37 Electromagnetic Induction

The discovery that magnetism could be produced with electrical wires was a turning point in physics and the technology that followed. The question arose as to whether electricity could be produced from magnetism. At that time in the early nineteenth century, the only current-producing devices were voltaic cells, which produced small currents by dissolving expensive metals in acids. These were the forerunners of our present-day batteries. A major alternative to these crude devices was discovered independently in 1831 by two physicists: Michael Faraday in England and Joseph Henry in the United States. Their discovery was to change the world by making electricity so commonplace that it would power industries by day and light up cities by night.

37.1 Electromagnetic Induction

Faraday and Henry both discovered that electric current could be produced in a wire by simply moving a magnet in or out of a wire coil (Figure 37-1). No battery or other voltage source was needed—only the motion of a magnet in a coil or in a single wire loop. They discovered that voltage was induced by the relative motion between a wire and a magnetic field.

The production of voltage depends only on the relative motion between the conductor and the magnetic field. Voltage is induced whether the magnetic field of a magnet moves past a stationary conductor, or the conductor moves through a stationary magnetic field (Figure 37-2). The results are the same whether either or both move.

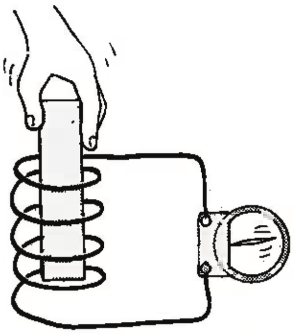

Fig. 37-1 When the magnet is plunged into the coil, charges in the coil are set in motion; voltage is induced in the coil.

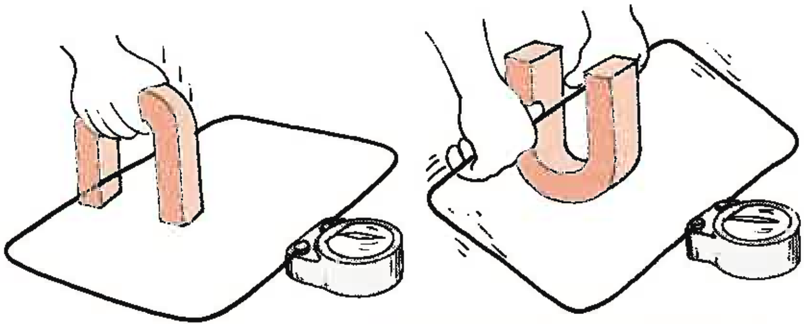

Fig. 37-2 Voltage is induced in the wire loop whether the magnetic field moves past the wire or the wire moves through the magnetic field.

The amount of voltage induced depends on how quickly the magnetic field lines are traversed by the wire. Very slow motion produces hardly any voltage at all. Quick motion induces a greater voltage.

The greater the number of loops of wire that move in a magnetic field, the greater the induced voltage and the greater the current in the wire (Figure 37-3). Pushing a magnet into twice as many loops will induce twice as much voltage; pushing it into ten times as many loops will induce ten times as much voltage; and so on.

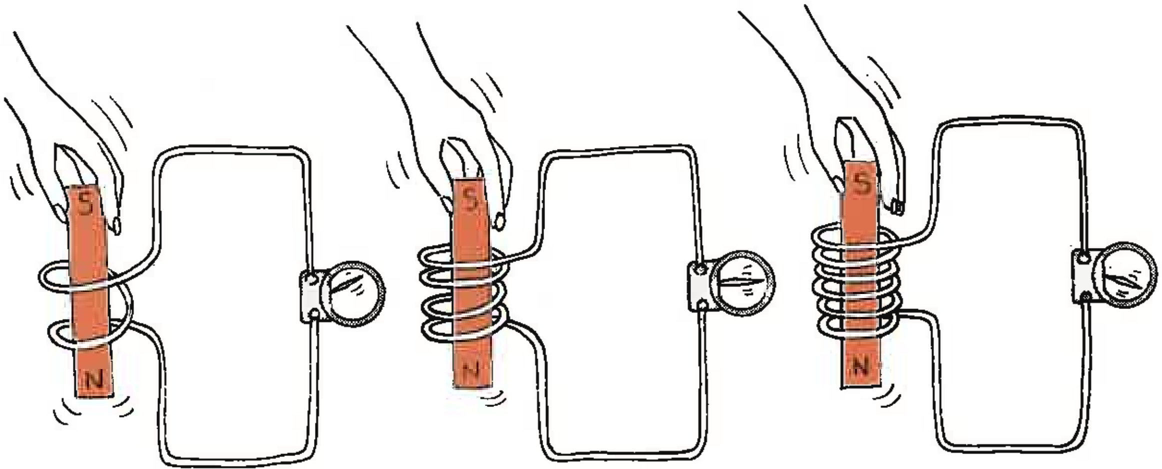

Fig. 37-3 When a magnet is plunged into a coil of twice as many loops as another, twice as much voltage is induced. If the magnet is plunged into a coil with three times as many loops, then three times as much voltage is induced.

Fig. 37-4 It is more difficult to push the magnet into a coil with more loops because the magnetic field of each current loop resists the motion of the magnet.

It may seem that we get something (energy) for nothing by simply increasing the number of loops in a coil of wire, but we don't. It is more difficult to push the magnet into a coil with more loops. Think of it this way: Each additional current loop is an additional electromagnet to resist the motion of your magnet. There is a repulsion between the magnet and the electromagnet that is induced. You do more work to induce more voltage (Figure 37-4).

The amount of voltage induced depends on how quickly the magnetic field changes. Very slow movement of the magnet into the coil produces hardly any voltage at all. Quick motion induces a greater voltage.

It doesn't matter which moves—the magnet or the coil. It is the relative motion between the coil and the magnetic field that induces voltage. It so happens that any change in the magnetic field around a conductor induces a voltage. This phenomenon of inducing voltage by changing the magnetic field around a conductor is called **electromagnetic induction.**

37.2 Faraday's Law

Electromagnetic induction can be summarized in a statement that is called **Faraday's law**:

> The induced voltage in a coil is proportional to the product of the number of loops and the rate at which the magnetic field changes within those loops.

Voltage is one thing, current is another. The amount of current produced by electromagnetic induction depends not only on the induced voltage, but on the resistance of the coil and the circuit that it connects.* For example, you can plunge a magnet in and out of a closed rubber loop and in and out of a closed loop of copper. The voltage induced in each is the same, providing each intercepts the same number of magnetic field lines. But the current in each is quite different—a lot in the copper but almost none in the rubber. The electrons in the rubber sense the same voltage as those in the copper, but their bonding to the fixed atoms prevents the movement of charge that occurs so freely in the copper.

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* Current also depends on the "reactance" of the coil. Reactance is similar to resistance and is important in ac circuits; it depends on the number of loops in the coil and on the frequency of the ac source, among other things. This complication will not be treated in this book.

▶ **Question**

If you push a magnet into a coil, as shown in Figure 37-4, you'll feel a resistance to your push. Why is this resistance greater in a coil with more loops?

37.3 Generators and Alternating Current

If a magnet is plunged in and out of a coil of wire, the induced voltage alternates in direction. As the magnetic field strength inside the coil is increased (magnet entering), the induced voltage in the coil is directed one way. When the magnetic field strength diminishes (magnet leaving), the voltage is induced in the opposite direction. The greater the frequency of field change, the greater the induced voltage. The frequency of the induced alternating voltage is equal to the frequency of the changing magnetic field within the loop.

Rather than moving the magnet, it is more practical to move the coil. This is best accomplished by rotating the coil in a stationary magnetic field (Figure 37-5). This arrangement is called **a generator**. It is essentially a motor running backward. Whereas a motor converts electric energy into mechanical energy, a generator converts mechanical energy into electric energy.

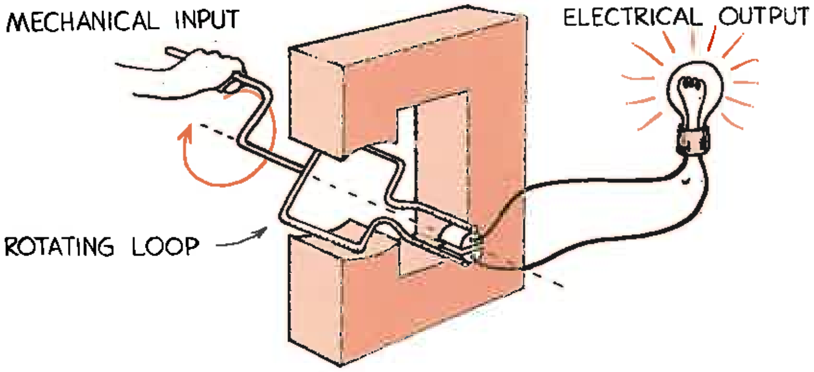

Fig. 37-5 A simple generator. Voltage is induced in the loop when it is rotated in the magnetic field.

▶ **Answer**

Simply put, more work is required to induce the greater voltage induced by more loops. You can also look at it this way: When the magnetic fields of two magnets (electro or permanent) overlap, the two magnets are either forced together or forced apart. When one of the fields is induced by motion of the other, the polarity of the fields is always such as to force the magnets apart. This produces the resistive force you feel. Inducing more current in more coils simply increases the induced magnetic field and hence the resistive force.

When the loop of wire is rotated in the magnetic field, there is a change in the number of magnetic field lines within the loop (Figure 37-6). In sketch *a* the loop has the largest number of lines inside it. As the loop rotates (sketch *b*), it encircles fewer of the field lines until it lies along the field lines (sketch *c*) and encloses none at all. As rotation continues, it encloses more field lines (sketch *d*) and reaches a maximum when it has made a half revolution (sketch *e*). As rotation continues, the magnetic field inside the loop changes in cyclic fashion.

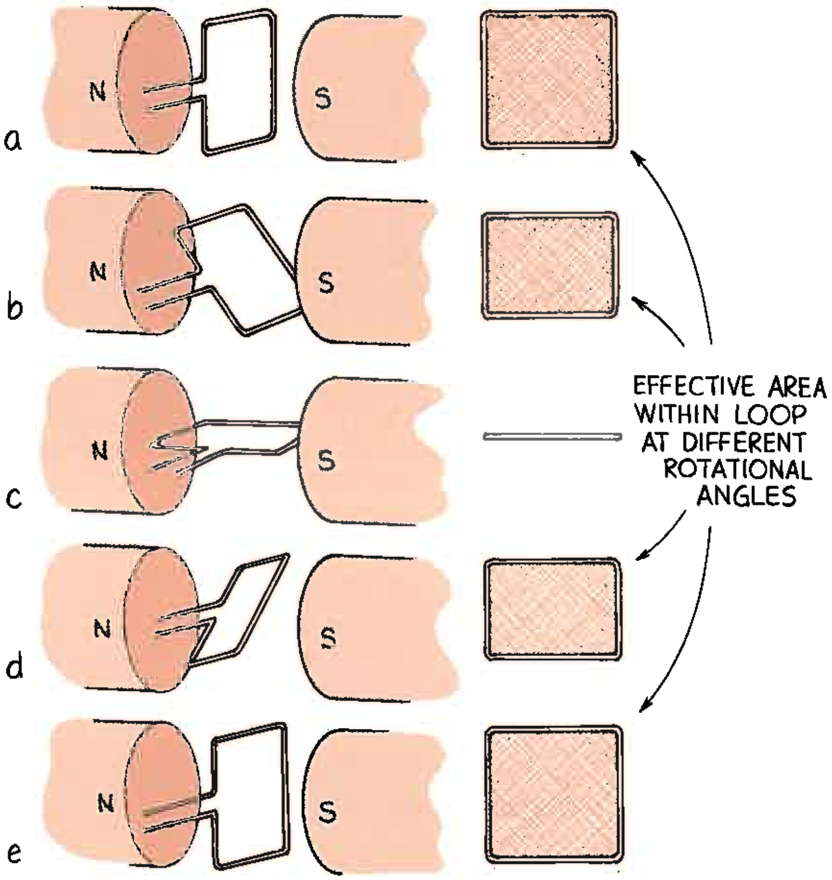

Fig. 37-6 As the loop rotates, there is a change in the number of magnetic field lines it encloses. It varies from a maximum (a) to a minimum (c) and back to a maximum again (e).

The voltage induced by the generator alternates, and the current produced is alternating current (ac). It changes magnitude and direction periodically (Figure 37-7). The standard alternating current in North America changes its magnitude and direction during 60 complete cycles per second—60 hertz.

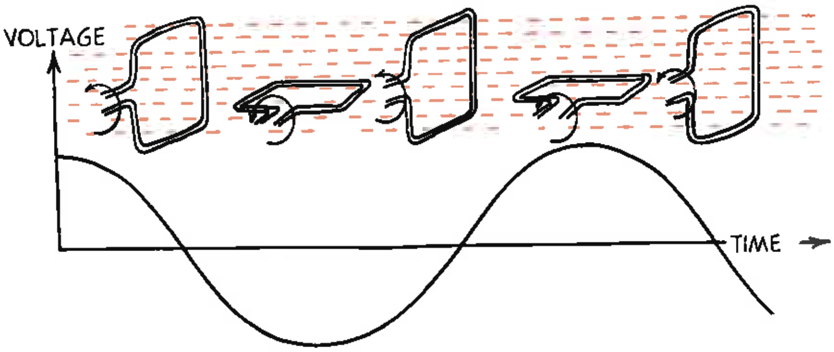

Fig. 37-7 As the loop rotates, the magnitude and direction of the induced voltage (and current) change. One complete rotation of the loop produces one complete cycle in voltage (and current).

The generators used in power plants are much more complex than the model discussed here. Huge coils made up of many loops of wire are wrapped in an iron core, to make an armature much like the armature of a motor. They rotate in the very strong magnetic fields of powerful electromagnets. The armature is connected externally to an assembly of paddle wheels called a *turbine*. Energy from wind or falling water can produce rotation of the turbine, but those of most commercial generators are driven by moving steam. The steam itself requires an energy source, which is usually fossil or nuclear fuel.

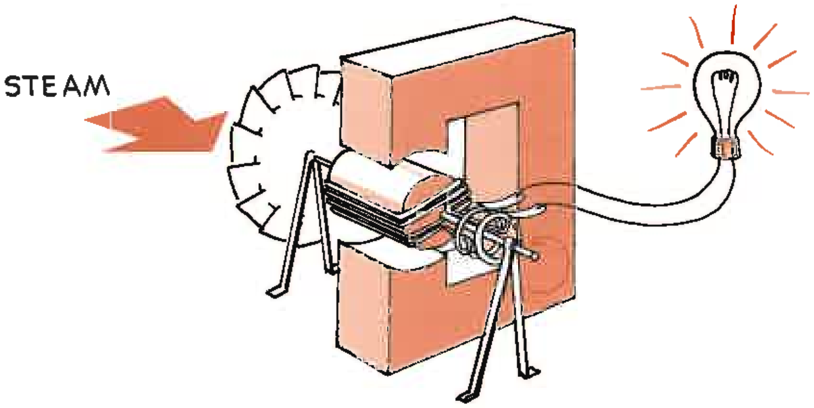

Fig. 37-8 Steam drives the turbine, which is connected to the armature of the generator.

It is important to emphasize that an energy source of some kind is required to operate a generator. Energy from the source, usually some type of fuel, is converted to mechanical energy to drive the turbine, and the generator converts most of this to electric energy. The electricity that is produced simply carries this energy to distant places. Some people think that electricity is a *source* of energy. It is not. It is a *form* of energy that must have a source.

37.4 Motor and Generator Comparison

Chapter 36 discussed how an electric current is deflected in a magnetic field, which underlies the operation of the motor. This discovery occurred ten years before Faraday and Henry discovered electromagnetic induction, which underlies the operation of a generator. Both of these discoveries, however, stem from the same single fact: Moving charges experience a force that is perpendicular to both their motion and the magnetic field they traverse (Figure 37-9). We will call the deflected wire the *motor effect* and the law of induction the *generator effect*. Each of these effects is summarized in the figure. Study them. Can you see that the two effects are related?

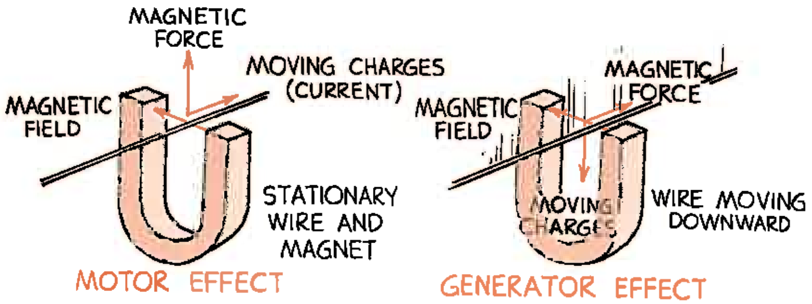

Fig. 37-9 (Left) The motor effect. When a current moves to the right, there is a perpendicular upward force on the electrons. Since there is no conducting path upward, the wire is tugged upward along with the electrons. (Right) The generator effect. When a wire with no initial current is moved downward, the electrons in the wire experience a deflecting force perpendicular to their motion. There *is* a conducting path in this direction, and the electrons follow it, thereby constituting a current.

37.5 Transformers

Consider a pair of coils, side by side (Figure 37-10). One is connected to a battery and the other is connected to a galvanometer. It is customary to refer to the coil connected to the power source as the *primary* (input), and the other as the *secondary* (output). As soon as the switch is closed in the primary and current passes through its coil, a current occurs in the secondary also—even though there is no material connection between the two coils. Only a brief surge of current occurs in the secondary, however. Then when the primary switch is opened, a surge of current again registers in the secondary but in the opposite direction.

The explanation is that the magnetic field that builds up around the primary extends to the secondary coil. Changes in the magnetic field of the primary are sensed by the nearby secondary. These changes of magnetic field intensity at the secondary induce voltage in the secondary, in accord with Faraday's law.

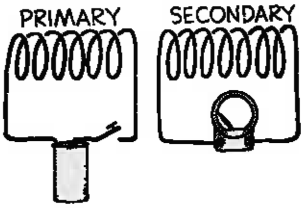

Fig. 37-10 Whenever the primary switch is opened or closed, voltage is induced in the secondary circuit.

▶ **Question**

When the switch of the primary in Figure 37-10 is opened or closed, the galvanometer in the secondary registers a current. But when the switch remains closed, no current is registered on the galvanometer of the secondary. Why?

If we place an iron core inside the primary and secondary coils of the arrangement of Figure 37-10, the magnetic field about the primary is intensified by the alignment of magnetic domains in the iron. The magnetic field is also concentrated in the core which extends into the secondary, so the secondary intercepts more of the field change. The galvanometer will show greater surges of current when the switch of the primary is opened or closed.

Instead of opening and closing a switch to produce the change of magnetic field, suppose that alternating current is used to power the primary. Then the rate at which the magnetic field changes in the primary (and hence in the secondary) is equal to the frequency of the alternating current. Now we have a **transformer** (Figure 37-11).

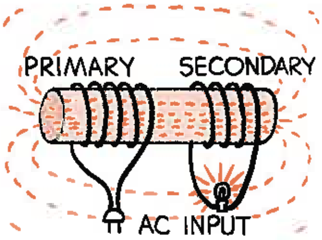

Fig. 37-11 A simple transformer arrangement.

A more efficient arrangement is shown in Figure 37-12, where the iron core forms a complete loop to guide all the magnetic field lines through the secondary. All the magnetic field lines in the primary are intercepted by the secondary.

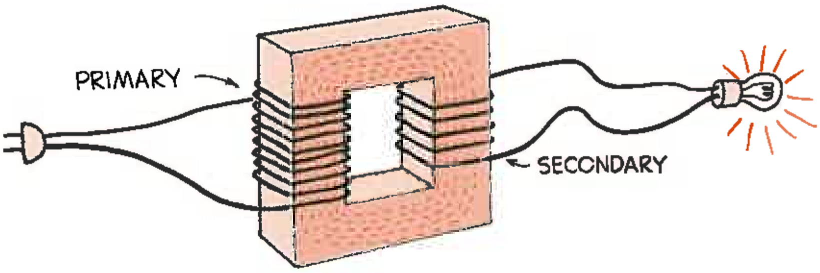

Fig. 37-12 The iron core guides the changing magnetic field lines, which makes a more efficient transformer.

▶ **Answer**

When the switch remains in the closed position, there is a steady current in the primary, and a steady magnetic field about the coil. This field extends to the secondary, but unless there is a *change* in the field, electromagnetic induction does not occur.

Voltages may be stepped up or stepped down with a transformer. To see how, consider the simple case shown in sketch *a* of Figure 37-13. Suppose the primary consists of one loop connected to a 1-V alternating source. Consider the symmetrical arrangement of a secondary of one loop that intercepts all the changing magnetic field lines of the primary. Then a voltage of 1 V is induced in the secondary.

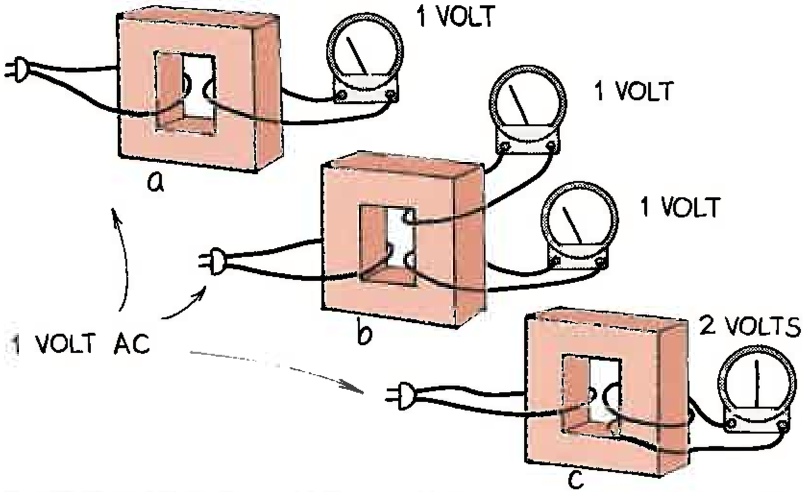

Fig. 37-13 (a) The voltage of 1 V induced in the secondary equals the voltage of the primary. (b) A voltage of 1 V is induced in the added secondary also because it intercepts the same magnetic field change from the primary. (c) The voltages of 1 V each induced in the two one-turn secondaries are equivalent to a voltage of 2 V induced in a single two-turn secondary.

If another loop is wrapped around the core so the transformer has two secondaries (sketch *b*), it intercepts the same magnetic field change. A voltage of 1 V is induced in it too. There is no need to keep both secondaries separate, for we could join them (sketch *c*) and still have a total induced voltage of 1 V + 1 V, or 2 V. This is equivalent to saying that a voltage of 2 V will be induced in a single secondary that has twice the number of loops as the primary. So twice as much voltage will be induced in a secondary that has twice as many loops as the primary.

If the secondary is wound with three times as many loops, or *turns* as they are called, then three times as much voltage will be induced. If the secondary has a hundred times as many turns as the primary, then a hundred times as much voltage will be induced, and so on. This arrangement of a greater number of turns on the secondary than on the primary makes up a *step-up transformer*. Stepped-up voltage may light a neon sign or operate the picture tube in a television receiver.

If the secondary has fewer turns than the primary, the alternating voltage produced in the secondary will be *lower* than that in the primary. The voltage is said to be stepped down. If the secondary has half as many turns as the primary, then only half as much voltage is induced in the secondary. Stepped-down voltage may safely operate a toy electric train.

So electric energy can be fed into the primary at a given alternating voltage and taken from the secondary at a greater or lower alternating voltage, depending on the relative number of turns in the primary and secondary coil windings.

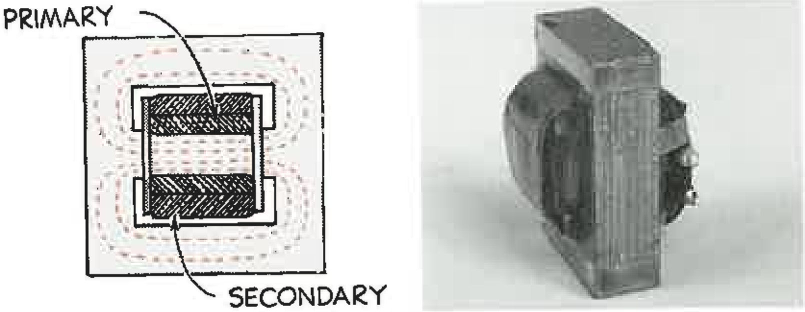

Fig. 37-14 A practical transformer.

The relationship between primary and secondary voltages with respect to the relative number of turns is:

$$\frac{\text{primary voltage}}{\text{number of primary turns}} = \frac{\text{secondary voltage}}{\text{number of secondary turns}}$$

It might seem that you get something for nothing with a transformer that steps up the voltage. But this is not without cost, which is increased current drawn by the primary. The transformer actually transfers energy from one coil to the other. The rate at which energy is transferred is the power. The power used in the secondary is supplied by the primary. The primary gives no more power than the secondary uses, in accord with the conservation of energy. If the slight power losses due to heating of the core are neglected, then:

$$\text{power into primary} = \text{power out of secondary}$$

Electric power is equal to the product of voltage and current, so we can say

$$(\text{voltage} \times \text{current})_{\text{primary}} = (\text{voltage} \times \text{current})_{\text{secondary}}$$

The ease with which voltages can be stepped up or down with a transformer is the principal reason that most electric power is ac rather than dc.

▶ **Questions**

The following questions refer to a transformer with 100 turns in the primary and 200 turns in the secondary.

1. If a voltage of 100 V is put across the primary, what will be the voltage output in the secondary?
2. The secondary is connected to a floodlamp with a resistance of 50 ohms. Assuming the answer to the last question is 200 V, what will be the current in the secondary circuit?
3. What is the power in the secondary coil?
4. What is the power in the primary coil?
5. What is the current drawn by the primary coil?
6. The voltage has been stepped up, and the current has been stepped down. Ohm's law says that increased voltage will produce increased current. Is there a contradiction here, or does Ohm's law not apply to transformers?

37.6 Power Transmission

Almost all electric energy sold today is in the form of alternating current because of the ease with which it can be transformed from one voltage to another. Power is transmitted great distances at high voltages and correspondingly low currents, a process that otherwise would result in large energy losses owing to the heating of the wires. Power may be carried from power plants

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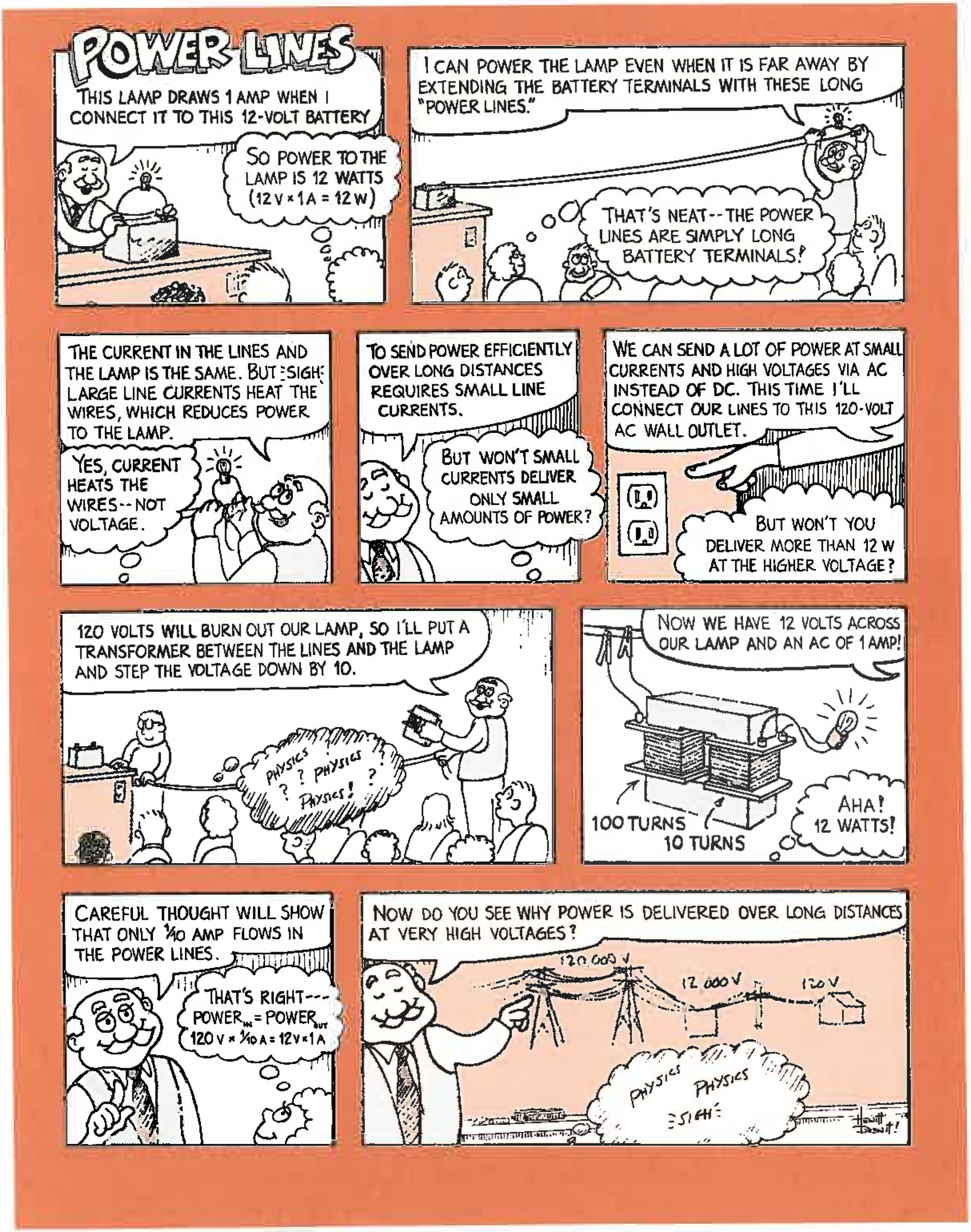
▶ **Answers**

1. From (100 V)/(100 primary turns) = (? V)/(200 secondary turns), you can see that the secondary puts out 200 V.
2. From Ohm's law, (200 volts)/(50 ohms) = 4 A.
3. Power = (200 V) × (4 A) = 800 watts.
4. By the conservation of energy, the power in the primary is the same, 800 watts.
5. Power = 800 watts = (100 V) × (? A), so the primary must draw 8 A. (Note that the voltage is stepped up from primary to secondary and that the current is correspondingly stepped down.)
6. Ohm's law still holds and there is no contradiction. The voltage induced across the secondary circuit, divided by the load (resistance) of the secondary circuit, equals the current in the secondary circuit. The current is stepped down in comparison to the larger current that is drawn in the *primary* circuit.


POWER LINES
THIS LAMP DRAWS 1 AMP WHEN I CONNECT IT TO THIS 12-VOLT BATTERY
SO POWER TO THE LAMP IS 12 WATTS (12 V × 1 A = 12 W)
I CAN POWER THE LAMP EVEN WHEN IT IS FAR AWAY BY EXTENDING THE BATTERY TERMINALS WITH THESE LONG "POWER LINES."
THAT'S NEAT--THE POWER LINES ARE SIMPLY LONG BATTERY TERMINALS!
THE CURRENT IN THE LINES AND THE LAMP IS THE SAME. BUT :SIGH: LARGE LINE CURRENTS HEAT THE WIRES, WHICH REDUCES POWER TO THE LAMP.
YES, CURRENT HEATS THE WIRES--NOT VOLTAGE.
TO SEND POWER EFFICIENTLY OVER LONG DISTANCES REQUIRES SMALL LINE CURRENTS.
BUT WON'T SMALL CURRENTS DELIVER ONLY SMALL AMOUNTS OF POWER?
WE CAN SEND A LOT OF POWER AT SMALL CURRENTS AND HIGH VOLTAGES VIA AC INSTEAD OF DC. THIS TIME I'LL CONNECT OUR LINES TO THIS 120-VOLT AC WALL OUTLET.
BUT WON'T YOU DELIVER MORE THAN 12 W AT THE HIGHER VOLTAGE?
120 VOLTS WILL BURN OUT OUR LAMP, SO I'LL PUT A TRANSFORMER BETWEEN THE LINES AND THE LAMP AND STEP THE VOLTAGE DOWN BY 10.
PHYSICS ? ? PHYSICS ? PHYSICS!
NOW WE HAVE 12 VOLTS ACROSS OUR LAMP AND AN AC OF 1 AMP!
100 TURNS
10 TURNS
AHA! 12 WATTS!
CAREFUL THOUGHT WILL SHOW THAT ONLY 1/10 AMP FLOWS IN THE POWER LINES.
THAT'S RIGHT--- $POWER_{in} = POWER_{out}$ $120\ V \times 1/10\ A = 12\ V \times 1\ A$
NOW DO YOU SEE WHY POWER IS DELIVERED OVER LONG DISTANCES AT VERY HIGH VOLTAGES?
120 000 V
12 000 V
120 V
PHYSICS PHYSICS :SIGH:
Hewitt

to cities at about 120 000 volts or more, stepped down to about 2200 volts in the city, and finally stepped down again to provide the 120 volts used in household circuits.

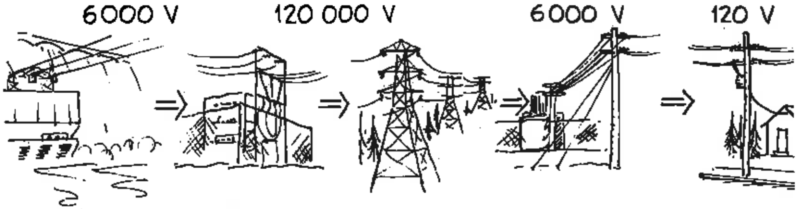


Fig. 37-15 Power transmission.

Energy, then, is transformed from one system of conducting wires to another by electromagnetic induction. The same principles account for eliminating wires and sending energy from a radio-transmitter antenna to a radio receiver many kilometers away, and to the transformation of energy of vibrating electrons in the sun to life energy on earth. The effects of electromagnetic induction are very far-reaching.

37.7 Induction of Electric and Magnetic Fields

Electromagnetic induction has thus far been discussed in terms of the production of voltages and currents. Actually, the more fundamental electric and magnetic fields underlie both voltages and currents. The modern view of electromagnetic induction holds that electric and magnetic *fields* are induced, which in turn give rise to the voltages we have considered. Induction takes place whether or not a conducting wire or any material medium is present. In this more general sense, Faraday's law states

> An electric field is induced in any region of space in which a magnetic field is changing with time. The magnitude of the induced electric field is proportional to the rate at which the magnetic field changes. The direction of the induced electric field is at right angles to the changing magnetic field.

There is a second effect, which is the counterpart to Faraday's law. It is the same as Faraday's law, only the roles of electric and magnetic fields are interchanged. It is one of the many symmetries in nature. This effect was advanced by the British physicist James Clerk Maxwell in about 1860. According to Maxwell:

> A magnetic field is induced in any region of space in which an electric field is changing with time. The magnitude of the induced magnetic field is proportional to the rate at which the electric field changes. The direction of the induced magnetic field is at right angles to the changing electric field.

These statements are two of the most important statements in physics. They underlie an understanding of electromagnetic waves.

37.8 Electromagnetic Waves

Shake the end of a stick back and forth in still water and you will produce waves on the water surface. Similarly shake a charged rod to and fro in empty space and you will produce electromagnetic waves in space. This is because the shaking charge can be considered an electric current. What surrounds an electric current? The answer is a magnetic field. What surrounds a *changing* electric current? The answer is, a changing magnetic field. What do we know about a changing magnetic field? The answer is, it will induce a changing electric field, in accord with Faraday's law. What do we know about a changing electric field? The answer is, in accord with Maxwell's counterpart to Faraday's law, the changing electric field will induce a changing magnetic field.

An electromagnetic wave is composed of vibrating electric and magnetic fields that regenerate each other. No medium is required. The vibrating fields emanate (move outward) from the vibrating charge. At any point on the wave, the electric field is perpendicular to the magnetic field, and both are perpendicular to the direction of motion of the wave (Figure 37-17).

Fig. 37-16 Shake a charged object to and fro and you produce electromagnetic waves.

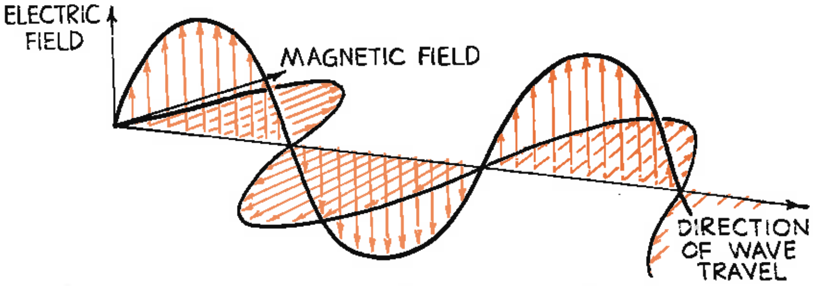


Fig. 37-17 The electric and magnetic fields of an electromagnetic wave are perpendicular to each other.

The intensity of the induced fields very much depends on this speed of emanation. Let's see why this is so.

The magnitude of each induced field depends not only on the vibrational rate, but on the *motion* of the other field—on the speed at which the other field emanates from the vibrating charge. The higher the speed, the greater the magnitude of the field that is induced. A high-speed changing magnetic field induces a stronger electric field than a low-speed changing magnetic field, and vice versa. If the speed of emanation is low, the strength of the induced field is weak. Too low a speed would mean the mutual induction would die out. But what of the energy of the fields in this case? The fields contain energy acquired from the vibrating charge. If the fields disappeared with no means of transferring energy to some other form, energy would be destroyed. So low-speed emanation of electric and magnetic fields is incompatible with the law of energy conservation.

At emanation speeds too high, on the other hand, the fields would be induced to greater and greater magnitudes, with a crescendo of ever increasing energies—again clearly a no-no with respect to energy conservation. At some critical speed, however, mutual induction would continue indefinitely, with neither a loss nor a gain in energy.

From his equations of electromagnetic induction, Maxwell calculated the value of this critical speed and found it to be 300 000 kilometers per second. But this is the speed of light! Maxwell quickly realized that he had discovered the solution to one of the greatest mysteries of the universe—the nature of light. If the electric charge is set into vibration within the incredible frequency range from 4.3×10^{14} to 7×10^{14} vibrations per second, the resulting electromagnetic wave will activate the "electrical antennae" in the retina of the eye. Light is simply electromagnetic waves in this range of frequencies! The lower frequency appears red, and the higher frequency appears violet.

On the evening of Maxwell's discovery, he had a date with a young lady he was later to marry. While walking in a garden, his date remarked about the beauty and wonder of the stars. Maxwell asked how she would feel to know that she was walking with the only person in the world who knew what the starlight really was. For it was true. At that time, James Clerk Maxwell was the only person in the world to know that light of any kind is energy carried in waves of electric and magnetic fields that continually regenerate each other.

37 Chapter Review

Concept Summary

Electromagnetic induction is the inducing of voltage by changing the magnetic field in a conductor.

- According to Faraday's law, the induced voltage in a coil is proportional to the product of the number of loops and the rate at which the magnetic field within the loops changes.
- A generator uses electromagnetic induction to convert mechanical energy to electric energy.
- A transformer uses electromagnetic induction to induce a voltage in the secondary that is different from that in the primary coil.

Electromagnetic induction may be described in terms of fields.

- A changing magnetic field induces an electric field.
- A changing electric field induces a magnetic field.
- Electromagnetic waves are composed of vibrating electric and magnetic fields that regenerate each other.

Important Terms

electromagnetic induction (37.1)
Faraday's law (37.2)
generator (37.3)
transformer (37.5)

Review Questions

1. What did Michael Faraday and Joseph Henry discover? (37.1)
2. How can voltage be induced in a wire with the help of a magnet? (37.1)
3. A magnet moved into a coil of wire will induce voltage in the coil. What is the effect of moving a magnet into a coil with more loops? (37.1)
4. Why is it more difficult to move a magnet into a coil of more loops? (37.1)
5. Current, as well as voltage, is induced in a wire by electromagnetic induction. Why is Faraday's law expressed in terms of induced voltage, and not induced current? (37.2)
6. How does the frequency of the changing magnetic field compare to the frequency of the alternating voltage that is induced? (37.3)
7. What is a generator, and how does it differ from a motor? (37.3)
8. Why is alternating voltage induced in the rotating armature of a generator? (37.3)
9. The armature of a generator must rotate in order to induce voltage and current. What causes the rotation? (37.3)
10. A motor is characterized by three main ingredients: magnetic field, moving charges, and magnetic force. What are the three main ingredients that characterize a generator? (37.4)
11. How can a change in voltage in a coil of wire (the primary) be transferred to a neighboring coil of wire (the secondary) without physical contact? (37.5)
12. Why does an iron core that extends inside and connects the primary and secondary pair of coils intensify electromagnetic induction? (37.5)

13. What does a transformer actually transform—voltage, current, or energy? (37.5)

14. What does a step-up transformer step up—voltage, current, or energy? (37.5)

15. How does the relative number of turns on the primary and secondary coil in a transformer affect the step-up or step-down voltage factor? (37.5)

16. If the number of secondary turns is ten times the number of primary turns, and the input voltage to the primary is 6 volts, how many volts will be induced in the secondary coil? (37.5)

17. a. In a transformer, how does the power input to the primary coil compare to the power output of the secondary coil?
    b. How does the product of voltage and current in the primary compare to the product of voltage and current in the secondary? (37.5)

18. Why is it advantageous to transmit electrical power long distances at high voltages? (37.6)

19. What fundamental quantity underlies the concepts of voltages and currents? (37.7)

20. Distinguish between Faraday's law expressed in terms of fields and Maxwell's counterpart to Faraday's law. How are the two laws symmetrical? (37.7)

21. In what way is the speed of electromagnetic waves consistent with the law of energy conservation? (37.8)

22. What is light? (37.8)

Think and Explain

1. How is the amount of current induced in a loop of wire affected by the frequency of an oscillating magnetic field?

2. Why is a generator armature more difficult to rotate when it is connected to and supplying electric current to a circuit?

3. Some bicycles have electric generators that are made to turn when the bike wheel turns. These generators provide energy for the bike's lamp. Will a cyclist coast farther if the lamp connected to the generator is turned off? Explain.

4. Why does a transformer require alternating voltage?

5. Can an efficient transformer step up energy? Defend your answer.

6. A portable tape deck requires 12 volts to operate correctly. A transformer nicely allows the device to be powered from a 120-volt outlet. If the primary has 500 turns, how many turns should the secondary have?

7. A model electric train requires a low voltage to operate. If the primary coil of its transformer has 400 turns, and the secondary has 40 turns, how many volts will power the train when the primary is connected to a 120-volt household circuit?

8. An induction coil in an automobile is actually a form of transformer that boosts 12 volts to about 24 000 volts. What is the ratio of secondary to primary turns? (The 12 volts in a car is dc. In order to make the induction coil operate, the dc must be interrupted frequently. This is controlled by a switch in the distributor.)

9. If a car made of iron and steel moves over a wide closed loop of wire embedded in a road surface, will the magnetic field of the earth in the loop be altered? Will this produce a current pulse? (Can you think of a practical application of this?)

10. What is wrong with this scheme? To generate electricity without fuel, arrange a motor to run a generator that will produce electricity that is stepped up with a transformer so that the generator can run the motor while furnishing electricity for other uses.