20.2 Motors, Generators, and Transformers

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain how electric motors, generators, and transformers work
- Explain how commercial electric power is produced, transmitted, and distributed

Teacher Support

Teacher Support The learning objectives in this section will help your students master the following standards:

- (5) The student knows the nature of forces in the physical world. The student is expected to:
  - (G) investigate and describe the relationship between electric and magnetic fields in applications such as generators, motors, and transformers.

Section Key Terms

Electric Motors, Generators, and Transformers

As we learned previously, a current-carrying wire in a magnetic field experiences a force—recall $F = I\ell B\sin\theta$. Electric motors, which convert electrical energy into mechanical energy, are the most common application of magnetic force on current-carrying wires. Motors consist of loops of wire in a magnetic field. When current is passed through the loops, the magnetic field exerts a torque on the loops, which rotates a shaft. Electrical energy is converted to mechanical work in the process. Figure 20.23 shows a schematic drawing of an electric motor.

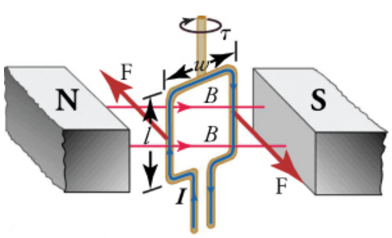

Figure 20.23 Torque on a current loop. A vertical loop of wire in a horizontal magnetic field is attached to a vertical shaft. When current is passed through the wire loop, torque is exerted on it, making it turn the shaft.

Let us examine the force on each segment of the loop in Figure 20.23 to find the torques produced about the axis of the vertical shaft—this will lead to a useful equation for the torque on the loop. We take the magnetic field to be uniform over the rectangular loop, which has width w and height ℓ, as shown in the figure. First, consider the force on the top segment of the loop. To determine the direction of the force, we use the right-hand rule. The current goes from left to right into the page, and the magnetic field goes from left to right in the plane of the page. Curl your right fingers from the current vector to the magnetic field vector and your right thumb points down. Thus, the force on the top segment is downward, which produces no torque on the shaft. Repeating this analysis for the bottom segment—neglect the small gap where the lead wires go out—shows that the force on the bottom segment is upward, again producing no torque on the shaft.

Consider now the left vertical segment of the loop. Again using the right-hand rule, we find that the force exerted on this segment is perpendicular to the magnetic field, as shown in Figure 20.23. This force produces a torque on the shaft. Repeating this analysis on the right vertical segment of the loop shows that the force on this segment is in the direction opposite that of the force on the left segment, thereby producing an equal torque on the shaft. The total torque on the shaft is thus twice the toque on one of the vertical segments of the loop.

To find the magnitude of the torque as the wire loop spins, consider Figure 20.24, which shows a view of the wire loop from above. Recall that torque is defined as $\tau = rF\sin\theta$, where F is the applied force, r is the distance from the pivot to where the force is applied, and is the angle between r and F. Notice that, as the loop spins, the current in the vertical loop segments is always perpendicular to the magnetic field. Thus, the equation $F = I\ell B\sin\theta$ gives the magnitude of the force on each vertical segment as $F = I\ell B$. The distance r from the shaft to where this force is applied is $w/2$, so the torque created by this force is

$\tau_{\text{segment}} = rF\sin\theta = w/2I\ell B\sin\theta = (w/2)I\ell B\sin\theta.$

20.10

Because there are two vertical segments, the total torque is twice this, or

$\tau = wI\ell B\sin\theta.$

20.11

If we have a multiple loop with N turns, we get N times the torque of a single loop. Using the fact that the area of the loop is $A = w\ell$; the expression for the torque becomes

$\tau = NIAB\sin\theta.$

20.12

This is the torque on a current-carrying loop in a uniform magnetic field. This equation can be shown to be valid for a loop of any shape.

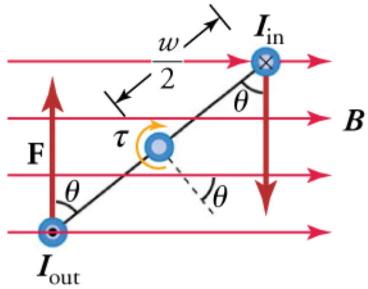

Figure 20.24 View from above of the wire loop from Figure 20.23. The magnetic field generates a force F on each vertical segment of the wire loop, which generates a torque on the shaft. Notice that the currents I_{in} and I_{out} have the same magnitude because they both represent the current flowing in the wire loop, but I_{in} flows into the page and I_{out} flows out of the page.

From the equation $\tau = NIAB\sin\theta$, we see that the torque is zero when $\theta = 0$. As the wire loop rotates, the torque increases to a maximum positive torque of $w\ell B$ when $\theta = 90^\circ$. The torque then decreases back to zero as the wire loop rotates to $\theta = 180^\circ$. From $\theta = 180^\circ$ to $\theta = 360^\circ$, the torque is negative. Thus, the torque changes sign every half turn, so the wire loop will oscillate back and forth.

For the coil to continue rotating in the same direction, the current is reversed as the coil passes through $\theta = 0$ and$\theta = 180^\circ$ using automatic switches called *brushes*, as shown in Figure 20.25.

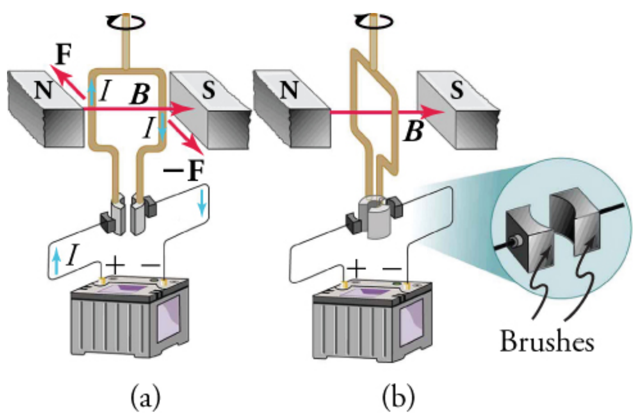

Figure 20.25 (a) As the angular momentum of the coil carries it through $\theta = 0$, the brushes reverse the current and the torque remains clockwise. (b) The coil rotates continuously in the clockwise direction, with the current reversing each half revolution to maintain the clockwise torque.

Consider now what happens if we run the motor in reverse; that is, we attach a handle to the shaft and mechanically force the coil to rotate within the magnetic field, as shown in Figure 20.26. As per the equation $F = qvB\sin\theta$ —where θ is the angle between the vectors $\vec{v}$ and $\vec{B}$—charges in the wires of the loop experience a magnetic force because they are moving in a magnetic field. Again using the right-hand rule, where we curl our fingers from vector $\vec{v}$ to vector $\vec{B}$, we find that charges in the top and bottom segments feel a force perpendicular to the wire, which does not cause a current. However, charges in the vertical wires experience forces parallel to the wire, causing a current to flow through the wire and through an external circuit if one is connected. A device such as this that converts mechanical energy into electrical energy is called a generator.

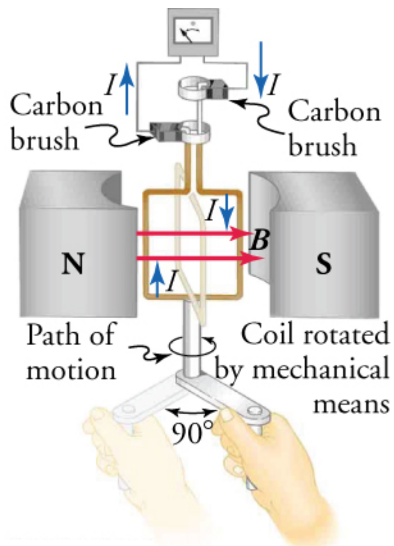

Figure 20.26 When this coil is rotated through one-fourth of a revolution, the magnetic flux Φ changes from its maximum to zero, inducing an emf, which drives a current through an external circuit.

Because current is induced only in the side wires, we can find the induced emf by only considering these wires. As explained in Induced Current in a Wire, motional emf in a straight wire moving at velocity v through a magnetic field B is $E = B\ell v$, where the velocity is perpendicular to the magnetic field. In the generator, the velocity makes an angle θ with B (see Figure 20.27), so the velocity component perpendicular to B is $v\sin\theta$. Thus, in this case, the emf induced on each vertical wire segment is $E = B\ell v\sin\theta$, and they are in the same direction. The total emf around the loop is then

$E = 2B\ell v\sin\theta.$

20.13

Although this expression is valid, it does not give the emf as a function of time. To find how the emf evolves in time, we assume that the coil is rotated at a constant angular velocity ω. The angle θ is related to the angular velocity by $\theta = \omega t$, so that

$E = 2B\ell v \sin\omega t$.

20.14

Recall that tangential velocity v is related to angular velocity ω by $v = r\omega$. Here, $r = w/2$, so that $v = (w/2)\omega$ and

$E = 2B\ell\left(\frac{w}{2}\omega\right)\sin\omega t = B\ell w\omega \sin\omega t$.

20.15

Noting that the area of the loop is $A = \ell w$ and allowing for N wire loops, we find that

$E = NAB\omega \sin\omega t$

20.16

is the emf induced in a generator coil of N turns and area A rotating at a constant angular velocity ω in a uniform magnetic field B. This can also be expressed as

$E = E_0 \sin\omega t$

20.17

where

$E_0 = NAB\omega$

20.18

is the maximum (peak) emf.

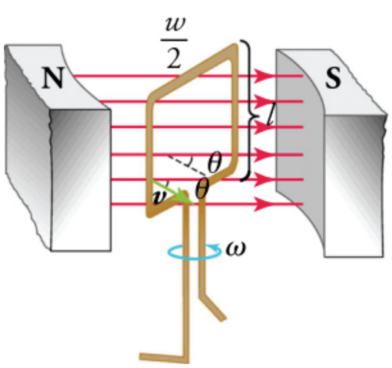

Figure 20.27 The instantaneous velocity of the vertical wire segments makes an angle θ with the magnetic field. The velocity is shown in the figure by the green

arrow, and the angle θ is indicated.

Figure 20.28 shows a generator connected to a light bulb and a graph of the emf vs. time. Note that the emf oscillates from a positive maximum of E_0 to a negative maximum of $-E_0$. In between, the emf goes through zero, which means that zero current flows through the light bulb at these times. Thus, the light bulb actually flickers on and off at a frequency of $2f$, because there are two zero crossings per period. Since alternating current such as this is used in homes around the world, why do we not notice the lights flickering on and off? In the United States, the frequency of alternating current is 60 Hz, so the lights flicker on and off at a frequency of 120 Hz. This is faster than the refresh rate of the human eye, so you don't notice the flicker of the lights. Also, other factors prevent various different types of light bulbs from switching on and off so fast, so the light output is *smoothed out* a bit.

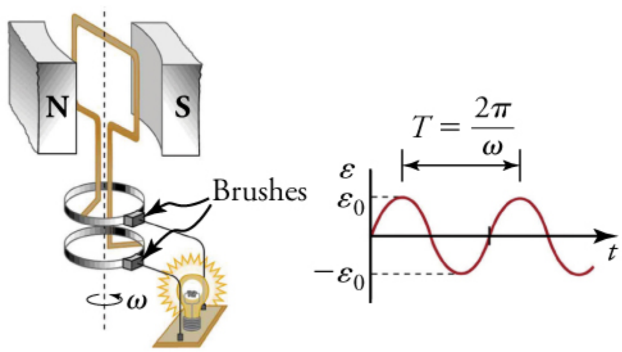

Figure 20.28 The emf of a generator is sent to a light bulb with the system of rings and brushes shown. The graph gives the emf of the generator as a function of time. E_0 is the peak emf. The period is $T = 1/f = 2\pi/\omega$, where f is the frequency at which the coil is rotated in the magnetic field.

Virtual Physics

Generator Click to view content

Use this simulation to discover how an electrical generator works. Control the water supply that makes a water wheel turn a magnet. This induces an emf in a nearby wire coil, which is used to light a light bulb. You can also replace the light bulb with a voltmeter, which allows you to see the polarity of the voltage, which changes from positive to negative.

Grasp Check

Set the number of wire loops to three, the bar-magnet strength to about 50 percent, and the loop area to 100 percent. Note the maximum voltage on the voltmeter. Assuming that one major division on the voltmeter is 5V, what is the maximum voltage when using only a single wire loop instead of three wire loops?

a. 5 V
b. 15 V
c. 125 V
d. 53 V

In real life, electric generators look a lot different than the figures in this section, but the principles are the same. The source of mechanical energy that turns the coil can be falling water—hydropower—steam produced by the burning of fossil fuels, or the kinetic energy of wind. Figure 20.29 shows a cutaway view of a steam turbine; steam moves over the blades connected to the shaft, which rotates the coil within the generator.

Figure 20.29 Steam turbine generator. The steam produced by burning coal impacts the turbine blades, turning the shaft which is connected to the generator. (credit: Nabonaco, Wikimedia Commons)

Another very useful and common device that exploits magnetic induction is called a transformer. Transformers do what their name implies—they transform voltages from one value to another; the term voltage is used rather than emf because transformers have internal resistance. For example, many cell phones, laptops, video games, power tools, and small appliances have a transformer built into their plug-in unit that changes 120 V or 240 V AC into whatever voltage the device uses. Figure 20.30 shows two different transformers. Notice the wire coils that are visible in each device. The purpose of these coils is explained below.

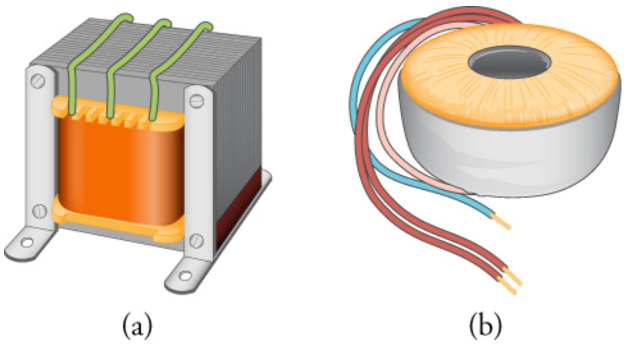

Figure 20.30 On the left is a common laminated-core transformer, which is widely used in electric power transmission and electrical appliances. On the right is a toroidal transformer, which is smaller than the laminated-core transformer for the same power rating but is more expensive to make because of the equipment required to wind the wires in the doughnut shape.

Figure 20.31 shows a laminated-coil transformer, which is based on Faraday's law of induction and is very similar in construction to the apparatus Faraday used to demonstrate that magnetic fields can generate electric currents. The two wire coils are called the primary and secondary coils. In normal use, the input voltage is applied across the primary coil, and the secondary produces the transformed output voltage. Not only does the iron core trap the magnetic field created by the primary coil, but also its magnetization increases the field strength, which is analogous to how a dielectric increases the electric field strength in a capacitor. Since the input voltage is AC, a time-varying magnetic flux is sent through the secondary coil, inducing an AC output voltage.

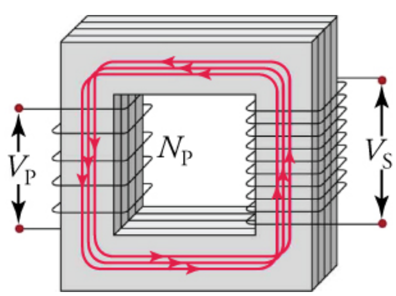

Figure 20.31 A typical construction of a simple transformer has two coils wound

on a ferromagnetic core. The magnetic field created by the primary coil is mostly confined to and increased by the core, which transmits it to the secondary coil. Any change in current in the primary coil induces a current in the secondary coil.

Links To Physics

Magnetic Rope Memory To send men to the moon, the Apollo program had to design an onboard computer system that would be robust, consume little power, and be small enough to fit onboard the spacecraft. In the 1960s, when the Apollo program was launched, entire buildings were regularly dedicated to housing computers whose computing power would be easily outstripped by today's most basic handheld calculator.

To address this problem, engineers at MIT and a major defense contractor turned to *magnetic rope memory*, which was an offshoot of a similar technology used prior to that time for creating random access memories. Unlike random access memory, magnetic rope memory was read-only memory that contained not only data but instructions as well. Thus, it was actually more than memory: It was a hard-wired computer program.

The components of magnetic rope memory were wires and iron rings—which were called *cores*. The iron cores served as transformers, such as that shown in the previous figure. However, instead of looping the wires multiple times around the core, individual wires passed only a single time through the cores, making these single-turn transformers. Up to 63 *word* wires could pass through a single core, along with a single *bit* wire. If a word wire passed through a given core, a voltage pulse on this wire would induce an emf in the bit wire, which would be interpreted as a *one*. If the word wire did not pass through the core, no emf would be induced on the bit wire, which would be interpreted as a *zero*.

Engineers would create programs that would be hard wired into these magnetic rope memories. The wiring process could take as long as a month to complete as workers painstakingly threaded wires through some cores and around others. If any mistakes were made either in the programming or the wiring, debugging would be extraordinarily difficult, if not impossible.

These modules did their job quite well. They are credited with correcting an astronaut mistake in the lunar landing procedure, thereby allowing Apollo 11 to land on the moon. It is doubtful that Michael Faraday ever imagined such an application for magnetic induction when he discovered it.

If the bit wire were looped twice around each core, how would the voltage induced in the bit wire be affected?

a. If number of loops around the wire is doubled, the emf is halved.
b. If number of loops around the wire is doubled, the emf is not affected.
c. If number of loops around the wire is doubled, the emf is also doubled.

d. If number of loops around the wire is doubled, the emf is four times the initial value.

For the transformer shown in Figure 20.31, the output voltage V_{S} from the secondary coil depends almost entirely on the input voltage V_{P} across the primary coil and the number of loops in the primary and secondary coils. Faraday's law of induction for the secondary coil gives its induced output voltage V_{S} to be

$V_S = -N_S \frac{\Delta\Phi}{\Delta t}$,

20.19

where N_{S} is the number of loops in the secondary coil and $\Delta\Phi/\Delta t$ is the rate of change of magnetic flux. The output voltage equals the induced emf ($V_{\mathrm{S}} = E_{\mathrm{S}}$), provided coil resistance is small—a reasonable assumption for transformers. The cross-sectional area of the coils is the same on each side, as is the magnetic field strength, and so $\Delta\Phi/\Delta t$ is the same on each side. The input primary voltage V_{P} is also related to changing flux by

$V_{\mathrm{P}} = -N_{\mathrm{P}} \frac{\Delta\Phi}{\Delta t}$.

20.20

Taking the ratio of these last two equations yields the useful relationship

$\frac{V_{\mathrm{S}}}{V_{\mathrm{P}}} = \frac{N_{\mathrm{S}}}{N_{\mathrm{P}}}\,(3.07)\,.$

20.21

This is known as the transformer equation. It simply states that the ratio of the secondary voltage to the primary voltage in a transformer equals the ratio of the number of loops in secondary coil to the number of loops in the primary coil.

Transmission of Electrical Power

Transformers are widely used in the electric power industry to increase voltages—called *step-up* transformers—before long-distance transmission via high-voltage wires. They are also used to decrease voltages—called *step-down* transformers—to deliver power to homes and businesses. The overwhelming majority of electric power is generated by using magnetic induction, whereby a wire coil or copper disk is rotated in a magnetic field. The primary energy required to rotate the coils or disk can be provided by a variety of means. Hydroelectric power plants use the kinetic energy of water to drive electric generators. Coal or nuclear power plants create steam to drive steam turbines that turn the coils. Other sources of primary energy include wind, tides, or waves on water.

Once power is generated, it must be transmitted to the consumer, which often means transmitting power over hundreds of kilometers. To do this, the voltage of the power plant is increased by a step-up transformer, that is stepped up, and the current decreases proportionally because

$P_{\text{transmitted}} = I_{\text{transmitted}} V_{\text{transmitted}}.$

20.22

The lower current $I_{\text{transmitted}}$ in the transmission wires reduces the *Joule losses*, which is heating of the wire due to a current flow. This heating is caused by the small, but nonzero, resistance R_{wire} of the transmission wires. The power lost to the environment through this heat is

$P_{\text{lost}} = I^2_{\text{transmitted}} R_{\text{wire}},$

20.23

which is proportional to the current *squared* in the transmission wire. This is why the transmitted current $I_{\text{transmitted}}$ must be as small as possible and, consequently, the voltage must be large to transmit the power $P_{\text{transmitted}}$

Voltages ranging from 120 to 700 kV are used for transmitting power over long distances. The voltage is stepped up at the exit of the power station by a step-up transformer, as shown in Figure 20.32.

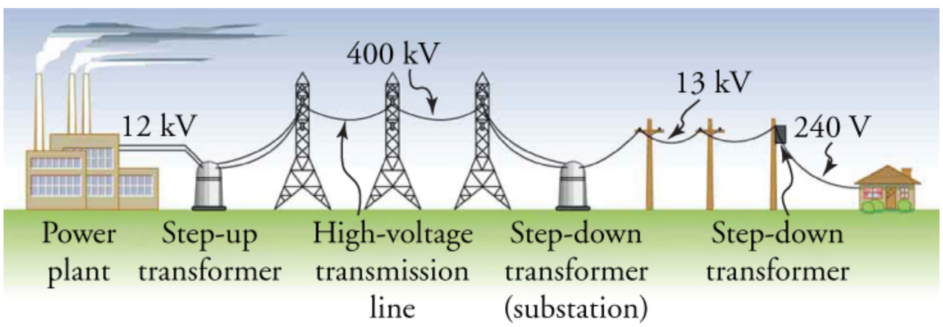

Figure 20.32 Transformers change voltages at several points in a power distribution system. Electric power is usually generated at greater than 10 kV, and transmitted long distances at voltages ranging from 120 kV to 700 kV to limit energy losses. Local power distribution to neighborhoods or industries goes through a substation and is sent short distances at voltages ranging from 5 to 13 kV. This is reduced to 120, 240, or 480 V for safety at the individual user site.

Once the power has arrived at a population or industrial center, the voltage is stepped down at a substation to between 5 and 30 kV. Finally, at individual homes or businesses, the power is stepped down again to 120, 240, or 480 V. Each step-up and step-down transformation is done with a transformer designed based on Faradays law of induction. We’ve come a long way since Queen Elizabeth asked Faraday what possible use could be made of electricity.

Check Your Understanding

7.

What is an electric motor?

a. An electric motor transforms electrical energy into mechanical energy.
b. An electric motor transforms mechanical energy into electrical energy.
c. An electric motor transforms chemical energy into mechanical energy.
d. An electric motor transforms mechanical energy into chemical energy.

8.

What happens to the torque provided by an electric motor if you double the number of coils in the motor?

a. The torque would be doubled.
b. The torque would be halved.
c. The torque would be quadrupled.
d. The torque would be tripled.

9.

What is a step-up transformer?

a. A step-up transformer decreases the current to transmit power over short distances with minimum loss.
b. A step-up transformer increases the current to transmit power over short distances with minimum loss.
c. A step-up transformer increases voltage to transmit power over long distances with minimum loss.
d. A step-up transformer decreases voltage to transmit power over short distances with minimum loss.

10.

What should be the ratio of the number of output coils to the number of input coil in a step-up transformer to increase the voltage fivefold?

a. The ratio is five times.
b. The ratio is 10 times.
c. The ratio is 15 times.
d. The ratio is 20 times.