance, R = resistance ($X_c + X_L$).

Worked examples of the laws that govern some aspects of the operation of electrical systems are found in Chapter 19, Reference Material.

THREE-PHASE POWER

Two wires are required for electrical power to flow in a circuit. One to pass power from the source of supply, over the path, through the protection, control, and to the load, and back to the source of supply. By changing

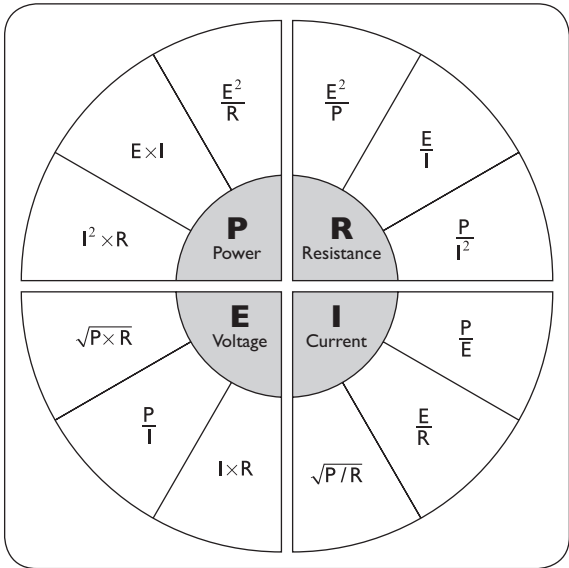


Figure 1-4 Ohm's Law Wheel

the system (starting inside of the generator), and adding one more coil of wire, the power provided can be increased by about 73 percent.

That is, by using three pulses of electrical power, each 120 electrical degrees out of phase, the amount of power produced can be increased by 73 percent. That is why most of the heavy work is done using three-phase electrical power systems. Visualizing a bicycle with three people pushing on three individual sets of peddles can be likened to the idea of a three-phase generator. Each rider provides a pulse of power (voltage) that peaks at separate times. This system produces a much smoother flow of electrical power to the loads, resulting in more power.

Adding one more wire will not magically produce a three-phase power source. The entire system must be changed, starting at the generator (the utility company's generators are about the size of a school bus) and moving all the way to the electrical load(s).

Chapter 2, *Power Generation and Distribution Within Commercial and Industrial Facilities*, provides more details about electrical power systems.

Most electrical wires used in buildings are made using stranded annealed electrical grade copper. In the United States, wire sizes are measured in units known as American Wire gauge (AWG). With this unit of measurement, the smaller the wire, the larger the number.

A #18 AWG is about 0.136 inches in diameter and a #1 AWG is about 0.582 inches in diameter.

The capacity of electrical conductors is stated in terms of its ampacity. *Ampacity* is the maximum continuous current that a conductor can carry without exceeding its temperature rating. Most conductors are rated for safe operation at either 140, 167, or 194 °F.

The farther electrons must be pushed over a wire, the more resistance they must overcome. This resistance (like friction in a water pipe produces a pressure drop) in electrical circuits causes a voltage drop. To reduce electrical resistance, a larger wire can be used. A longer or smaller wire will increase the voltage drop in the circuit.

Electrical conductors installed in buildings must be protected from physical damage. This is accomplished by installing them in protective envelopes called conduits, raceways, wireways, gutters, and enclosures. These envelopes are made of metal, PVC, fiberglass, aluminum, and HDPE plastic. Some are rigid, while others can be easily bent by hand.

As heat is generated when power is flowing in an electrical circuit, this heat must be transferred to the surrounding area to keep the conductors from overheating. There are several factors that cause a conductor's ampacity to be reduced, or derated. These are found in various tables in the *National Electrical Code* (NEC).

Materials such as air, paper, cotton, glass, rubber, and plastics are used as electrical insulators. Normal ambient air is commonly used as an electrical insulator. Each type of insulator is provided with a voltage rating for a specific thickness.

CIRCUIT PROTECTIVE DEVICES

Two types of overcurrent protective devices are fuses and black plastic-cased automatic switches called Molded Case Circuit Breakers (MCCB). These protective devices are designed to primarily protect insulating materials from overheating.

MCCB have two types of sensing elements, one that operates to clear running overloads, and one to clear dangerous short circuits. The overload element, called a *thermal element*, adds an amount of time delay before opening the protected circuit. The element that protects against short circuits and acts without any intentional delay is called the *magnetic element*.

When an MCCB has opened (or “tripped”) to protect the circuit, it can be physically reset immediately. This allows it to be ready to protect the circuit again should the need arise.

The thermal element in an MCCB has a varying amount of time delay built into it by design. This element is typically two pieces of very thin metal bonded together. Each metal has a different expansion and contraction rate. When bonded together, with the least expansive metal (invar) on the inside, the strip of metal will bend in an arc as it is heated and cooled. This bending action allows it to be used as a trip lever to open the circuit if an overload condition is sensed by the MCCB.

Fuses are another kind of circuit protective device. When the current flowing in the circuit creates sufficient heat, the fuse element will melt. When this occurs an electrical arc will develop, accelerating the melting of the link. It is the combination of melting of the link and stretching of the electrical arc that opens the electrical circuit. Additional details about circuit protective devices are provided in Chapter 6, Personnel Protective Devices.

To improve safety many rules in the National Electrical Code (NEC, copyright © NFPA) in the United States and the International Electro Technical Commission (IEC) (standard 6036) in Switzerland are followed in over 90 percent of the world.

