CHAPTER 1

ELECTRICITY—BASIC CONCEPTS

"I am an expert of electricity. My father occupied the chair of applied electricity at the state prison."
—W. C. Fields (first half of the twentieth century)

"It is the triumph of civilization that at last communities have obtained such a mastery over natural laws that they drive and control them. The winds, the water, ***electricity***, all aliens that in their wild form were dangerous, are now controlled by human will, and are made useful servants."
—Henry Ward Beecher (mid-nineteenth century)

"We've arranged a civilization in which most crucial elements profoundly depend on science and technology."
—Dr. Carl Sagan (second half of the twentieth century)

1.1 INTRODUCTION

Electrical power and its applications so completely pervade our lives that it is hard to imagine that a little over 100 years ago electricity in homes and businesses was a novelty about which architects did not have to concern themselves. As Carl Sagan's quote implies, today we are fully dependent on electrical power. It is not surprising that the architecture of a building can be significantly affected by the need to supply power to lights and appliances. Although the architect rarely designs the electrical system, space must be allocated to transformer vaults and electrical closets. When supplying power to an open-plan office, the architect must understand the options in power and communication distribution systems since they can have major aesthetic consequences. For example, using power poles in an open plan office may be efficient but not desirable from an aesthetic point of view.

Specifying appliances and lighting fixtures sometimes requires an understanding of electricity. For example, some lighting fixtures are available in both 277V and 120V versions, and some appliances are available in both 120V and 240V. On what basis does one choose? Some appliances have a poor power factor. What does that mean, and what are the consequences? Should the building use one-phase or three-phase power? What is the difference?

Since many fires are caused by electrical failures, understanding electricity is also important for the safety of buildings and their occupants. Electrocution, although rare, can be practically avoided by proper design and specifications. Understanding electricity provides the reader with personal safety as well. For example, electrical shock can usually be prevented by the use of a ground fault circuit interrupter. How does such a device function, and how should it be used?

And most important of all, buildings must become much more sustainable. Since buildings consume over 70 percent of all electricity in the United States, reducing the consumption of electricity by buildings is of the utmost importance.

Thus, for many reasons, it is important to have an understanding of the basic concepts of electricity.

1.2. HISTORY OF ELECTRICITY

Static electricity was known to and described by the ancient Greeks around 600 BCE. Electricity was rediscovered during the Scientific Revolution of the sixteenth and seventeenth centuries. Investigation into electricity began in earnest in the seventeenth century, and by the middle of the eighteenth century, with the increased knowledge of its properties, Benjamin Franklin concluded that lightning must be made of electricity, which he proved with his famous kite and key experiment in 1752 (Fig. 1.2a). It was not only luck that prevented him from being electrocuted as were some other experimenters. He knew enough about electricity to take certain precautions, such as standing in a dry, sheltered location while flying his kite in a thunderstorm. He also knew that some materials were conductors (his wet kite string) and insulators (a dry silk ribbon by which he held the key). His understanding of electricity allowed him to invent the lightning rod for the purpose of protecting buildings.

Fig. 1.2a Benjamin Franklin was internationally recognized for his research on electricity, and through his work, he invented the much needed lightning rod. Do not try his kite experiment at home! Other researchers trying this experiment died. Franklin took more precautions than this fanciful artwork shows. He was also lucky lightning did not strike his kite. *Source: Currier & Ives, Prints and Photographs Division of the Library of Congress.*

The science of electricity developed rapidly after Alessandro Volta invented the battery in 1792, and thereby made available a steady flow (current) of electricity. Thereafter, the discovery of the relationship between magnetism and electricity made the development of electric motors, generators, and transformers possible. Besides Volta, some of the other scientists whose names have been immortalized by their adoption for use as names for electrical units are: Andre *Ampere*, George *Ohm*, and Heinrich *Hertz*. Although much was known about electricity, its composition remained a mystery until the end of the nineteenth century, when it was discovered that electricity is a stream (current) of electrons flowing from negative to positive charges.

Thomas Edison put electricity to work. Until Edison perfected the electric lamp in 1879, all light sources came from open flames that created soot, heat, and often fire. Many had experimented with electric lighting, but Edison was the first to make it a practical reality. His creativity, versatility, and perseverance allowed him to succeed where many others had failed. To sell electric lamps, Edison had to also supply electricity, which required the invention of the electrical production and supply system. He opened his first direct-current central generating stations in both New York City (Fig. 1.2b) and London in 1882.

Of course, being an innovator, Edison also made mistakes. One of his biggest was to believe that direct current (dc) was better than alternating current (ac). Nicola Tesla, the great inventor and scientist, tried to convince Edison of the superiority of ac. Because he could not convince Edison, he sold his patents to George Westinghouse. Consequently, by the late nineteenth century, there were two competing electrical industries in the United States: Westinghouse for alternating current and Edison for direct current. To convince the public that his system was better, Edison claimed that dc was safer than ac because the electric chair used ac for executions. In reality, there is nothing inherently safer about dc.

The electric chair was developed in 1890 because it was considered more humane than hanging. However, it has now been almost completely replaced by lethal injection. In the electric chair, a high voltage (about 2,000 volts) is used to drive about 5 amperes of current through the body

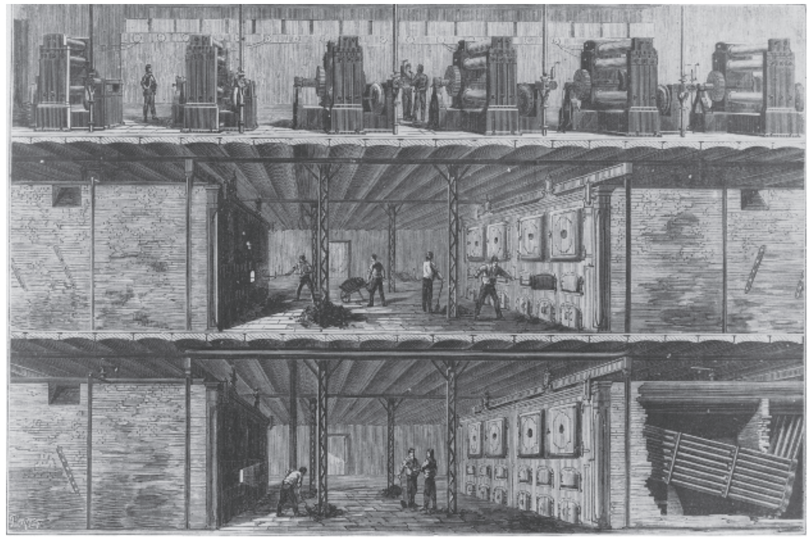


Fig. 1.2b This cut-away drawing shows Edison's 1882 Pearl Street Electric Power Station in New York City. The bottom two floors illustrate the coal-fired boilers, and the top floor shows a series of steam-engine-driven generators.
Source: U.S. Department of Interior, National Park Service, Edison National Historic Site.

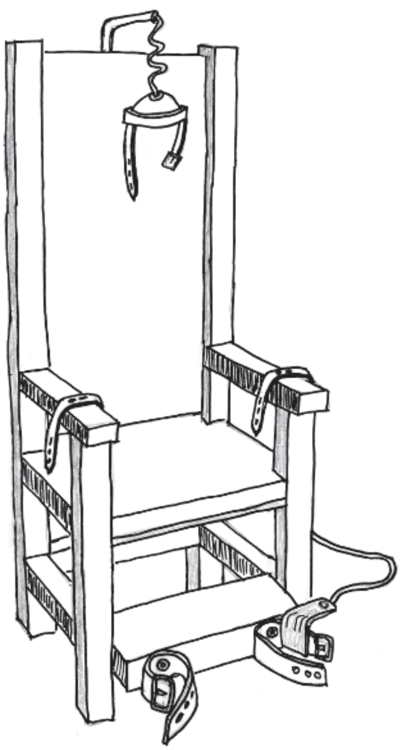


Fig. 1.2c The electric chair did not turn out to be as humane as its promoters believed. The intent of the skull cap was to direct electricity through the brain in order to destroy it first to eliminate pain.

(Fig. 1.2c). Metal head and leg bands are used to create a low resistance path through the whole body. Although most people die within a few minutes, some have survived more than 20 minutes. Electrocution is actually a high-tech version of burning someone at the stake. In the old days, people were burnt from outside in and now we can burn them from the inside out because **electric currents always generate heat**.

The reason that Edison was wrong in promoting dc over ac will become clear later.

1.3 THE WATER ANALOGY

Because water is similar to electricity in many ways, and because we all have a very good understanding of the behavior of water, it makes a great analogy for many aspects of electricity. The scientists who named some of the properties of electricity understood this when they used the word current to describe the flow of electrons. Since all analogies have limits, we will only use the water analogy where it is helpful.

When people built water wheels, they understood that they would get the most power if the water fell from a great height and there was a large flow (current). In Figure 1.3a, you can see that the pressure (potential) powering the water wheel is a function of the height from which the water falls. However, the power output of the water wheel is also a function of the amount of water falling on it. Similarly, the output of an electric motor is a function of the electrical pressure, called the electromotive force, imposed on it and the electric current flowing through it (Fig. 1.3b). Electrical pressure results from a difference of electrical charges. Electrons will flow from a negative charge to a positive charge, and the greater the difference in charges the greater the **electromotive force (E)** measured in **volts (V)***. The electrical **current (I)** is propelled

* In most cases the following terms are interchangeable: electromotive force, voltage, electrical potential, and potential difference. They are all measured in volts.

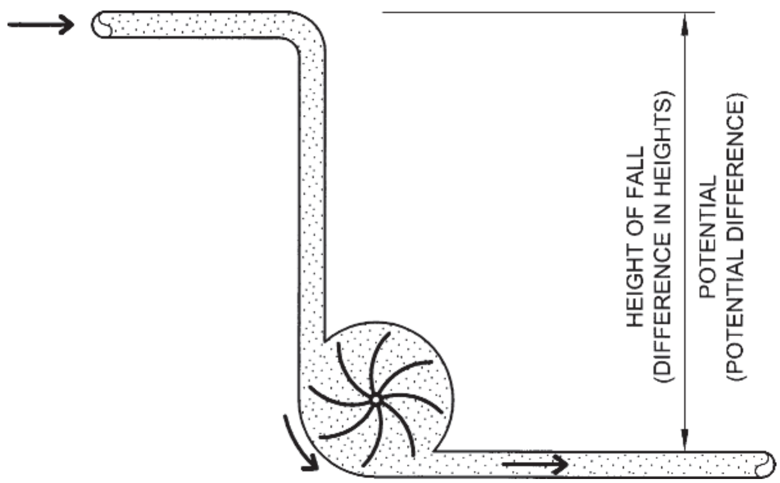


Fig. 1.3a The power output of the waterwheel is a function of the magnitude of the flow (current) and the difference in height, which creates the pressure.

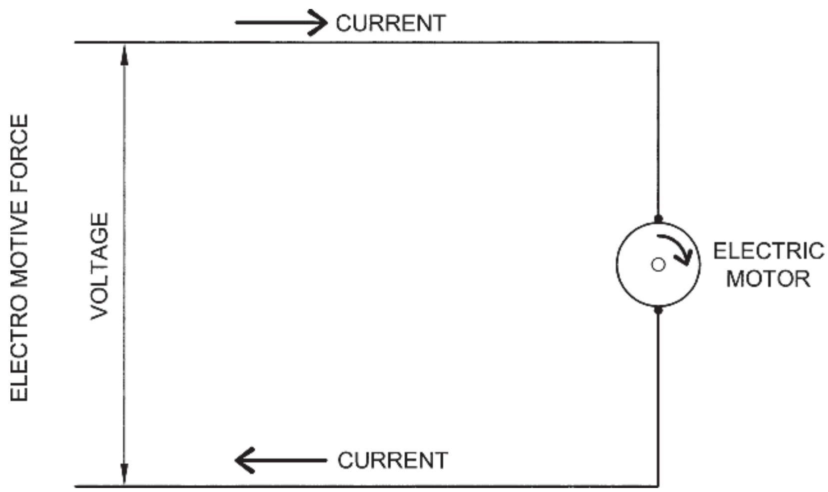


Fig. 1.3b The power output of the electric motor is a function of the magnitude of the electric current and the electromotive force (voltage).

by the voltage and its units are **amperes (amps or A)**. The electrical current is also impeded by the electrical **resistance (R)** measured in **ohms** (Ω) (see Table 1.3).

The flow of water in Fig. 1.3a is opposed not only by the resistance of the pipes but also by the resisting force as the waterwheel does work. Similarly, the current through a motor is opposed not only by the resistance of the wires in the motor but also by the resisting forces of the motor doing work. The first of these two properties that opposes the flow of electricity is called *electrical resistance* and will be discussed now. The second property that opposes the current is called inductive reactance and will be discussed later.

Just as the function of the water wheel system was to deliver **power**, so the function of an electrical circuit is also to deliver power (i.e., watts). Furthermore, as the power produced by a water wheel is a function of both height and flow, so too the power output of an electric circuit is a function of both the electromotive force (voltage) and current (amperes).

Table 1.3 The key properties of electricity (units are the same for S.I. and the American System)

Property	Symbol	Units
Electromotive force	E	volts (V)
Current	I	amperes (amps or A)
Resistance	R	ohms (Ω)

1.4 OHM'S LAW

The simple relationship between current, voltage, and resistance is called **Ohm's law**. It states that the current is directly proportional to the voltage and inversely proportional to the resistance as stated in the following formula:

$$I = \frac{E}{R}$$

where:
 I is the current measured in amperes (A)
 E is the electromotive force measured in volts (V)
 R is the resistance measured in ohms (Ω)

For example: What is the current flowing through an incandescent lamp that is rated 120 volts and 240 ohms?

$$I = \frac{E}{R} = \frac{120\,V}{240\Omega} = 0.5 \text{ amps} \quad \text{Answer}$$

1.5 TYPES OF ELECTRICITY

Static electricity, which is usually created by friction, creates very high voltages but, luckily, very low currents. Thus, when static electricity discharges, the resulting spark is extremely short lived and is harmless unless the tiny spark ignites a combustible gas.

On the other hand, in normal electricity, the voltage and current **are maintained over time**. In direct current (dc), the voltage and current remain constant over time (Fig. 1.5a), while in alternating current (ac), the voltage and current change rhythmically over time (Fig. 1.5b). The rhythm is a sine curve because that is the natural outcome from generating electricity with a rotating generator. In the United States, each complete cycle of the sine curve is 1/60 sec long. Consequently there will be 60 such **cycles per second (cps),** and we call that a frequency of 60 **hertz (Hz)**. Most of Europe and Asia, however, produce ac at a frequency of 50 Hz.

Almost all electricity used in buildings today is ac because it is so versatile. Its main virtue is that it can be easily changed from one voltage to another by means of a transformer. Nevertheless, there are still times when dc is required. The main application for dc in buildings today is for charging storage batteries for emergency power. This is similar to an automobile, where an alternator produces ac, but dc is needed to charge the battery that starts the engine. The ac is converted to pulsating dc by means of rectifiers or diodes, which are electrical devices that allow current to flow in only one direction (Fig. 1.5c).

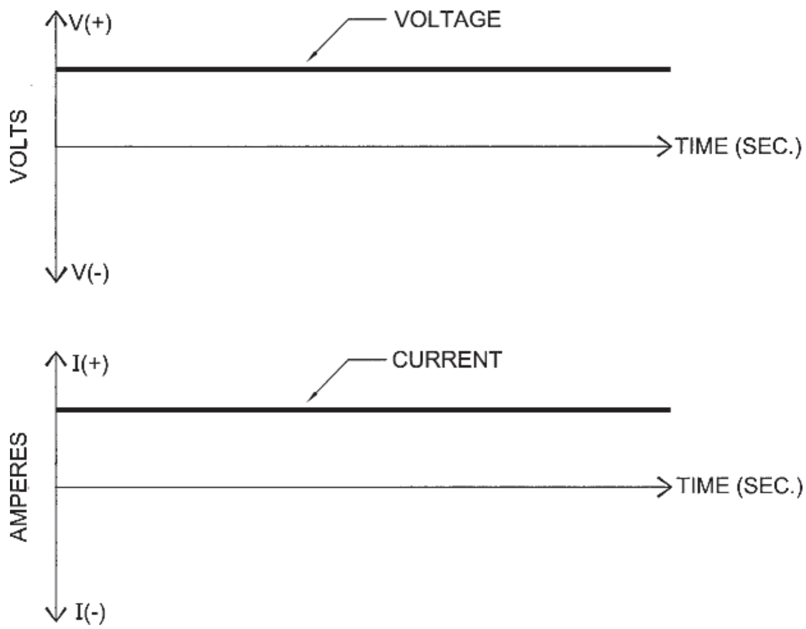


Fig. 1.5a These graphs show the voltage and current output from a battery. Because the voltage is constant and does not reverse (it stays above the horizontal axis), and since the current is driven by the voltage, it will likewise remain constant and will not reverse. Consequently, a battery produces direct current (dc).

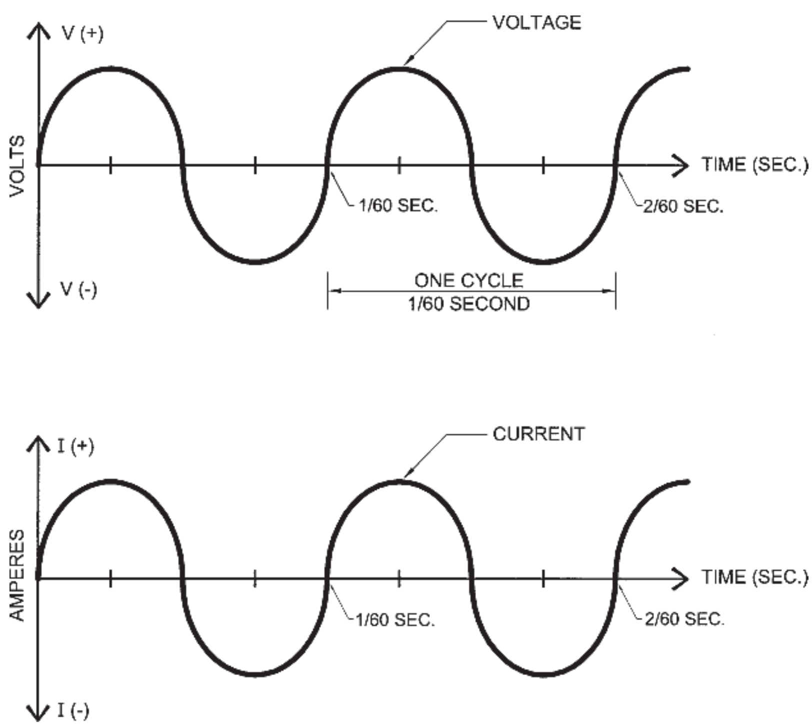


Fig. 1.5b These graphs illustrate the behavior of alternating current (ac). The voltage changes in magnitude and direction (top graph), and since the current is driven by the voltage, it follows the same pattern (bottom graph).

Because most electronic devices, such as computers, run on low-voltage dc, they have their own power supply, which converts the 120V ac line voltage to both dc and the required low voltage. In many electronic devices, the power supply is attached to the plug (Fig. 1.5d). Since electronic equipment, such as computers, are now a major electrical load in commercial buildings, there is increasing interest in providing low-voltage dc outlets along with 120V ac outlets. One of the benefits would be the elimination of all the wasteful power supplies that presently come with each electronic device. Another benefit would be the easy and efficient use

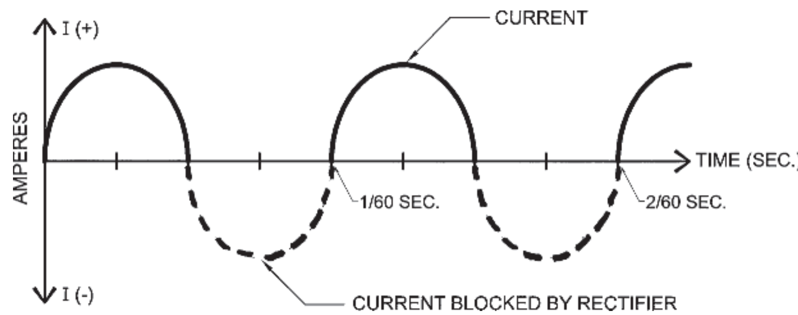


Fig. 1.5c Because direct current is needed to charge batteries, the output of a car alternator which is ac is rectified to create pulsating dc.

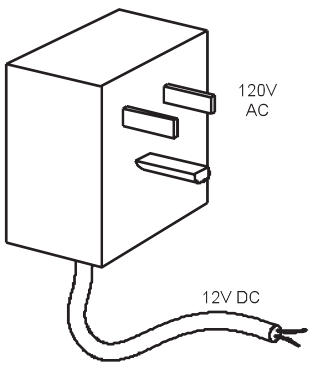


Fig. 1.5d Many electronic devices have their small power supply attached to the plug. The power supplies contain a step-down transformer and rectifier to create low-voltage dc.

of native power sources, such as solar, wind, fuel cells, and batteries, all of which supply dc. Converting these dc sources first into ac and then back into dc is a significant waste of money and energy.

It is important to understand some of the consequences of supplying ac electricity at 60 Hz. An electrical cycle can be described by time (e.g., 1/60 second per cycle or 1/120 second per half-cycle) or in degrees (e.g., 360° per cycle or 180° per half-cycle). In a normal ac cycle, the voltage varies from zero at the start to a positive maximum at 90°, to zero at 180° to a negative maximum at 270°, and back to zero at 360°, which is also the start of the next cycle (Fig. 1.5e top graph). Consequently, the voltage

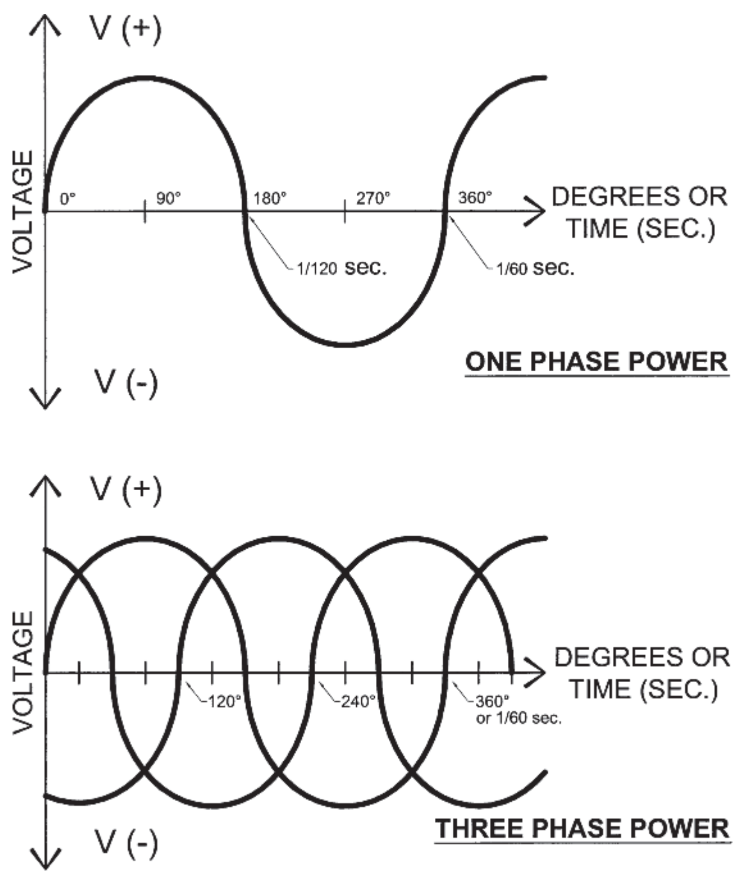


Fig. 1.5e In the normal electric service, which is also called one-phase power, there are two times each cycle when no power is delivered (see top graph). Three-phase power can deliver more power at the same voltage, because it consists of three separate ac currents that are 120° out of phase of each other. Consequently, there is never a time when current is not flowing through the motor.

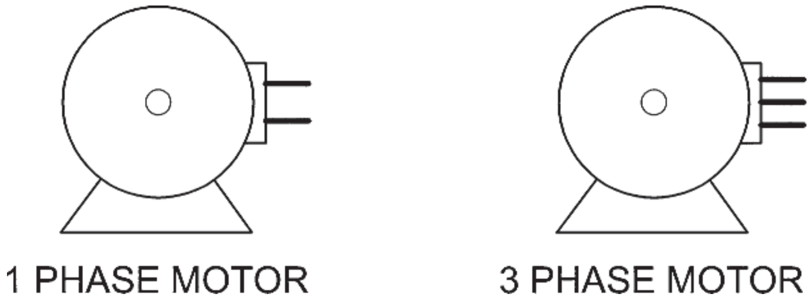


Fig. 1.5f Three-phase motors need to have three electrical connections, whereas a normal (one-phase) motor needs only a two-wire connection. Grounding wires are not included here and will be explained later.

is zero twice each cycle, or 120 times each second (i.e., 2 times 60 Hz). And, of course, if there is no voltage, there is no current, or power being transmitted. Thus, electric motors receive 120 electric pushes per second, and old-style fluorescent lamps flashed 120 times each second. It is no wonder that Thomas Edison was convinced that dc is more efficient than ac; however, the benefits of ac greatly outnumber the disadvantages.

The fact that in ordinary ac there is no current 120 times a second is in most cases not a problem. For example, our eyes see 120 flashes per second as a smooth continuous light. The ac pulses are only a problem for large motors that consume a lot of power. For such motors, three-phase power is available that consists of *three* separate ac currents 120° apart or, in other words, 120° out of phase (360° ÷ 3 = 120°) with each other. As can be seen in Fig. 1.5e (bottom graph), there is never a time when current is not flowing in at least two of the three phases. Three-phase motors are made differently from one-phase motors and the two types cannot be interchanged (Fig. 1.5f).

1.6 POWER FACTOR

The formula of Ohm's law (I = E/R) is only valid for circuits that supply power to devices that operate purely by electrical resistance (e.g., incandescent lamps and resistance heating elements). Almost all other electrical devices, such as motors and ballasts in lighting fixtures, use a magnetic field and are called inductors. These devices create an opposition to the flow of the current called inductive reactance, which together with the resistance is called **impedance (Z)**, also measured in ohms. Thus, in most ac circuits, Ohm's law states that the current is directly proportional to the voltage and inversely proportional to the impedance, as stated in the following formula:

$$I = \frac{E}{Z}$$

where
I = current (amps)
E = electromotive force (volts)
Z = impedance (ohms)

Because magnetic coils (inductors) throw the current out of phase with the voltage, the power in a circuit is reduced. The negative impact of this phenomenon is often described by the **power factor** (**PF**), which is a number between zero and one, where one is the ideal. The power factor

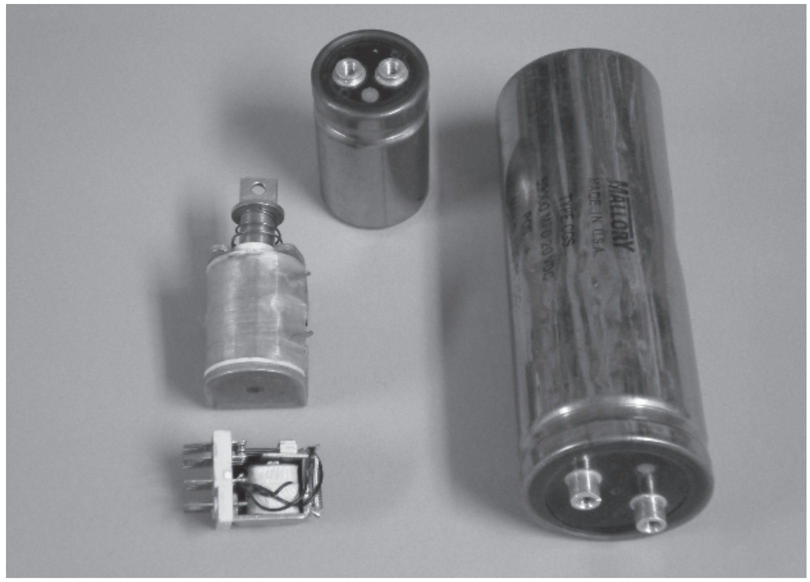


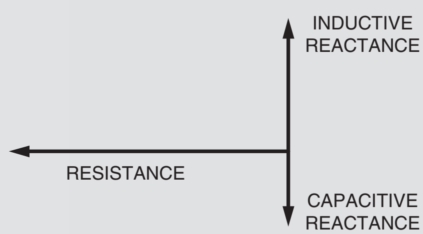
Fig. 1.6 Any electrical device (e.g., electric motor) that has a coil of wire will operate by creating a strong magnetic field. Electrical coils, which are also called inductors, throw the current out of phase with the voltage, which is a problem for both the consumer and the power company. Fortunately, by adding capacitors this problem can be corrected (a small and a large capacitor are shown top and right). In a relay (lower left), a magnetic coil in one circuit operates switches in another circuit. In a solenoid (middle left), a magnetic coil moves a plunger to operate some mechanical device such as in a washing machine as it goes through its different operations.

affects both the consumer and producer of electricity. Fortunately, electrical devices called capacitors (condensers) can correct this problem (Fig. 1.6). Consequently, many higher-quality electrical devices, such as motors and ballasts, have capacitors added at the factory to give them a high power factor. If too many electrical appliances are specified that have a low power factor, then the electric utility will apply a surcharge to the electric bill because it then has to spend money to correct the problem. The relationship between resistance, inductance, and capacitance is explained further in Sidebox 1.6.

SIDEBOX 1.6

Impedence

Impedance is the vector addition of resistance, inductive reactance, and capacitive reactance. The following vector diagram represents a particular motor that has a capacitor attached to it.



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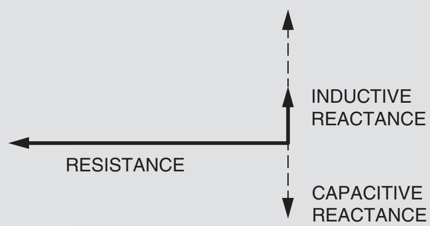
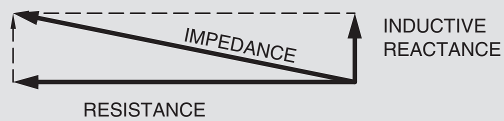
Since inductive and capacitive reactance are in line, they can be added algebraically. Thus, the resulting inductive reactance is smaller and the capacitive reactance is canceled out.



The impedance (Z) of the motor is then the resultant of the resistance and remaining inductive reactance.



Note that the impedance is larger than the resistance and not in line (i.e., out of phase) with the resistance (or current). Also note that without the capacitor the impedance would be both larger in magnitude and more out of phase. The ideal situation would be to use a larger capacitor so that the capacitive and inductive reactances would be equal but opposite. Then, the impedance would be the same as the resistance.

1.7 TYPES OF CIRCUITS

Electrical devices can be connected either in series or in parallel or both. To better understand the consequences of these arrangements, let us again use a water analogy. For example, in heavy equipment, hydraulic instead of electrical systems are often used to transmit power. One way to transmit power with water is shown in Fig. 1.7a.

If we wanted to power three hydraulic motors we could arrange them either in series (Fig. 1.7b) or in parallel (Fig. 1.7c). The power output of each of the motors in series will be much less than its normal rating for two related reasons: (1) each motor receives only 1/3 the pressure (potential), and (2) because the same water must flow through each motor and is resisted by each, the total water flowing down is also one-third of that in Fig. 1.7a.

With the help of the water analogy of a series circuit, let us look at an electrical series circuit, as shown in Fig. 1.7d. In series circuits, the total resistance is equal to the sum of all the resistances.

Or:

$$R_T = R_1 + R_2 + R_3 + \ldots$$

Thus, in a series circuit, the more resistances the greater the total resistance.

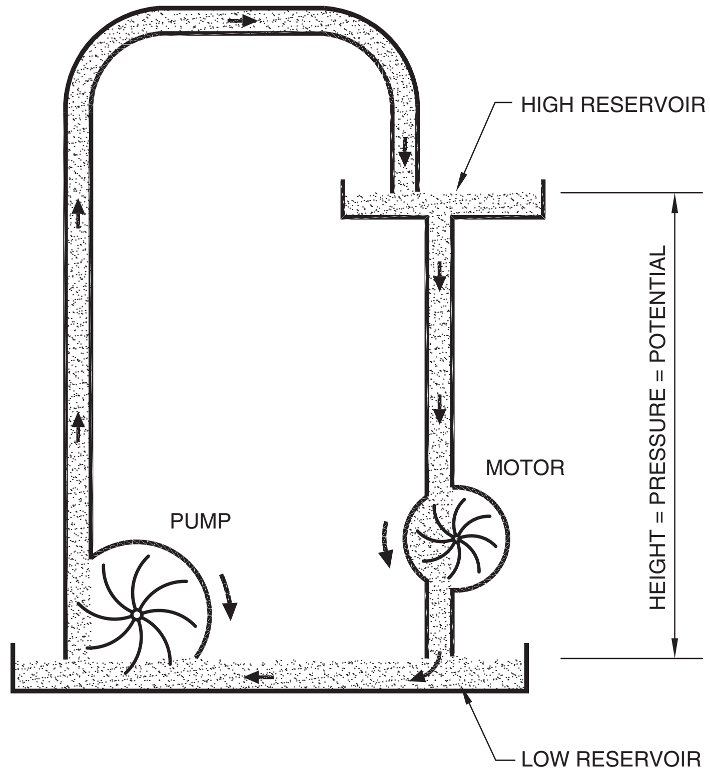


Fig. 1.7a In this water analogy for an electric circuit, a pump raises water from a low to a high reservoir—thus creating a pressure (potential) proportional to the height. As the water falls, it powers the hydraulic motor (turbine).

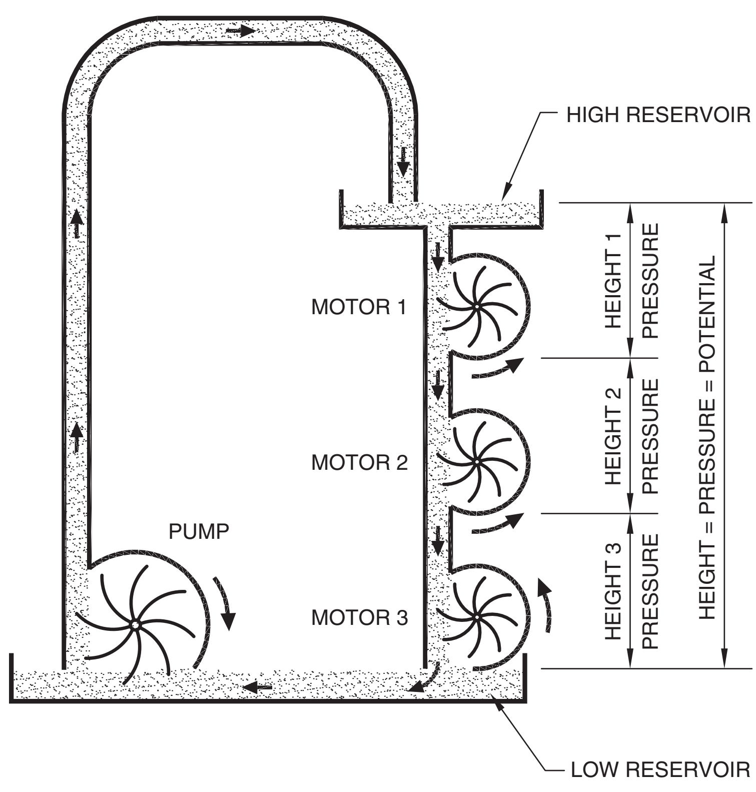


Fig. 1.7b Three motors of the type used in Fig 1.7a are now placed in series. Note that each motor operates at only one-third pressure and, therefore, delivers much less power.

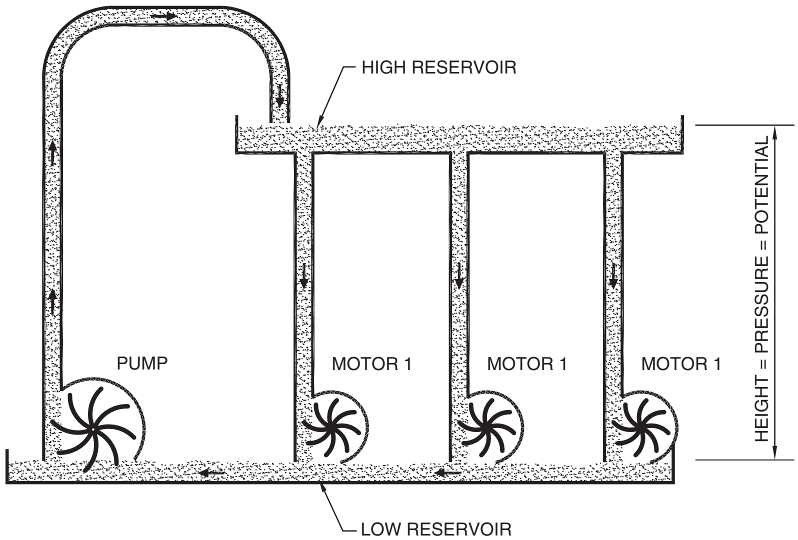


Fig. 1.7c The same three motors are now arranged in parallel. Note that each motor operates under full pressure and, therefore, delivers full power. Note also that the total water flowing in this system (circuit) is three times that in Fig. 1.7a.

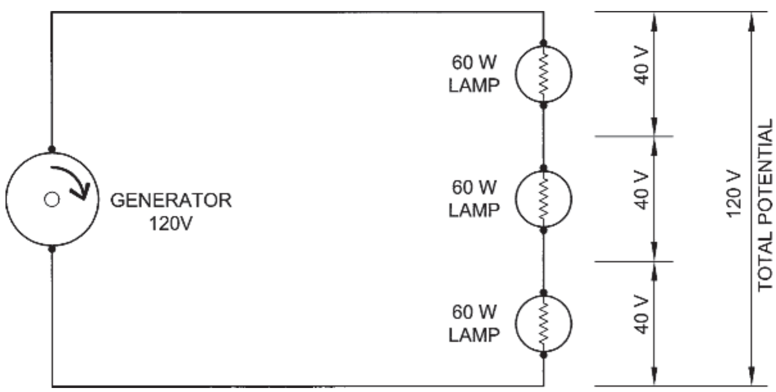


Fig. 1.7d Three 60W incandescent lamps are placed in series. Since the same electricity must go through all three lamps, if one burns out the others go out also. Furthermore, each lamp will barely glow because only 40v rather than the rated 120v are powering each lamp. For these reasons, electrical appliances and lights are never placed in series with each other (some older Christmas tree strings of lights being an exception).

EXAMPLE

Figure 1.7d shows an electrical circuit with three 60 W, 120V incandescent lamps in series. This is the same lamp used in Section 1.4. Since each lamp has a resistance of 240 Ω, what is the total resistance and current in this circuit?

Solution: In a series circuit, the formula for the total resistance is:

$$R_T = R_1 + R_2 + R_3 + \ldots$$
$$= 240\Omega + 240\Omega + 240\Omega$$
$$= 720\ \Omega\ \textit{Ans}.$$

The current can then be found with Ohm's law:

$$I = \frac{E}{R} = \frac{120V}{760\Omega} = \frac{1}{6}\ \text{A Answer}$$

Note that this is one-third of the current of the one-lamp example. In Sidebox 1.4 we found the current for one 60W lamp to be 0.5 amps or 3/6 amps. Thus, 1/6 vs. 3/6 is the same as 1 vs. 3.

The three lamps will only glow dimly because there is not enough current flowing through each of them.

EXAMPLE

Figure 1.7e shows a circuit with three 60 W, 120V incandescent lamps in parallel. If again the resistance of each one is 240Ω, what is the total resistance and total current in this parallel circuit?

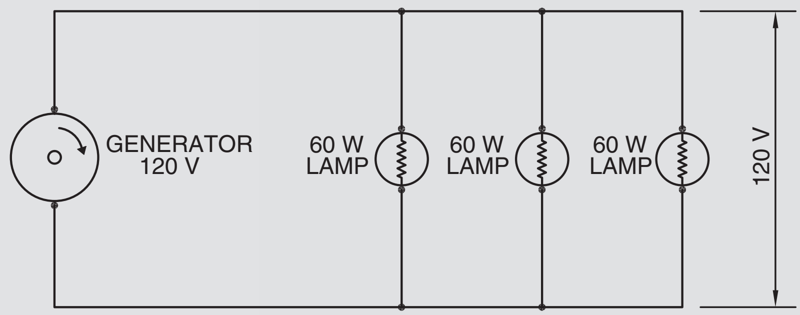


Fig. 1.7e Three 60 W incandescent lamps are placed in parallel. Note that if one lamp burns out, the others are not affected. Also, each lamp will glow at its proper intensity because each one is powered with the full 120V. All appliances and lights are placed in parallel for these reasons.

Solution: In a parallel circuit the formula for total resistance is:

$$\frac{1}{R_T} = \frac{1}{R_T} + \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

$$\frac{1}{R_T} = \frac{1}{240\Omega} + \frac{1}{240\Omega} + \frac{1}{240\Omega} + \ldots$$

$$\frac{1}{R_T} = \frac{3}{240} = \frac{1}{80}$$

$$R_T = 80\Omega \text{ Answer}$$

Note that the total resistance of this parallel circuit is only one-third of the resistance of a one lamp circuit.

$$\frac{80\Omega}{240\Omega} = \frac{1}{3}$$

The current can again be found by Ohm's law

$$I = \frac{E}{R} = \frac{120V}{80\Omega}$$

$$= 1.5 \text{ Answer}$$

As expected, the three lamps in parallel draw three times the total current of the one-lamp example described in Section 1.4 (i.e., 1.5 amps versus 0.5 amps).
Note that in a parallel circuit each lamp is properly lit, because each one receives its proper current (0.5 amps in this case).

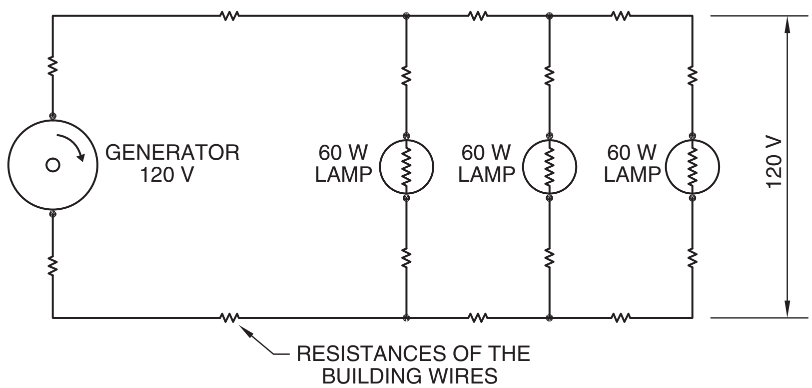


Fig. 1.7f Most real circuits are a combination of resistances in both parallel and series. The loads are always in parallel, but the wire resistances are always in series with the loads.

Let us again use a water analogy but this time to understand parallel circuits. If three hydraulic motors are in parallel (see again Fig. 1.7c), each will have the same pressure applied to it and the total flow of water will be 3 times greater than if there were only one motor. Furthermore, the total resistance of the circuit is reduced every time another motor is added.

In buildings, all electrical appliances and lights are placed in parallel circuits, as shown in Figure 1.7e, so that they all receive the same voltage. In a parallel circuit, as shown in Figure 1.7e, the formula for the total resistance is:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

Consequently, in a parallel circuit the more resistances, the smaller is the total resistance.

Although almost all electrical appliances and lights are placed in parallel, it is important to understand series circuits because the resistances of the building wiring are in series with its electrical devices (Fig. 1.7f). This situation creates a problem called voltage drop, which will be discussed later.

1.8 POWER GENERATORS IN SERIES AND PARALLEL

Just as devices that use electricity can be placed in series or parallel circuits, so can the electric power producers such as generators, batteries, fuel cells, and photovoltaics (PV). The generators of the national power grid are in parallel, whereas in flashlights we usually have two or three batteries in series. If the power producers are placed in series, their voltages are added (Fig. 1.8a), and if they are placed in parallel, their currents (amperes) are added. To get the required voltage and current, a combination of series and parallel circuits is often used (Fig. 1.8b).

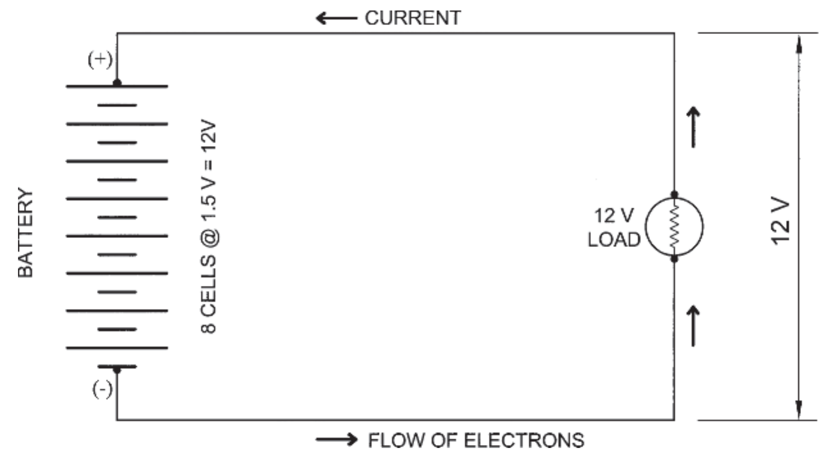


Fig. 1.8a When power producers like these cells in a battery are placed in series, their voltages are added.

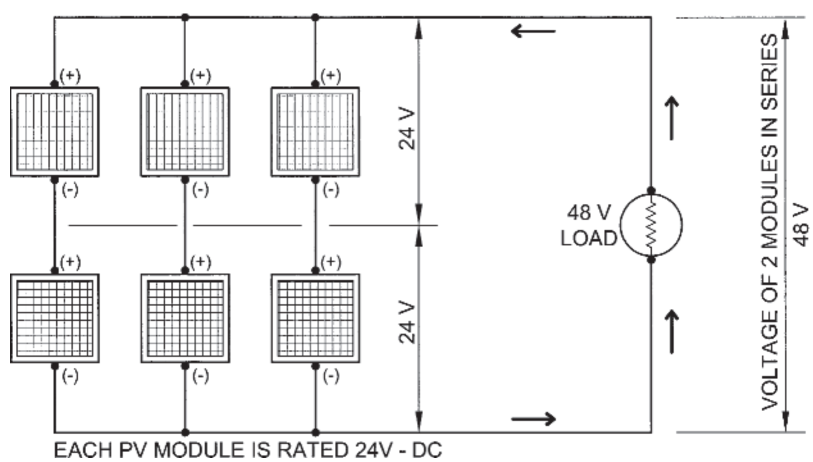


Fig. 1.8b To get the desired voltage, the photovoltaic modules are connected in series, and to get the desired current, the modules are connected in parallel. Thus, for example, to power a pump that operates at 48V with panels rated at 24V, two panels would be placed in series. To provide the current needed by the pump, as many sets of two panels in series would be added as necessary. As shown in this figure, the total current would be three times as large as that provided by two panels in series.

1.9 VOLTAGE DROP

To understand voltage drop, it is useful to again use a water analogy. Figure 1.9a shows a decorative fountain with a water pump and a waterwheel. The pump raises the water from the lower reservoir to the higher reservoir (high potential), and as the water drops to the lower reservoir, it loses all capacity to do work in this fountain. Note that some pressure is lost before and after the waterfall, which powers the waterwheel. The more pressure lost in these regions, the less is left to do work at the waterwheel. Similarly, in an electrical circuit, such as the one in Fig. 1.9b, the total **voltage drop (VD)** of 120V occurs in three steps.

Although electrical appliances or lights are never placed in series, the resistance of the building wiring is always in series with the electrical devices. The magnitude of the resistance of the building wiring is a function of wire length, size, and metal type. Since the length of building wire to each appliance or light varies, the voltage drop varies within a building. The voltage drop will be greatest for the most remote appliances or lights, since the resistance of the wire increases with its length.

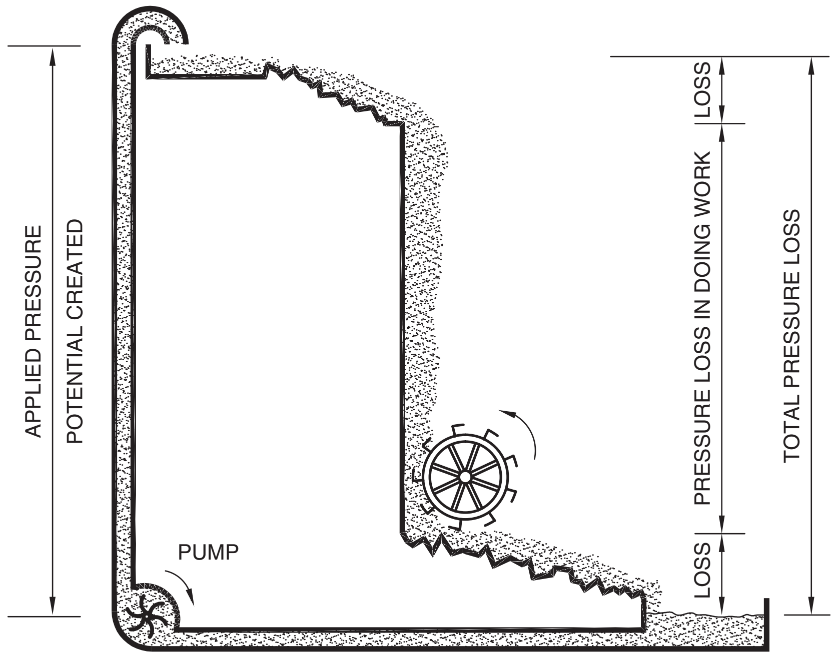


Fig. 1.9a In this water analogy of voltage drop, the pump creates the pressure necessary to lift the water to the top reservoir where it now has the potential to do work. However, all of this potential (pressure) will be lost as the water falls back to the bottom reservoir. Although the main potential (pressure) loss will occur at the falls with the water wheel, small amounts of pressure are lost in the rapids from the top reservoir to the top of the falls and again from the base of the falls to the bottom reservoir.

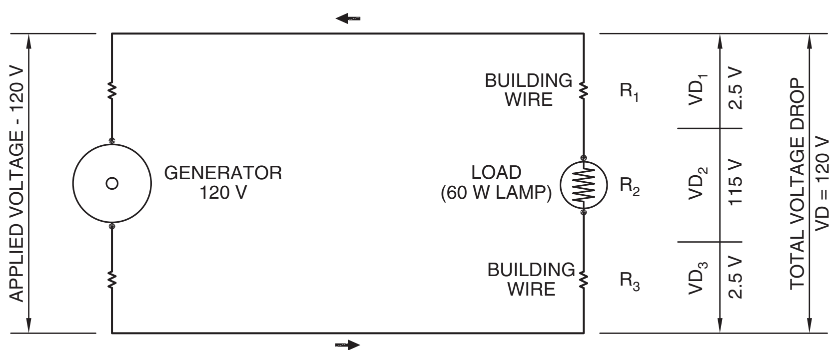


Fig. 1.9b Because the resistance of the building wiring is in series with the load, there will be a voltage drop across the wiring as well as across the load. The total voltage drop will always be equal to the applied voltage (e.g., 115V + 2.5V + 2.5V = 120V). In this example, the total voltage drop from the wiring is 5v, but in an actual case the voltage drop will vary with the location of the load in a building.

Since in an electrical circuit the voltage drops are proportional to the resistances, the main voltage drop occurs across the load and only small voltage drops occur in the building wiring. For example, in the United States the most common voltage supplied to a building by the power utility is 120V. In a large building, there will be hundreds of feet of wire between where the power enters and the location of the load. For a particular length and size of copper wiring, the voltage drop might be 2.5V, as in the example shown in Fig. 1.9b. Since the electricity must make a round trip, another 2.5V is lost. That leaves only 115V to power the appliance. It is for this reason that electrical devices are often rated at 115V even though they are meant to be used in 120V systems (see Sidebox 1.9).

In the next chapter, when we discuss wire sizing design, the voltage drop will be an important consideration. Voltage drop is also a problem when using long extension cords (i.e., over 50 ft.).

SIDEBOX 1.9

Calculating Voltage Drop (VD)

Voltage drop is calculated by using a variation of Ohm's law.

$$I = \frac{E}{R}$$

can be rewritten as E = I × R

Since the total voltage drop is always equal to the total applied electromotive force (voltage), or

$$VD = E$$

The formula E = I × R can become VD = I × R
where VD is voltage drop in volts (V)
E is applied electromotive force in volts (V)
I is current in amperes (A)
R is resistance in ohms (Ω)

Example:

What is the voltage drop across the building wire if the current is 0.5 amps, and the resistance of the wire (one way) is 5 ohms (see Fig. 1.9b).

Solution: V.D. = I × R = 0.5A x 5Ω = 2.5V one way

Thus, 2.5 volts are lost each way, and the total voltage drop in the wiring is 2 (2.5) = 5V Answer

1.10 ELECTRICAL POWER

In physics, power is defined as the rate at which energy is supplied or used:

$$\text{Power} = \frac{\text{Energy}}{\text{Time}}$$

In electricity, the unit of power is called the **watt** (W). Since a watt is a small amount of power and because we use large amounts of power, we usually talk about kilowatts, where:

1 kilowatt (1 kW) = 1,000 watts
1 megawatt = 1,000,000 watts
1 gigawatt = 1,000,000,000 watts

Because watts are a direct function of both voltage and current, the formula is:

$$W = E \times I$$

where:
W is watts (W)
E is electromotive force (V)
I is current (A)

EXAMPLE

What is the wattage consumed by the lamp in Fig. 1.9b, if the current flowing through the lamp is 0.5 amps? Also, what are the total watts consumed by the circuit?

Solution: Because of the 5V voltage drop in that particular circuit, there are only 115V across the lamp. Thus,

$$W_{lamp} = E \times I = 115V \times 0.5A = 57.5W \text{ Answer}$$

The wattage consumed by the wire is:

$$W_{wire} = E \times I = 5V \times 0.5A = 2.5W$$

And the total wattage consumed by the circuit is:

$$W_{total} = 57.5\text{ W} + 2.5\text{ W} = 60\text{ W Answer}$$

The 2.5W consumed by the building wiring was turned into heat. When the load is large, the wires can get quite warm. This problem is potentially dangerous when an extension cord designed for small loads is used for large loads. The excessively high load could cause the extension cord to overheat.

Electric utilities must plan and design their systems so that they can meet the maximum power (wattage) demand; otherwise, brownouts and blackouts will occur. A building's impact on the utility is the result of both its maximum power requirement, also known as **maximum demand**, and the amount of electrical energy required. This important point will be explained in more detail later in this chapter after a discussion of electrical energy.

1.11 ELECTRICAL ENERGY

In electricity, the unit of energy is defined in terms of the unit of power, the watt. Since power is defined as:

$$\text{Power} = \frac{\text{Energy}}{\text{Time}}$$

$$\text{Energy} = \text{Power} \times \text{Time}$$

and

$$\text{Electrical energy} = \text{Watts} \times \text{hours} = \text{Wh}$$

Because the Wh is a small unit of energy and because we use so much of it, we generally measure electrical energy in kilowatt-hours.

$$1{,}000 \text{ Wh} = 1 \text{ kWh}$$

The amount of **electrical energy (kWh)** used by a building mainly affects the amount of fuel the utility must burn. As we said before, however, the size of the power plant and the capacity of the distribution system are determined not by the energy used but by the combined maximum power demand (kW) of all the power users.

1.12 PAYING FOR ELECTRICITY

Electrical power is consumed in a very uneven pattern. The least power is consumed in the middle of the night when most people are sleeping. The time of maximum power demand depends on building type and climate. In most of the United States, the maximum demand on the utility occurs on a hot summer afternoon. In Figure 1.12a, we see the power demand of a typical office building on a hot summer day. The power demand usually peaks during the late afternoon when all the loads coincide: all the lights, computers, and other electrical appliances are on; all the people are giving off heat; and when the greatest cooling load occurs because of high outdoor temperatures and a low sun shining right into west windows.

As mentioned previously, the power company must invest large sums of money to build enough equipment (capacity) to meet the maximum demand. It is, therefore, reasonable that electric consumers should pay according to their maximum demand (kW). It is also reasonable that consumers should pay according to their energy use (kWh) because energy use determines how much fuel the utility must purchase. Consequently, the electric bills of large consumers of electricity are determined by both their energy use (kWh) and their maximum power demand (kW). Small users of electricity, such as residential customers, pay only for the energy use (kWh) for the sake of simplicity. Since their use pattern is fairly predictable, the power company can factor the demand cost into the energy bill. The meters are different for small and large users of electricity (Fig. 1.12b).

For a small user, the cost of electricity is equal to the amount of electrical energy consumed (kWh) multiplied by the price of a unit of electrical energy (\$/kWh).

Or

$$\text{cost} = \text{kWh} \times \frac{\$}{\text{kWh}}$$

Large users, whose maximum power demand is a high spike, as in Figure 1.12a, will pay a large-demand surcharge. For example, if the monthly bill for electrical energy is $10,000, there could be a $40,000 surcharge for the spike in power. For this reason, building owners and users have a great incentive to reduce the size of their maximum power demand. There are many ways to do that and some of those will be discussed next.

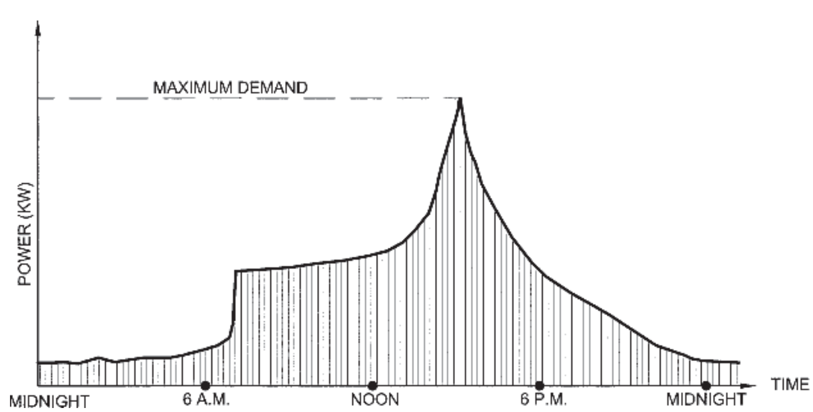


Fig. 1.12a This is a graph of the power demand curve (kW) for a typical office building in the summer. The maximum demand usually occurs in the late afternoon on a hot sunny day when everybody is working and the cooling load is at a maximum. The area under the curve represents the energy used (kWh).

EXAMPLE 1

What is the cost of the electricity for a residence, if the meter shows that 800 kWh of electricity were used in one month and the price is \$0.10 per kWh?

Solution:

$$\text{cost} = \text{kWh} \times \frac{\$}{\text{kWh}}$$
$$= 800\,(\text{kWh}) \times \frac{\$0.10}{\text{kWh}}$$
$$= \$80 \text{ Answer}$$

EXAMPLE 2

How much does it cost to have a 60 w lamp burning continuously for one month (30 days) if the price for electricity is \$0.10 per kWh?
Since 1 kW = 1000W, the lamp wattage in kW is 60 /1000 = 0.06 kW
And since the number of hours per month are:

$$h = (24) \times (30) = 720$$

The energy consumed is:

$$\text{energy} = \text{kW} \times \text{h}$$
$$= (0.06 \text{ kW}) \times (720 \text{ h}) = 43.2 \text{ kWh}$$

And since the cost of electricity is \$0.10 per kWh,

$$\text{Cost} = \text{kWh} \times \$/\text{kWh} = (43.2 \text{ kWh}) \times (\$0.10/\text{kWh})$$
$$= \$4.32 \text{ Answer}$$

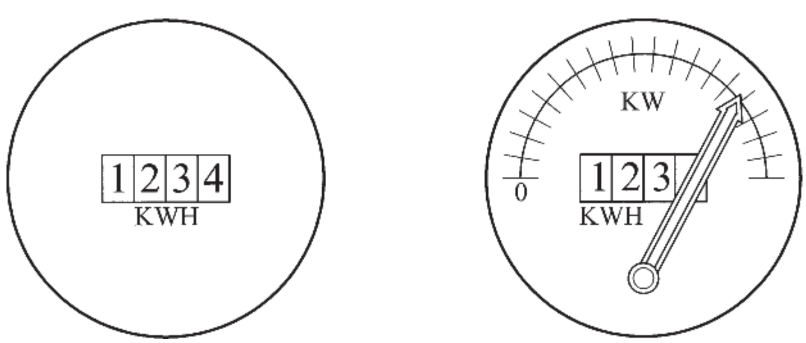


Fig. 1.12b Meters for small users of electricity only measure electrical energy (kWh) use, while the meters for large users measure both the energy (kWh) use and the maximum power demand (kW).

1.13 REDUCTION IN MAXIMUM DEMAND

There are three major approaches to reducing maximum demand of electricity: (A) use less electricity through efficiency, (B) shift the use of power to a time of day when there is less demand, and (C) produce on-site power. The following three lists provide examples of strategies for reducing maximum demand by each of these three approaches. As you read the lists, keep in mind that for most of the United States the maximum power demand occurs in summer on a hot *sunny* afternoon.

(A) Reduce maximum demand through efficiency by means of:

- High levels of insulation in walls and roofs and high performance windows (low-e)
- Shading devices on all windows
- Efficient lighting systems
- High-efficiency electrical appliances (HVAC equipment, computers, etc.)
- Daylighting to reduce or eliminate the need for electric lighting during the day
- Heat recovery devices to save on cooling load (or heating load in winter) because of ventilation requirements
- And many more

(B) Reduce maximum demand by shifting load by means of:

- Massive exterior walls and roofs to create a time lag
- Massive building materials that will act as a heat sink for cooling and as a heat storage device for heating
- Running air conditioning equipment during the night, when electricity is very cheap, to create chilled water or ice used for cooling the next day
- Heating water only at night and storing it for use during the next day
- Operating appliances during off-peak times (e.g., dishwashers and clothes washers would not be used during afternoons and evenings)
- Giving the utility control over the air conditioning by means of remote switching. As a result, during times of maximum demand, the utility can remotely turn off the air conditioning for a maximum of 15 minutes per hour in each participating building. Thus, by rotation among its consumers, the utility can reduce its peak demand. In return, the utility will charge the participating consumers a lower rate for its electricity.
- Using a building energy management system that can turn off noncritical electrical appliances when a high power demand is sensed

(C) Reduce Max Demand by producing electricity on site by means of:

- Photovoltaics (PV) to generate electricity when the demand is greatest (i.e., a *sunny* summer afternoon). This is exactly the time when the PV will have its greatest output.
- Fuel cells to efficiently produce electricity from natural gas
- Engine-driven generators in combined heat and power (CHP) systems, also known as cogeneration systems. These systems not only reduce or eliminate the power demand on the utility, but also provide free hot water because the normally wasted heat in the production of electricity can be utilized. Where much hot water is required, these systems are very efficient and cost-effective.
- Wind turbines where there is sufficient wind at peak demand times

Most of the techniques mentioned for reducing maximum demand also reduce the total energy required and thereby save even more money and also help the environment.

1.14 TRANSFORMERS

Earlier in this chapter, it was mentioned that Thomas Edison was wrong to promote dc rather than ac electricity. Because it is frequently necessary to change voltages in various parts of an electrical system, alternating current is much better than direct current. For example, to minimize transmission losses it is always desirable to use the highest voltage possible. Thus, overland transmission is often accomplished with voltages over 100,000V.

A transformer is a super-efficient machine for changing voltages. It uses the ever-changing magnetic field created by the alternating current in a primary coil to induce a current in a secondary coil at a different voltage (Fig. 1.14). Note that the power sent into the primary coil will always equal the power output at the secondary coil minus a small loss in the transformer that shows up as heat (see Sidebox 1.14). Disposing of the waste heat created by transformers inside buildings is an important design consideration.

SIDEBOX 1.14

Transformers

The transformer shown in Fig. 1.14 is a step-up transformer because it raises the voltage from 12V in the primary to 24V in the secondary coil. If the current in the primary circuit is 4 amps, what will be the current in the secondary circuit?

If we ignore the small amount of power lost to heat in the transformer, then:

$$W_p = W_s$$

Where: W_p = watts in primary coil
W_s = watts in secondary coil

Since $W = E \times I$

Then $E_p \cdot I_p = E_s \cdot I_s$

And the current in the secondary is:

$$I_s = \frac{E_p \times I_p}{E_s}$$

$$= \frac{12V \times 4A}{24V}$$

$$= 2 \text{ amps Ans.}$$

Note that the transformer simultaneously raises the voltage (E) and lowers the amperage (I) so that the product (the watts) remains the same. Otherwise, we would be getting something for nothing. The same transformer could also be used as a step-down transformer to lower the voltage from 24V to 12V by switching the incoming and outgoing wires.

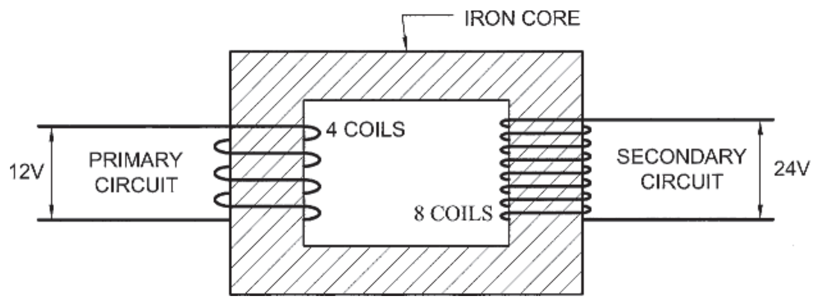


Fig. 1.14 A transformer can raise or lower voltages according to the ratio of the number of windings in the primary and secondary coils. However, the wattage remains the same, because the current increases or decreases in opposition to the voltage. Thus, if the voltage doubles the current is halved.

1.15 ELECTRICITY AND SAFETY

Even though the main danger from electricity results from fires caused by faulty equipment or wiring, people are also killed or injured by electrical shock. The severity of electrical shock is a function of the amount of current flowing through the body. Ohm's law states that the current (I) is directly proportional to the voltage (*E*) and inversely proportional to the resistance (R):

$$I = \frac{E}{R}$$

Consequently, a negligible current will flow through the body if either the voltage is low enough or the resistance is high enough. For example, touching the terminals of a 12-volt car battery is safe because the body's resistance is high enough at that voltage so that the current is too small to cause harm or even any sensation (tingling). The smallest current that people can feel is 1 milliampere (0.001 A), but 100 milliamperes (0.1 A) can be lethal if the current flows through a sensitive part of the body. For example, if the current goes through the chest, the heart might go into ventricular fibrillation, which can cause death. Most people do not feel any sensation until the voltage is above 50 volts, but it quickly becomes dangerous above that.

Since the total resistance to the flow of current consists of the sum of internal body resistance, skin resistances (2 times), shoe resistance, and floor resistance, the total resistance can vary greatly with the situation. For example, standing on a wet floor can be lethal, whereas standing on a dry floor with rubber-soled shoes may result in feeling only an unpleasant buzz (Fig. 1.15a). A common danger is touching a "hot" electrical device with one hand while touching a good ground, such as a water faucet, with the other (Fig. 1.15b). The result is a potentially lethal low-resistance path for the electricity. Also keep in mind, a situation that would be only unpleasant at 120V may well be deadly at 240V.

As with all safety issues, a balance must be found between safety level and the resulting cost in money or convenience. Usually, more safety costs more. Some countries use 120V as the standard because they view safety as more important, while other countries chose a higher voltage such as 210V because of its greater efficiency.

One additional factor comes into play in determining the severity of an electrical shock. The magnitude of the injury is also a function of the amount of time that the current flows. Although static electricity is in the thousands of volts, it generates a large current that only lasts an instant before it is discharged. Consequently, static electricity cannot cause a dangerous shock, but remember that it can ignite a flammable gas.

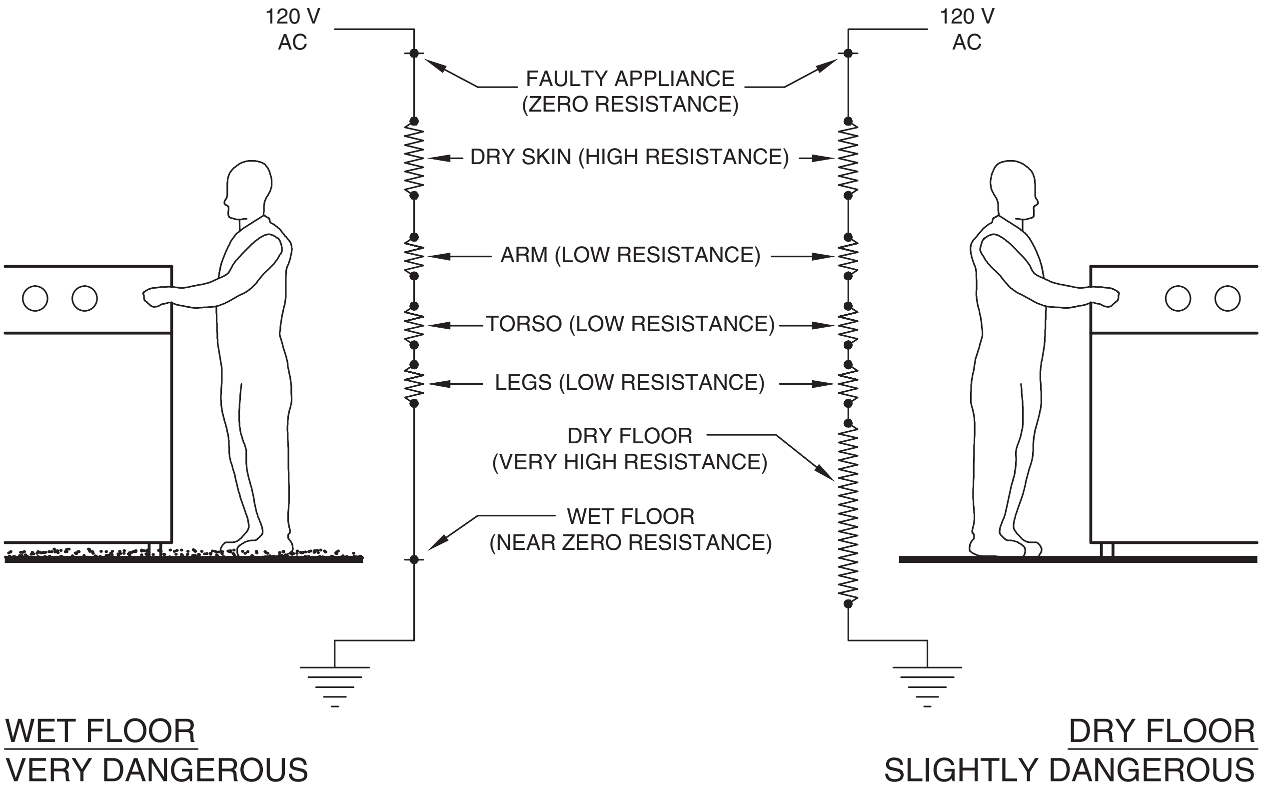


Fig. 1.15a The danger from electricity is a consequence not only of the voltage but also of how well a person is grounded, since the nature of the grounding determines the total electrical resistance and consequently the current. It will be shown in the next chapter how being grounded creates a complete circuit.

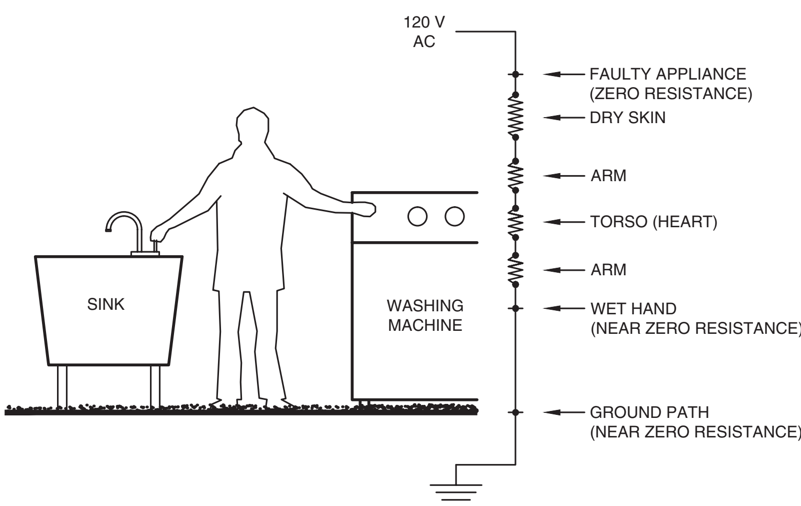


Fig. 1.15b It is extremely dangerous to simultaneously touch a "hot" electrical device, such as a faulty appliance, and a good ground path, such as a metal water pipe, because the resulting low-resistance path allows dangerously high currents to flow through the body. The resistance as shown are not high enough to prevent a fatally high current from flowing through the person.

Although lightning also has a short duration, the voltages are so high (millions) that extremely high currents flow long enough to cause major damage. Consequently, being hit by lighting will cause burns as well as electrical shock. Even at much lower voltages, such as those found in buildings, not only the magnitude but also the duration of electrical current can cause injury and/or death. To greatly reduce the exposure time, **ground fault circuit interrupters** are used in buildings wherever serious electric shock is likely. When these devices sense a fault to the ground, they automatically open the circuit in milliseconds. These devices and other safety devices will be explained in more detail in the next chapter.

1.16 ELECTROMAGNETIC FIELDS (EMF)

Electric and magnetic fields are intrinsic aspects of electricity that make electrical devices work. Electric fields are present whenever a voltage is present, but magnetic fields are only created by the flow of electrons. Thus, there are electric fields around all live wires and electrical devices even when they are turned off, whereas magnetic fields only exist around wires carrying a current and around electrical devices that are turned on. When people are close enough to wires or electrical devices, these **electromagnetic fields (EMF)** penetrate their bodies, and research has shown that EMF's can produce some hormonal and other changes in living things. Scientific research has not so far convincingly shown any serious adverse effects from exposure to EMFs created by the voltages people normally experience in buildings or elsewhere. Nevertheless, there are some people who believe that EMFs are or may be harmful.

Since the strength of the EMF drops off rapidly with distance, any potential negative effect would most likely occur only with close contact. Thus, for example, cautious people might avoid using electric blankets altogether, but if they are used only to preheat a bed, they must be unplugged; otherwise, electric fields could still be present even when the blankets are turned off.

1.17 CONCLUSION

The basic concepts of electricity described above are necessary for understanding the next chapter, which describes how electricity is distributed in a building, how it is integrated into the building fabric, and how it can be safely used. The goals of these two chapters are to help the reader create efficient, sustainable, and safe buildings. The goal of promoting electrical safety is not just for the benefit of buildings and their occupants, but also for the readers' personal safety whenever they come in contact with electricity.

Resources

1. Jill Jonnes, *Empires of Light: Edison, Tesla, Westinghouse, and the Race to Electrify the World.* New York: Random House, 2003.