CHAPTER 26

Electromagnetic Induction

26.1 INTRODUCTION

Since physicists like Oersted and Ampere had shown that an electric current could produce a magnetic motor effect, **Michael Faraday** predicted that the reverse situation must be true; hence quite a lot of his research was into **electromagnetic induction**. This is where a magnet is made to produce a flowing electric current as the result of an induced EMF. The discovery of electromagnetic induction is credited to Faraday on 29 August 1831 with a device described in an entry in his diary, 'Experiments on the production of electricity from magnetism'. Physicist Joseph Henry is reported to have discovered the phenomenon of self-induction in 1830, but through his failure to publish his research, credit was given to Michael Faraday.

It is interesting to look at Faraday's original notes in his diary referring to his experiments because the discovery of electromagnetic induction has led directly to the development of the rotary electric generator, which converts mechanical motion into electrical energy. This discovery has certainly led to the modern electrical age as we know it today. His diary entry reads:

> Have had an iron ring made, round and one-eighth inch thick and ring 6 inches in diameter. Wound many coils of copper wire round one half, the coil is being separated by twine and calico — there were 3 lengths of wire each about 24 feet long and they could be connected as one length or used as separate lengths. By trial with a trough each was insulated from the other. Will call this side of the ring A. On the other side but separated by an interval was wound wire in two pieces together amounting to about 60 feet in length, the direction being as with the former coils: this side call B.
>
> Charges a battery of 10 pr plates 4 inches square. Made the coil on B side one coil and connected its extremities by a copper wire passing to a distance and just over a magnetic needle (3 feet from the iron ring). Then connected the ends of one of the pieces on A side with battery; immediately a sensible effort on needle. It oscillated and settled at last in original position. On breaking connection of A side with battery again a disturbance of the needle happened.
>
> Made all the wires on A side one coil and sent current from the battery through the whole. Effect on needle much stronger than before.

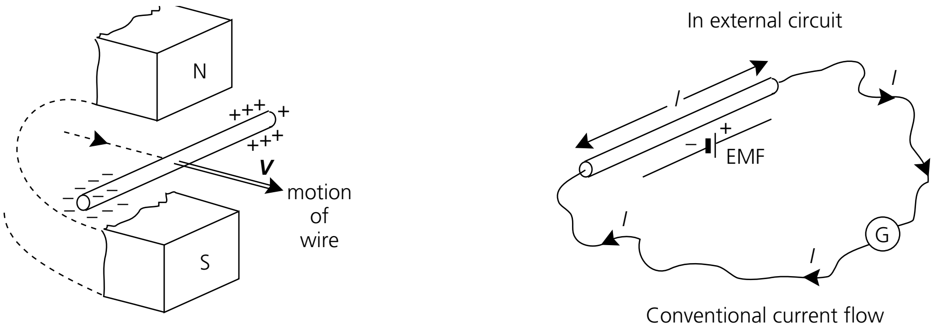
These words of Michael Faraday describe the very first transformer experiment and really represent the start of electrical technology. In this chapter we will look closely at electromagnetic induction, generators and transformers, as well as electrical power transmission.

26.2 LAWS OF ELECTROMAGNETIC INDUCTION

Faraday's law

As we found in the previous chapter, when a conductor, such as a wire, moves through the pole gap of a magnet, the electrons in the wire that are free to move will experience a force along the length of the wire (Figure 26.1). As electrons shift to one end of the wire, we are left with a net excess of negative charge at that end and a net excess of positive charge at the other. This leads to a potential difference or EMF across the ends of the wire and current will flow in any external circuit, which can be shown with a sensitive galvanometer. The direction of flow can be determined using the right-hand rule.

Figure 26.1
Electromagnetic induction.



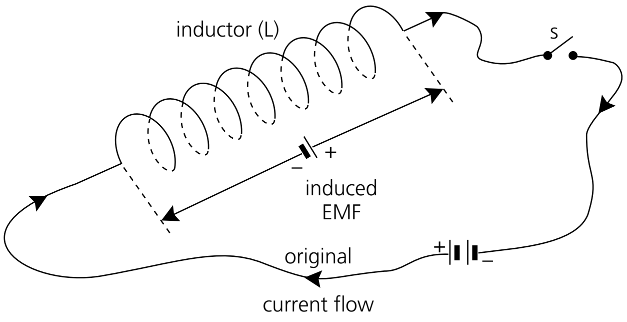
Notice in Figure 26.1 that for a maximum induced EMF and its consequent induced current, the conductor needs to be moved perpendicular to the lines of magnetic flux. We say that the magnetic flux lines are being cut in a perpendicular direction for maximum induced voltage. Alternatively, there will be no induced voltage across the ends of the wire if the movement of the conductor is parallel to the lines of flux. It is also important to realise that the effect also occurs if the conductor is held still and the magnetic field is moved perpendicular to the wire. Hence, what is really important is relative motion between the magnetic field and the conductor. This principle is often stated as Faraday's law of electromagnetic induction:

> *When the magnetic field in the region of a conductor changes, an electromotive force or EMF is induced across the ends of the conductor. If the conductor is made part of a complete circuit then an induced current will flow.*

An easy way to visualise this rule in terms of the separation of charge is to imagine a small test positive charge sitting within the conductor. As the conductor is moved this test charge moves in a direction as given by the thumb in the RH motor rule. The extended fingers point in the direction of the magnetic flux lines and the palm pushes in a direction that shows the way the test positive charge itself moves in the wire. Hence, the polarity of the EMF is established within the conductor and this will determine the direction of flow of conventional current in any external circuit, as shown in Figure 26.1.

Self-induction

Figure 26.2
Inductor self-induction.



Another method of varying the magnetic field is by using an electromagnet that provides a variable magnetic field. This method has greater application in electric generators and in transformers and will be discussed later in the chapter. Before we consider Faraday's law mathematically, consider another interesting situation. When a current is made to flow through any conductor, especially a solenoid coil, the external magnetic field produced will itself induce a voltage across the ends of the coil. This is called **self-induction** and was discussed in relation to inductor components in Chapter 23, Electronics. This self-induced voltage is always opposite in direction to the applied voltage causing current to flow through the solenoid coil in the first instance (Figure 26.2). The induced voltage tends to limit the original current, resulting in a form of resistance. Electric self-induction is analogous to mechanical inertia. An induction or choke coil tends to smooth out varying currents in a circuit just like a flywheel tends to smooth out the jerky rotation of an engine. The amount of self-inductance of any coil is measured in a unit called the henry, named after Joseph Henry. The self-inductance property of an inductor coil is determined solely by the geometry of the coil and by the magnetic properties of its core. You might like to refer back to the section on inductors in Chapter 23.

Faraday's law quantitatively

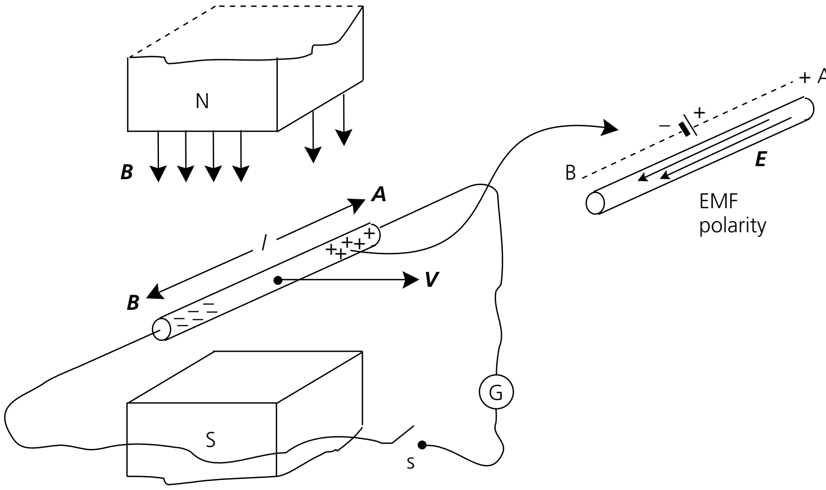


Figure 26.3
Faraday's law.

Let us now consider Faraday's law mathematically. Refer to Figure 26.3, showing a conductor in motion between the poles of a horseshoe magnet. Consider the free electron charges within the metallic conductor of length l being moved perpendicular to the field lines at a velocity $\mathbf{v}$. The magnetic force acting on each moving electron is given by:
where $\mathbf{B}$ = magnetic field strength in teslas; q = charge on the electron in coulombs; $\mathbf{v}$ = velocity of motion in m s^{-1}.

$$\mathbf{F}_\mathrm{B} = q\mathbf{v}\mathbf{B}$$

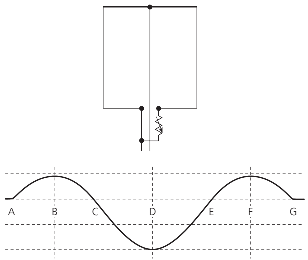
This force has a direction such that the electrons are pushed towards end B as the conductor is moved. This leaves end A equally charged but positive. As the charges build up at each end, AB, of the conductor, an electric field $\mathbf{E}$ is set up within the conductor, which begins to oppose the free flow of electrons. Movement of electrons and separation of charge will continue to occur until the magnitude of the electric force is equal to the magnetic force. That is, until:
but as the electric force is given by:

$$\mathbf{F}_\mathrm{E} = \mathbf{F}_\mathrm{B}$$

$$\mathbf{F}_\mathrm{E} = q\mathbf{E}$$

NOVEL CHALLENGE

Enemy submarines used to be detected by electromagnetic induction. The process involved laying long lengths of electrical cable on the seafloor at the entrance to important harbours. Submarines, like all ships, become magnetised as they are being built and as they travel though the Earth's magnetic field. When they pass over these loops of cable a small voltage is induced (in the order of microvolts) and this is recorded at the shore station. One of these shore stations still exists on Bribie Island (see Photo 26.1). The layout of the loops is as follows. Imagine that a submarine was magnetised north on its underside (as they mostly were), and it passed over the loop arrangement from left to right. The following 'magnetic signature' would be obtained if a CRO was connected to the two wires at the bottom.



Explain how the location of the ship in its passage over the loops matches with the signature. More information, photos and a solution can be found on the textbook website under the link 'antisubmarine loops'.

Photo 26.1
Shore station at Bribie Island, Queensland.

hence:

$$q\boldsymbol{E} = qv\boldsymbol{B}, \quad \text{or} \quad \boldsymbol{E} = v\boldsymbol{B}$$

but as the electric field strength is also given by the relationship:

$$\boldsymbol{E} = \frac{V}{d} = \frac{\text{EMF}}{L}$$

where EMF is the **induced voltage** in volts and *L* is the conductor length in metres. We can arrive at an expression for the magnitude of the induced EMF as:

$$\text{EMF} = \boldsymbol{B}Lv$$

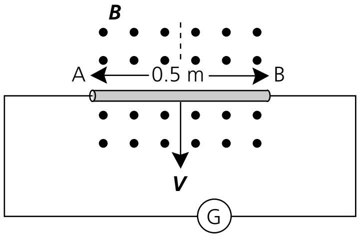
or if the conductor is not at right angles to the field, the net EMF is reduced, becoming:

$$\text{EMF} = \boldsymbol{B}Lv \sin\theta$$

If the switch in Figure 26.3 is closed, conventional current will flow from end A through the galvanometer to end B but, again, only while the conductor is physically being moved in relation to the magnetic field.

Example

Figure 26.4



Consider Figure 26.4, showing a conductor of length 50 cm moving at right angles to a magnetic field directed out of the page as shown. If the magnetic field strength is 5.6 mT and the conductor is moving at a velocity of 4.5 m s^{-1} across the flux lines, calculate:

(a) the induced EMF across the conductor AB;
(b) the direction of current flow in the galvanometer circuit AGB.

Solution

(a) Use the equation for induced EMF:

$$\begin{aligned} \text{EMF} &= \boldsymbol{B}L\boldsymbol{v} \\ \text{EMF} &= 5.6 \times 10^{-3} \times 0.5 \times 4.5 \\ \text{EMF} &= 1.26 \times 10^{-2}\ \text{V} \end{aligned}$$

Note that the polarity will be A positive, B negative and thus:

(b) in the external circuit conventional current will flow from A through G to B or anticlockwise around the external circuit.

Solenoids

Figure 26.5
Induction with a solenoid.

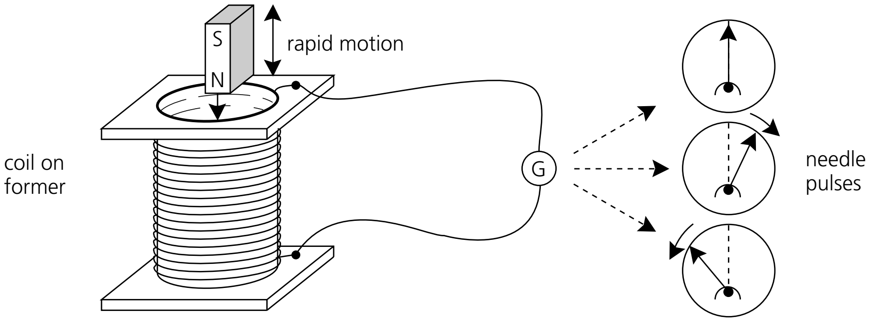


Figure 26.5 illustrates a solenoid connected to a galvanometer. This equipment is easy to obtain in the laboratory and you might like to set it up as a demonstration while going over the next bit of theory. An interesting effect is noted on the galvanometer as a bar magnet is rapidly inserted into, and withdrawn from, the air core of the solenoid. The needle of the meter is seen to flick one way and then the other, as shown. How can we explain this in terms of induction? Recall that relative motion between a conductor and a magnetic field is important if an EMF is to be induced. In this apparatus, the coils of the solenoid cut the lines of magnetic flux and while the magnet is moved a pulse of electric current will be produced. When the magnet is withdrawn, a second, opposite polarity pulse is induced as the solenoid again cuts the lines of flux. When the coil and magnet are stationary, even if for an instant, there is no induced current and the galvanometer needle returns to its zero point. A quite sensitive galvanometer is needed to show this effect, as the EMF and currents produced are very small.

Lenz's law

In the operation of the apparatus of Figure 26.5 it will be observed that the direction of the galvanometer needle pulse of current is reversed when the magnet is pushed into and pulled out of the solenoid. It will also be noticed that if the north pole of the magnet is pushed into the solenoid firstly, and then the magnet reversed and the south pole pushed in, the directions of the galvanometer needle deflections are reversed also. Check this out. Furthermore, if a very powerful magnet is used and a very large solenoid coil with thousands of turns, it will be noticed that considerable force and effort would be needed to push the magnet into the solenoid at all! It appears that nature is trying to prevent, or oppose, the induction of current flowing through the coil. The Russian physicist Heinrich Lenz (1804–64) first explained the direction of the induced current in a solenoid coil as the result of a changing magnetic field. He used the notion of nature trying to oppose any applied force. **Lenz's law**, as it is referred to today, really states that nature does not provide something for nothing! In the field of electromagnetics, Lenz's law states that:

> *The current induced in a conductor by a changing magnetic field is in such a direction that its own induced magnetic field opposes the change that produced it.*

Refer to Figure 26.6.

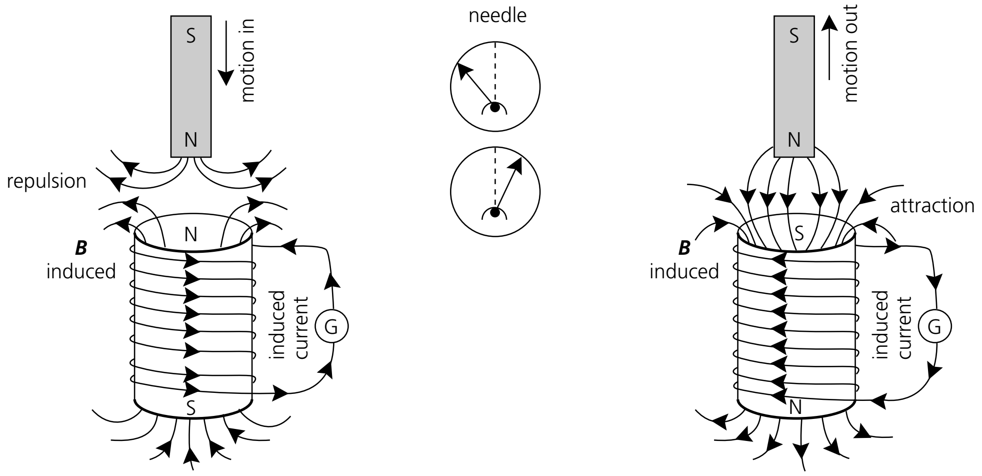


Figure 26.6
Lenz's law.

Lenz's law is only one expression of a fundamental law of nature. In biology you will meet negative feedback — if a light is shone in your eye, your pupil opposes the change and closes up. In chemistry you will meet Le Chatelier's principle in chemical equilibrium. They all work in the same way. When an induced current flows through the solenoid and the galvanometer, the magnetic field produced by the solenoid has a polarity that repels the incoming permanent magnet pole.

Of course, Lenz's law operates just as effectively when the permanent magnet is pulled out of the solenoid. Now the direction of the induced current in the solenoid is such that the magnetic field produced tries to attract the withdrawing permanent magnet back inside the coil again. In both situations a force needs to be exerted and work needs to be done in order to continue to move the magnet. It is this work done that is the origin of the induced electrical energy. We are really transforming mechanical energy into electrical energy and this principle is the basis of all electric generators. The big problem is how to organise for a continuous flow of electrical energy from a generator apparatus and not just single electric current pulses. This problem is examined in Section 26.3.

NOVEL CHALLENGE

When you swing an aluminium baseball bat through the Earth's magnetic field a small voltage is induced. Estimate the voltage produced, by making some assumptions about the size of the field, its direction, the direction and speed of the swing, and the size of the bat. These values should all be stated in your answer.

Magnetic flux

Recall the concept of **magnetic flux**, ϕ, from Chapter 25. The magnetic flux in a region of space is the product of both the magnetic field strength, $\boldsymbol{B}$, and the effective area, $A \cos \theta$, which is perpendicular to the direction of the field, namely:

$$\phi = \boldsymbol{B} A \cos \theta$$

and is measured in webers (Wb).

A mathematical statement of Faraday's law of electromagnetic induction can now be made, involving the notion of induced EMF and current direction as formulated by Lenz, namely:

The EMF induced in a loop is directly proportional to the rate at which the magnetic flux through the loop changes with time

or mathematically as:

$$\text{EMF} = \frac{\Delta\phi}{\Delta t} = \frac{-\Delta(\boldsymbol{B}A)}{\Delta t}$$

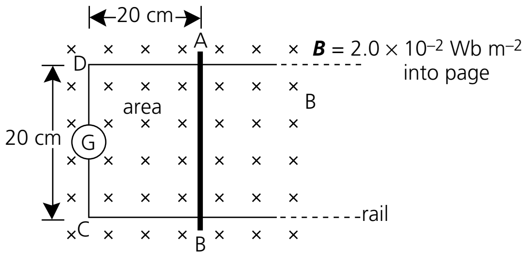
where the negative sign indicates the opposition factor.

If the loop contains N turns, then the EMF is increased by a factor of N. Notice that this equation states that an EMF will be induced if either the magnetic field strength or the area threaded changes with time or, in fact, if both factors change. This law really gives a method for producing an electric generator as all that is needed is a continuously rotating coil.

Example

Consider the apparatus of Figure 26.7. It shows a metal rod AB resting on conducting rails connected to a galvanometer CD. The apparatus is sitting in a magnetic field, as shown.

Figure 26.7



(a) Will there be an induced EMF across AB, if the magnetic field changes from a value of 2.0×10^{-2} Wb m^{-2} to zero in a time of 5.0 ms?

(b) Calculate the value of the EMF and the direction of the induced current around the loop ABCD.

(c) If the rod now is moved to the right at a velocity of 5×10^{-2} m s^{-1}, with the magnetic field remaining constant at its initial value, will there be an induced EMF across AB now?

(d) Calculate the value of the EMF and the direction of the induced current around ABCD for the case in **(c)**.

Solution

(a) Yes, there will be an induced EMF across AB, as the magnetic field strength, ***B***, changes with time.

(b) Use:

$$|\mathrm{EMF}| = \frac{\Delta(\boldsymbol{B}A)}{\Delta t} = \frac{\Delta \boldsymbol{B} \times A}{\Delta t} \quad \text{as area is constant}$$

$$= \frac{2.0 \times 10^{-2} \times 0.2 \times 0.2}{5.0 \times 10^{-3}}$$

$$|\mathrm{EMF}| = 0.16\ \mathrm{V}$$

Lenz's law will require the decreasing magnetic field to be opposed, hence the induced current around the loop will produce its own field to reinforce the original field lines. This requires a clockwise flow of conventional current around ABCD.

(c) Yes, there will be an induced EMF across AB again, because this time the area *A* is changing even though the magnetic field is constant.

(d) Its value is calculated by using:

$$|\mathrm{EMF}| = \frac{\boldsymbol{B}\Delta A}{\Delta t} \quad \text{as } \boldsymbol{B} \text{ is constant}$$

but area is changing because side DA is increasing at the rod velocity. Hence:

$$|\mathrm{EMF}| = \boldsymbol{B} \times DC \times \boldsymbol{v}_{\mathrm{AB}}$$

$$\mathrm{EMF} = 2.0 \times 10^{-2} \times 0.2 \times 5.0 \times 10^{-2}$$

$$\mathrm{EMF} = 2.0 \times 10^{-4}\ \text{volts}$$

In this instance, current will flow through AB so as to produce a force that opposes the applied force moving the rod to the right. Using the RH motor rule, the direction of conventional current must be from B to A. Hence, current flow is anticlockwise around the loop BADC.

Questions

1 Define the terms electromagnetic induction, Faraday's law, Lenz's law, induced voltage.

2 A conductor of length 55 cm is moving through a magnetic field of 3.6×10^{-2} T. What is the EMF induced between the ends of the conductor:

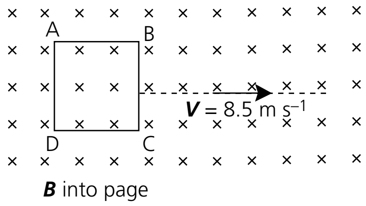
- **(a)** if it is moved perpendicularly to the field at a velocity of 12 m s^{-1};
- **(b)** if it is moved at an angle of 30° to the field at the same velocity?

3 Figure 26.8 illustrates a conductive metal square coil positioned within a magnetic field of strength 150 mT. If the coil has side AB = 5 cm and is moved sideways at 8.5 m s^{-1}, calculate:

- **(a)** the voltages induced across each of the sides of the coil AB, BC, CD, DA;
- **(b)** whether an induced current will flow around this coil as it is moved. Explain.

4 Consider the apparatus of Figure 26.9. Predict the nature of the galvanometer deflection when switch S is closed. What would occur if switch S is opened and closed repeatedly?

Figure 26.8
For question 3.



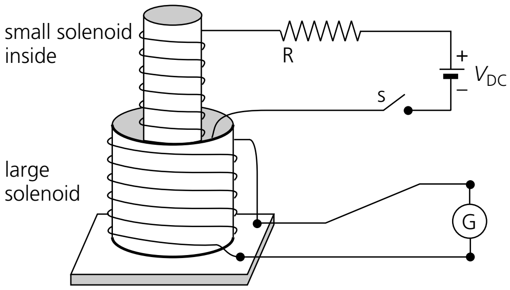


Figure 26.9
For question 4.

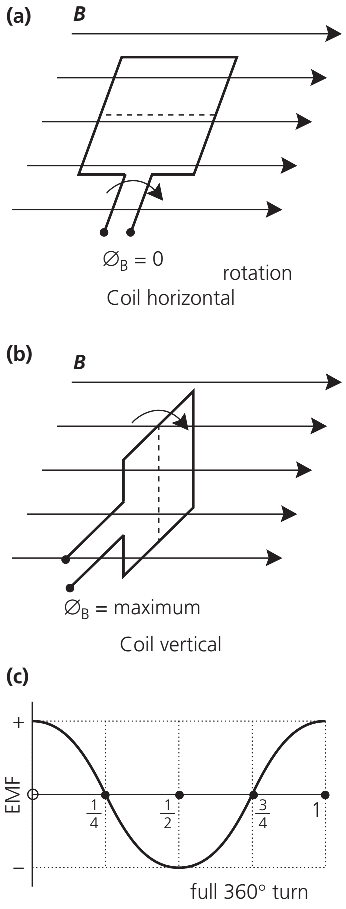


Figure 26.10
Change in flux in a rotating coil: **(a)** coil horizontal; **(b)** coil vertical; **(c)** the EMF waveform.

GENERATING ELECTRICITY

26.3

A machine that converts mechanical energy into electrical energy is called a generator, alternator or dynamo. All these machines rely on the induction principle between a coil and a magnetic field (Figure 26.10). A laboratory demonstration generator is shown in Photo 26.2. In Figure 26.10**(a)** the instantaneous flux through the flat coil is zero, but the rate at which the flux is changing, $\Delta\phi$, is maximal, so the induced EMF is maximal. In 26.10**(b)**, however, the instantaneous flux through the flat coil is maximal, but now the rate of change of flux, $\Delta\phi$, is minimal, so the induced EMF is at minimal. If the flat coil is made to rotate through a full 360°, the output induced EMF waveform at the commutator's split ring will be very close to a sinusoidal waveform. (Refer to Figure 26.10**(c)**.)

The magnetic fields of permanent magnets are usually only strong enough to operate small practical generators or motors. The larger devices employ electromagnets. All electrical generators contain two structures:

- the **field** coils, which are the magnetic field-producing coils or magnets
- the **armature**, which supports the coiled conductors that cut the magnetic field lines and carry the induced current externally to commutators or sliprings. The armature is usually made of a laminated soft iron core around which are wound the coils.

Direct current (DC) generators

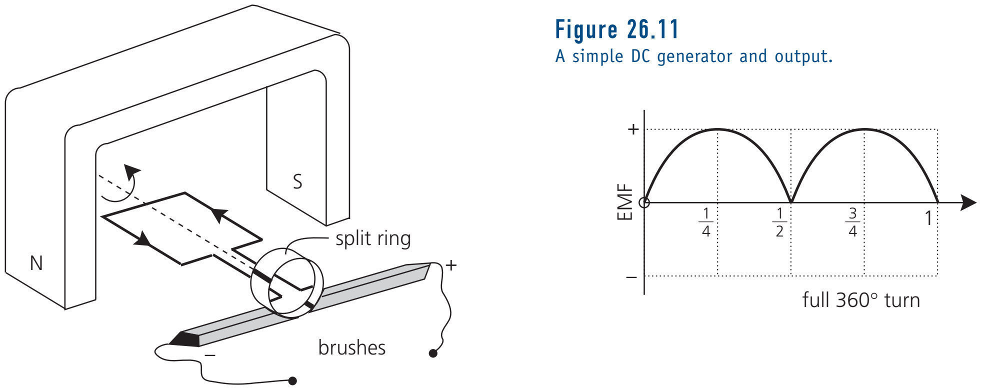
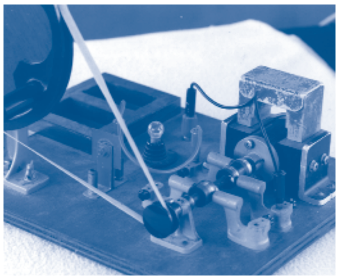


Figure 26.11
A simple DC generator and output.

Figure 26.11 illustrates the basic operation of a DC generator. To produce a steady flow of induced current in one direction only from this device, it is necessary to provide a way of reversing the current flow outside the generator every half-cycle of rotation. In older machines this is accomplished by the **split-ring commutator**. The two halves of the metal ring are insulated from each other and, through slipping contacts (brushes), serve as the terminals of the armature coil. In newer machines this reversal is often accomplished using power diode rectifiers, so in fact the DC generator internally is exactly the same as an AC generator. In order to provide even further smoothed DC output, modern DC generators often

Photo 26.2
Demonstration generator.



use drum armatures that consist of a large number of coil windings in longitudinal slits in the armature core. These coils are then connected to an appropriate multiple segmented commutator that allows contact to each coil in turn as the armature rotates. DC generators are usually operated at low voltages to avoid the electrical discharge sparking that will occur between brushes and commutator at higher voltages.

Activity 26.1 YOUR BICYCLE

Use the library or reference books to find a diagram of a bicycle dynamo. You might like to compare this with an actual device from a bike, and try to answer these questions:

1. How is the dynamo turned?
2. How does the device produce electric current?
3. How could the output current be increased?
4. Does the voltage vary with speed?

Alternating current (AC) generator

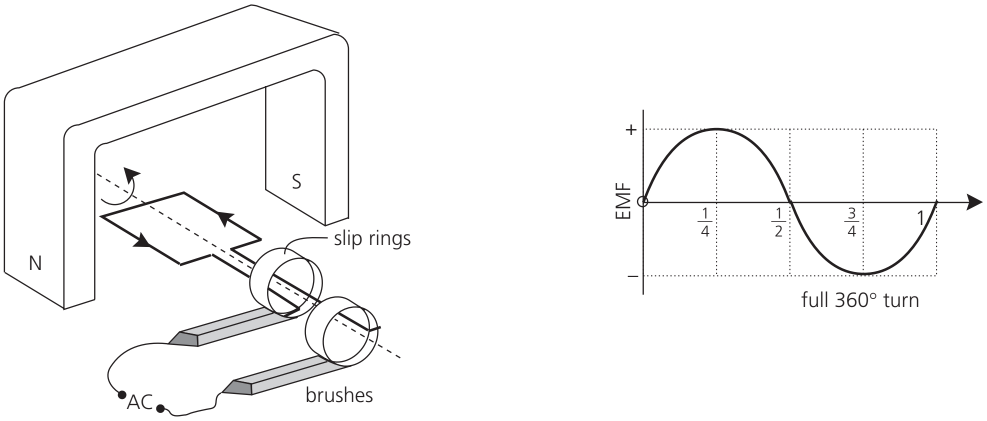


Figure 26.12
A simple AC generator.

Figure 26.12 illustrates the difference between the DC and AC generator design. This AC design has no commutator, with the armature coil being terminated simply at two sliprings. In practical electrical engineering, the transmission of generated electrical energy is in the form of alternating current, and so most large commercial generators are of the AC type, with the permanent magnet being replaced by electromagnetic field coils, energised by external DC sources of EMF. Low speed AC generators are often built with up to 100 poles to improve their efficiency and produce the required output AC frequency, but high speed AC generators most often are simple two-pole machines. It is common to refer to any AC generator as an **alternator**.

NOVEL CHALLENGE

Car stereo amplifiers generally need a higher voltage than the 12 V DC provided by the car battery. How is this achieved if transformers can only convert AC. The term 'oscillating switch' or 'switched-mode power supply' may give you a clue.

In Figure 26.12, if the coil is made to rotate continuously, then a continuous sinewave AC voltage will be produced. Mathematically, the output AC voltage produced is given by the sinusoidal equation:

$$E = E_0 \sin \omega t$$

where E_0 is the peak output voltage, given by:

$$E_0 = N A \boldsymbol{B} \omega$$

where N = number of turns in the coil; A = cross-sectional area of the coil in square metres; $\boldsymbol{B}$ = magnetic field strength in tesla (T); ω = angular velocity = $2\pi f$, where f = frequency in hertz (Hz).

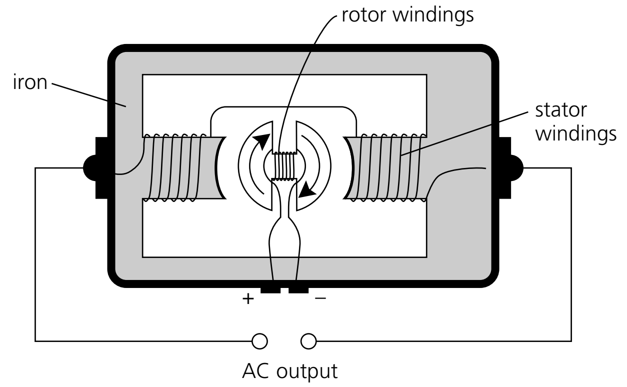


Figure 26.13
A simplified AC alternator.

High voltage alternators often use a design in which a stationary armature set of windings remains fixed in place, with field magnetic coils positioned on a rotor that revolves inside the armature windings. This design reduces sparking and helps to prevent mechanical failures (Figure 26.13). The current generated by all simple alternators follows a single sine waveform called **single phase** alternating current. If the armature windings are composed of a triple set of windings aligned at 120° to each other, the alternator will produce **three phase** alternating current. This three phase system is the most commonly used for electrical power generation and distribution. Three phase alternating current distribution will be discussed in Section 26.5. Typical specifications for the large industrial AC generator that is used in power stations throughout Australia are as follows:

- Generator weight — 350 to 400 tonnes
- Generator rotation — 3000 rpm at rotor
- Rotor assembly — electromagnet on steel, 15 m × 1 m
- Electromagnet field — 2500 A producing 1.68 T
- Generator output — 500 MW at 24 kV (3 phase at 50 Hz)

Usually the rotor assembly is connected to a superheated, steam-driven, four cylinder turbine, which itself may weigh 500–600 tonnes. Steam pressure at the turbine is 16.8 MPa at 540°.

Mini generator applications

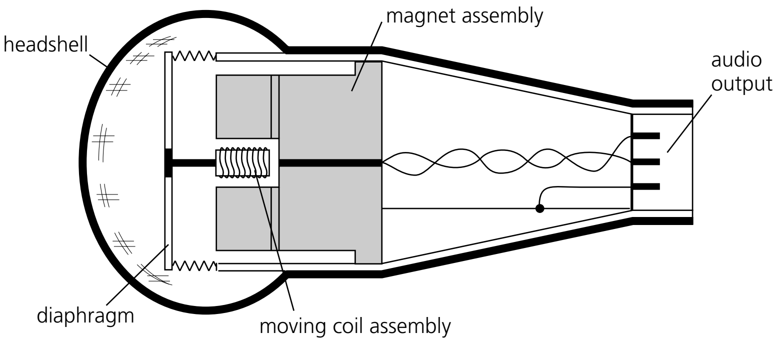


Figure 26.14
A moving coil microphone.

Numerous applications for the principle of induction exist, with most of them being simple AC generators. For example, a loudspeaker may be used in reverse to produce a **moving coil microphone**. However, these microphones are more usually constructed as in Figure 26.14. Sound vibrations cause the diaphragm plate to oscillate and move the coil within the poles of the permanent magnet. This generates a small AC voltage, which is fed to an amplifier.

A similar structure is the basis of a magnetic stylus and cartridge for a record player. Of course, today, CD players are more common in audio systems but high quality turntables are still used by audiophiles. The principle of operation of the **magnetic cartridge** is that an alternating voltage is induced as the pickup stylus is forced to vibrate when it passes along the record grooves. This small AC voltage is again fed to an amplifier.

Some automatic marine navigation buoys generate electricity using the induced current generated by relative motion of coils and magnets. As these devices bounce up and down in the waves the inertia differences between a solenoid coil and a spring-loaded magnet allow generation of an induced current, which is rectified and fed to batteries. These power navigation lights are attached to the buoys. You might like to sketch how they would be made.

26.4 MUTUAL INDUCTION AND TRANSFORMERS

Electromagnetic induction will also occur in the situation where the expanding or collapsing magnetic field of an electromagnet solenoid coil cuts through a stationary conductor or second coil. This type of induction between closely separated coils is called **mutual induction**. It is important in the construction of **ignition coils** and **transformers**.

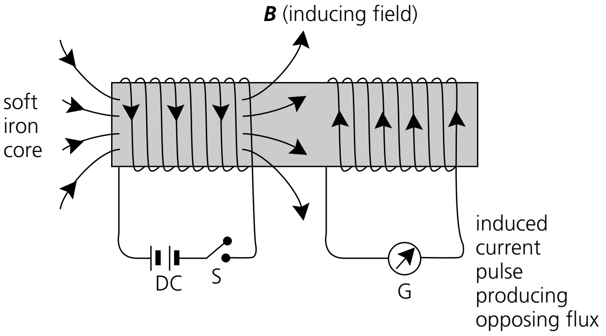


Figure 26.15
Mutual induction principle.

NOVEL CHALLENGE

A Year 9 student asks you: 'Does a transformer convert voltage to current?' What would you say, in language the student could understand?

Refer to Figure 26.15, showing two solenoid coils wound onto a common soft iron core. When the switch is closed in the left-hand circuit a magnetic flux that is expanding is produced and cuts the right-hand circuit. This induces a voltage pulse across the ends of the right-hand coil in such a way as to oppose this expanding flux, according to Lenz's law. No voltage is induced when the current in the left-hand coil is constant. However, if the switch is opened again, a collapsing magnetic flux now cuts the right-hand coil and again an induced voltage, opposite in direction to the original pulse, is produced. In a car electric ignition coil, the continuous switching action of the distributor points in the coil's primary circuit induces very high spark voltages in the coil's secondary circuit. This high voltage is passed in correct sequence via the distributor again to the engine's spark plugs to fire the fuel–air mixture in the cylinders.

Transformers

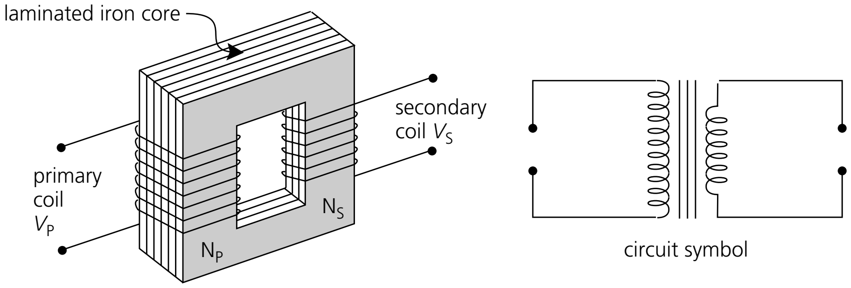


Figure 26.16
A simple transformer and its symbol.

Another obvious method of producing continuously expanding and collapsing magnetic fields is to use a primary circuit driven by AC current. This produces a transformer device that uses mutual induction to vary AC voltages. Two coils called the **primary** and **secondary** are wound onto a common soft iron core (Figure 26.16). The soft iron core concentrates the magnetic flux lines threading both coils. If the primary coil is fed with AC voltages at a particular frequency, an induced AC voltage of equal frequency will occur across the secondary coil. Notice that there is no physical electrical connection between the two sets of coils or windings. If the ratio of turns in the windings is varied, either a **step-up** or a **step-down** transformer is produced. For any transformer operating under ideal conditions the following relationship is determined by experiment:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

where V_P = AC voltage across the primary; V_S = AC voltage across the secondary; N_P = number of primary turns; N_S = number of secondary turns.

- If $N_P > N_S$, then the transformer is a step-down, which reduces AC voltage.
- If $N_P < N_S$ then the transformer is a step-up, which increases AC voltage.

This discussion makes transformers sound like marvellous devices for varying AC voltages and they are; however, energy is not created in these devices as the electrical power available at the output is never greater than the electrical power supplied to the input of the transformer; namely:

$$\text{Input power} = \text{output power}$$
$$V_P \times I_P = V_S \times I_S$$

In practice, although transformers are very efficient devices, there is always some energy loss. When an AC current passes through the primary coil, tiny circulating currents called **eddy currents** are set up in the soft iron core. This causes heating and represents lost energy. The coil conductors also lose heat through ohmic heating due to coil resistances. Practical transformers are constructed on a laminated soft iron core, where the core is made from insulated flat iron sheets of correct shape. This technique helps to reduce eddy current losses. Typical electromagnetic transformers are about 90–95% efficient in operation.

Example

A transformer purchased from an electronics store is labelled as 240 V AC input, 56 V CT @ 120 VA output. Calculate:

- **(a)** the voltages available at the output;
- **(b)** the maximum output current able to be drawn;
- **(c)** the current drawn from the mains supply at maximum output.

Solution

- **(a)** The term 56 V CT means that the secondary winding is 'centre tapped' and thus the 56 volts is divided into a positive and a negative 28 volts with respect to the zero volts centre tap. The full voltage available across the secondary would be 56 V.
- **(b)** Use power rating $P = VI = 120$ V A.
  Thus:

$$V_S \times I_S = 120$$

or

$$I_S = \frac{120}{V_S} = \frac{120}{56} = 2.1\ \text{A}$$

- **(c)** Use:

$$V_P \times I_P = V_S \times I_S = 120\ \text{V A}$$

or current drawn from the mains supply. $I_P = \frac{120}{V_P} = \frac{120}{240} = 0.5\ \text{A}$

Transformers are extremely useful engineering devices as they allow for the changing or transforming of AC voltages, not only in small construction circuits but on an electrical energy production and distribution level. Mains distribution high voltage transformers are a common sight on the poles of our suburban electricity networks. The earliest patent covering the construction of a transformer appears to be that applied for in Britain by the team of Carl Zipernowski, Max Deri and Otto Titus Blathy, all of Budapest, Hungary, on 27 April 1885, numbered Patent No. 5201 under the title, 'Improvements in induction apparatus for transforming electric currents'. Max Deri, in the same year, applied for and received the first patent for an electrical distribution transformer.

NEI Activity 26.2 TRANSFORMERS

1 Transformers are one of the easiest components to recognise in old radios and broken electrical appliances. See if you can get hold of one of these in order to examine it closely. Make diagrams of what you see. Can you identify the windings and the laminated core?

2 The grey boxes located on power poles in your street are the transformers. Make a diagram of these boxes showing where all the wires go. Can you hear a humming noise? What causes that?

Questions

5 Describe the differences in construction and design between a DC generator and an alternator.

6 Why would it be dangerous to connect a step-down transformer in reverse, that is, with the primary voltage connected across the secondary windings?

7 Explain the statement 'A motor run in reverse can act as a generator'.

8 A square loop of wire of side 8 cm is rotated through 90° in a magnetic field of 2.5×10^{-2} T in 0.1 s. Calculate the average EMF induced.

9 If neon lights require at least 12 kV for their operation and operate from a 240 V line, what is the turns ratio required of the transformer used? Would it be a step-up or a step-down transformer?

10 The armature of a 50 Hz AC generator rotates in a 0.15 T magnetic field. If the area of the coil is 2.0×10^{-2} m^2 and the coil contains 150 turns, calculate the peak output voltage, E_0.

26.5 POWER TRANSMISSION AND DISTRIBUTION

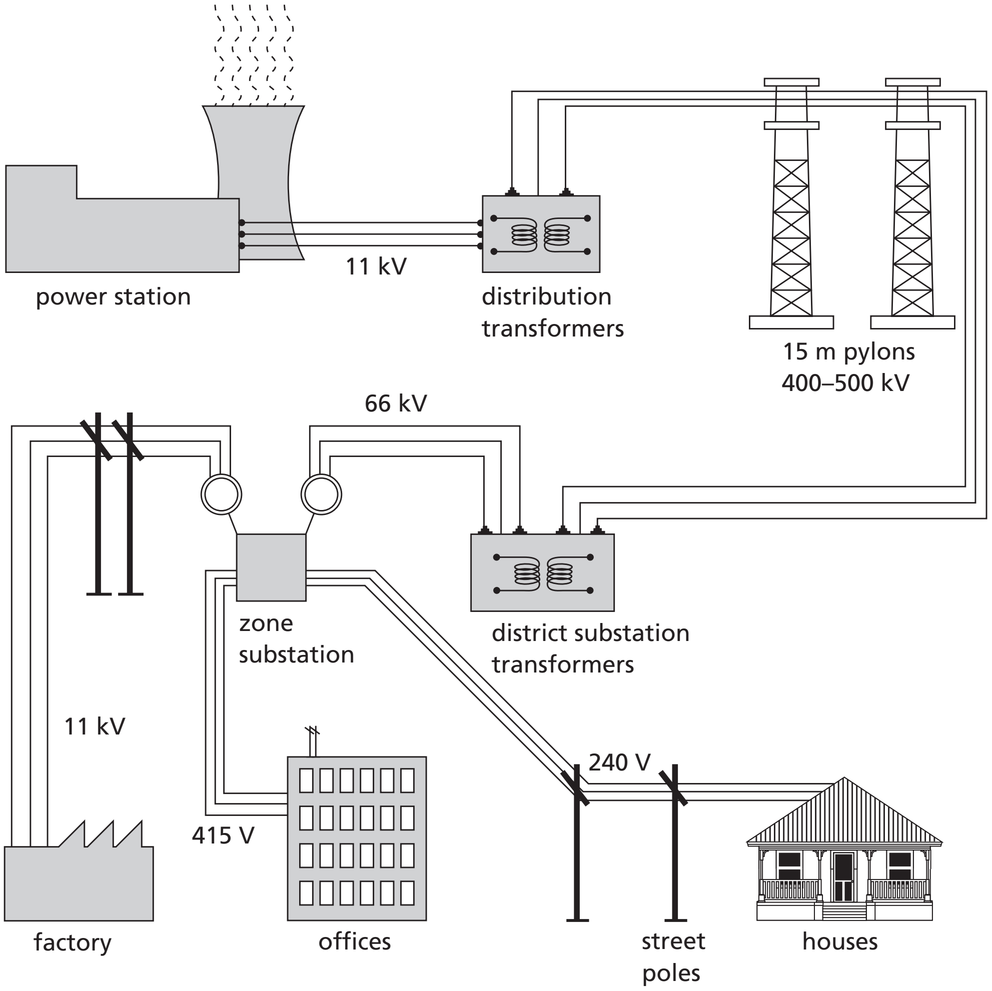
Because electricity generating stations are usually located at the sites of the primary fuels for the turbine generators, most electricity needs to be distributed over very long distances. This requires very large distribution networks, or 'grids' as they are called. For example, very large power stations are located near coal fields in both Queensland and Victoria, and in New South Wales and Tasmania they are located near large hydroelectric facilities. Often several separate power stations are combined to supply power to the distribution grids. Figure 26.17 illustrates the typical Australian distribution network from the generating power station to the industrial or domestic consumer.

Modern power station AC generators deliver power at between 11 kV and 33 kV. In order to distribute the electrical power, transformers at the station step up the voltage to typically 200 kV, 330 kV or 500 kV. These very high voltages are used because over long cable distances, the loss of energy through ohmic heating is reduced. Recall that electrical power loss is proportional to the square of the current ($P = I^2R$), so electrical engineers use very

NOVEL CHALLENGE

What does a power station sell you: power, voltage, current or energy (joules)? Who owns the electrons in the wires from the power station to your power point?

Figure 26.17
A typical Australian distribution network.



POWER STATIONS

Power stations typically generate AC at 11 kV to 33 kV, which is then transformer increased to 220–500 kV. Power switches called circuit breakers are placed throughout the distribution network to help to avoid damage due to lightning strikes. Street poles also often have a fused link to help to avoid damage caused by voltage surges and spikes.

INVESTIGATING

As mentioned above, when electricity is distributed it is stepped up to high voltages (e.g. 275 kV) to reduce 'ohmic losses' and then later stepped down for household or industry use.

Why don't they just generate it as 275 kV and cut the first step out? Engineers at your nearest power station may be able to help. Why wouldn't you contact Energex?

high voltages in order to keep the currents small and the power losses as heat to a minimum. Refer to the data contained in Table 26.1 illustrating the power losses in a distribution system of 150 km, assuming a total cable resistance of 6 Ω and a total power distributed of 500 MW. The table shows the losses incurred as a percentage for different voltages.

Table 26.1 POWER LOSSES IN A DISTRIBUTION SYSTEM

System voltage	500 kV	220 kV	66 kV
Current ($P = VI$)	1000 A	2270 A	7580 A
Power loss (I^2R)	6 MW	30.1 MW	345 MW
Power loss (%)	1.2	6.0	70

At even higher voltages than 500 kV the losses would be less, but the increased chance of high voltage discharge from the power cables to ground is regarded as unacceptable. Atmospheric conditions such as moisture, rainfall and high winds also make power distribution at even higher voltages impractical. In Australia the grid distribution voltages are stepped down again at substations to voltages of 22 kV and 11 kV for distribution to local areas or zone substations. Within the local neighbourhood, local electricity companies distribute power via street poles at typically 415 V_{RMS} three phase or 240 V_{RMS} single phase to factories, schools and houses. Local telegraph pole transformers do this job of stepping down from 11 kV and occasionally you may hear crackling in the vicinity of these pole transformers, especially in wetter climate conditions. This effect is generally nothing to worry about. The electricity supplied to our houses is AC at 240 V_{RMS} 50 Hz through a pole fuse often protecting a group of houses. Refer back to Chapter 22 for a discussion of household electricity and circuits.

If you investigate the nature of distribution electricity poles and towers in your local neighbourhood, you will certainly notice quite a large number of porcelain or glass insulator spacers and large encased oil filled transformers. Remember that even dry air breaks down under high voltage and will conduct. This again could lead to distribution power losses if the cables were not kept apart far enough. In the 500 kV transmission lines conductors need to be at least 600 mm away from pylons and each other. At smaller voltages, the separations can be reduced.

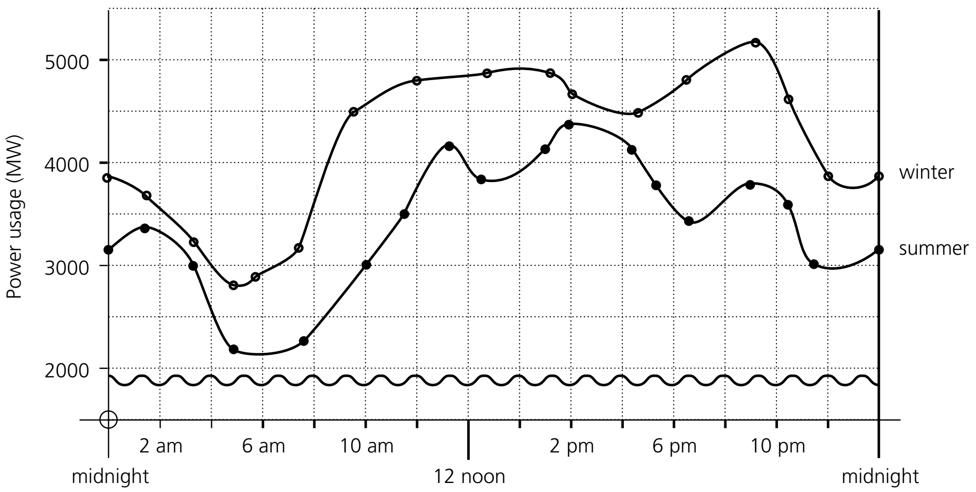


Figure 26.18
Power usage in Australia.

It is interesting to consider the changing demands of the electricity consumer over time. The graphs in Figure 26.18 illustrate typical electrical power usage curves on a summer and winter weekday for comparison. The electricity company is responsible for providing consumers with a supply of electrical energy that is as constant as possible. Our efforts at electrical energy conservation should help to lighten the load, but occasionally supply cannot be maintained and we experience an electrical **brownout** where the supply voltage suddenly reduces. This causes lights to dim, motors to slow down and is generally damaging to equipment. The opposite is a **power surge** where the average voltage increases. This is also damaging to equipment, leading to fuses blowing and transformers and motors overheating. Luckily, both of these occurrences are infrequent in Australia today. Power **blackouts** occur when physical damage, such as lightning strikes or trees breaking or shorting power lines, trips out circuit-breakers or fuses. In times when electricity workers go on strike or during power generating station mechanical failure, the electricity company will often shed the load by disconnecting sections of the distribution grid temporarily. At these times it is important to turn off all major appliances, so that when the power comes back on, a large surge will not cause even further problems. Electricity generating companies and engineers use the larger capacity AC generators at power stations to supply the **base load**. This usually represents about 70% of required demand. These large generators, usually coal fired, take up to 16 hours to reach maximum capacity. The rest of the load is covered by much more flexible oil-fired, gas-fired and hydroelectric generators. These smaller generators can come on-line very quickly, often in a matter of minutes. Overall, the generation of electricity for our community involves a fine balancing act between supply and demand, involving different generation methods, costs of development and maintenance, and accurate forecasting of future trends in consumer requirements. Being an electrical power engineer is a worthwhile profession.

Questions

11 Why is a DC electrical distribution not favoured by engineers in Australia? There are some places in the world where DC distribution does take place. See if you can find out where they are and present a report.

12 Using Figure 26.18, explain the following features:
- **(a)** The dip and sudden rise in power consumption at about 6 am.
- **(b)** The higher average demand on a winter's day.
- **(c)** The dip and sudden rise of the graphs at about 6 pm.

13 Suppose the total resistance of a power line distribution system is rated at 120 Ω. Calculate the power loss in the system if 600 kW is generated and transmitted at either 11 kV or 66 kV.

Practice questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

Review — applying principles and problem solving

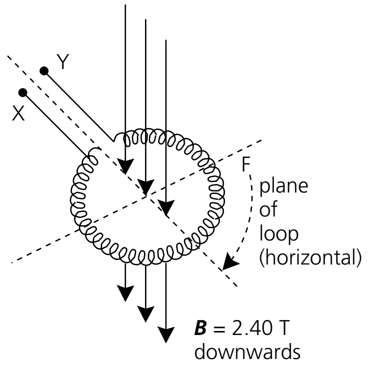


Figure 26.19
For question 14.

***14** Figure 26.19 shows a circular spring loop perpendicular to a magnetic field. If the spring is released and its area changes from 0.55 m^2 to 0.15 m^2 in 0.4 s, what is the EMF induced between the points X and Y shown on the loop?

***15** Find the average EMF induced in a coil having 15 turns when the magnetic flux threading it increases from 0.03 Wb to 0.15 Wb in a time of 0.02 s.

***16** If a dynamo is found to generate an EMF of 200 V when rotating at 60 rpm, what will be the induced EMF at a rotation of 80 rpm?

***17** Why is Lenz's law often stated as a law of commonsense when applied to electromagnetic induction?

***18** Why do the solenoids used in electromagnets and transformers need to have soft iron cores? Why are the cores laminated?

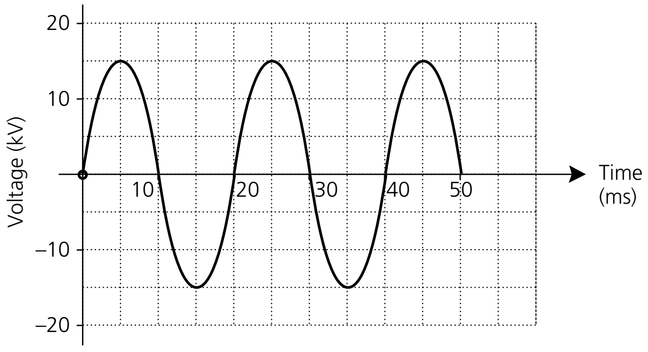
***19** A transformer is designed to step down the mains voltage used in Australia to a voltage of 6.3 V AC. If the primary coil has 2000 turns, how many turns will the secondary coil have?

***20** Why does the operation of a transformer depend on AC rather than DC voltage?

***21** Explain the following terms as applied to the electrical distribution system in the community: **(a)** thermal power station; **(b)** turbine-driven generator; **(c)** brownout; **(d)** power surge; **(e)** generated base load.

****22** Figure 26.20 represents graphically the output of an alternator that is rotating at 50 Hz in a magnetic field of 0.40 T. By superimposing your own curves on top of this one, illustrate the changes to the output waveform if **(a)** the magnetic field changes to 0.80 T; **(b)** the field remains the same but the rate of rotation increases to 100 Hz.

Figure 26.20
For question 22.



****23** Figure 26.21 illustrates two solenoid coils connected in series. Describe the behaviour of the suspended magnet in the right-hand coil after a bar magnet is dropped through the left-hand coil as shown. Explain your reasoning.

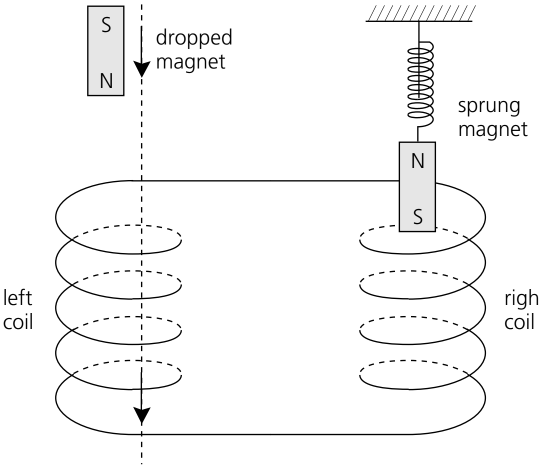


Figure 26.21
For question 23.

****24** What is the frequency and voltage of the AC supply to your home? Sketch a graph of the voltage as a function of time. Carefully note all peak and RMS values.

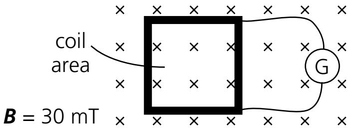
****25** Dynamic or moving coil microphones are generally used for live vocals in rock bands. Draw a diagram that illustrates their basic construction and describe the principle of electromagnetic induction on which they operate. Some household intercom units use a small loudspeaker for both speaking and listening functions. Explain how this is possible.

***26** What are the factors affecting the output EMF of any practical transformer? If these transformers are not perfect, where does the energy lost between input and output go to?

Extension — complex, challenging and novel

*****27** A galvanometer of internal resistance 5 Ω is wired in series with a 200-turn coil of area 50 cm^2, as shown in Figure 26.22. If this assembly is perpendicular to the field and its intensity varies from 30 mT to 10 mT in a time of 0.02 s, calculate the current reading on the galvanometer, assuming a total coil resistance of 20 Ω.

Figure 26.22
For question 27.



*****28** The diagram of Figure 26.23 shows a flexible loop of wire between the poles of an electromagnet that provides a uniform field ***B*** in the region of the loop. At time $t = 0$, the current through the electromagnet is turned off and the field ***B*** falls to zero at time t_1, as shown in the accompanying graph.

(a) Draw a corresponding graph of the nature of the induced EMF across the ends of the loop as a function of time.

(b) If the loop has an area of 0.04 m^2, with $\boldsymbol{B}_0 = 0.6$ T at time $t = 0$ s, find the average EMF induced if time $t_1 = 2.0$ s.

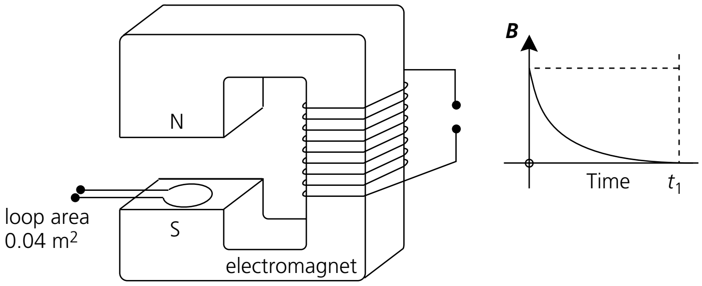
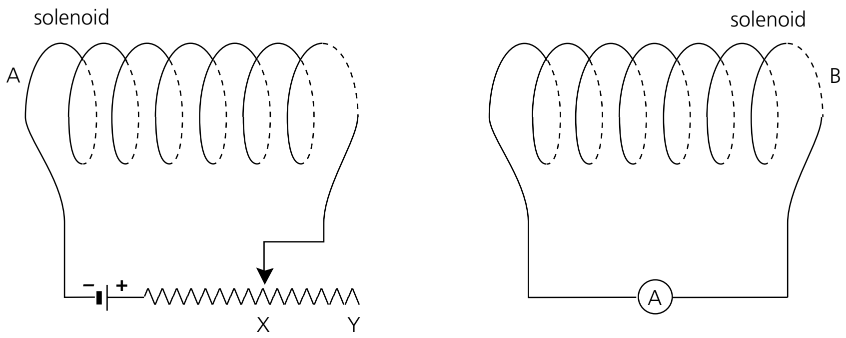


Figure 26.23
For question 28.

***29 A variable resistor is connected into circuit with solenoid A and a battery as shown in Figure 26.24. If the resistor is varied from position X to Y, what is the direction of induced current in solenoid B? Explain your analysis.

Figure 26.24
For question 29.



***30 A hospital generator, 600 m from the hospital, generates 40 kW of power at 250 V AC for use in an emergency. The power lines for distribution to the hospital complex have a total resistance of 0.2 Ω.

(a) How much power is lost in the system?

(b) Can the hospital staff use normal 240 V appliances?

(c) What would happen if the generator was sited 4 km away from the hospital and the total line resistance was 1.0 Ω?

(d) How much power would be lost if transformers were used at both ends of the lines changing the voltages up to 10.0 kV and down again?

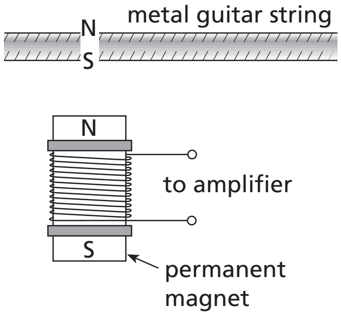
**31 A simple generator has a 100-loop square coil of 8.0 cm side length. How fast must it turn in a 0.50 T field to produce a peak voltage of 20 V AC?

**32 Discuss why the government doesn't want to legislate to force all consumers to use electrically efficient, electronic, compact, fluorescent-style lights in domestic homes.

**33 Photo 26.3 shows a copy of a Fender Stratocaster, the type of guitar used by Jimi Hendrix and many other musicians. Whereas an acoustic guitar depends for its sound on the acoustic resonance produced in the hollow body of the instrument by the oscillations of the strings, an electric guitar is a solid instrument, so there is no body resonance. Instead, the oscillations of the six metal strings are sensed by electric 'pickups', which send signals to an amplifier and a set of speakers.

Photo 26.3
A Yamaha Pacifica — one of the most popular copies of the Fender Stratocaster guitars.

Figure 26.25



The basic construction of a pickup is shown in Figure 26.25. Wire connecting the instrument to an amplifier is coiled around a small magnet. The magnetic field of the magnet produces a north and south pole in the section of the metal string just above the magnet. When the string is plucked and made to oscillate, its motion relative to the coil changes the flux of its magnetic field through the coil, inducing a current in the coil. As the string oscillates towards and away from the coil, the induced current also oscillates.

On a Stratocaster, there are three sets of pickups each with different frequency responses. The musician can choose which set to use. Hendrix would also sometimes rewrap the wire in the pickup coils to make them more sensitive.

(a) How would the frequency of the string compare with the frequency at which the flux changed in the coil? Explain.

(b) In Figure 26.25, as the string moved away from the pickup, would the current to the amplifier move out through the top or bottom wire in the pickup coil?

(c) What change could Hendrix have made to the pickup coil (as mentioned above)? Describe what difference this change would make and why.

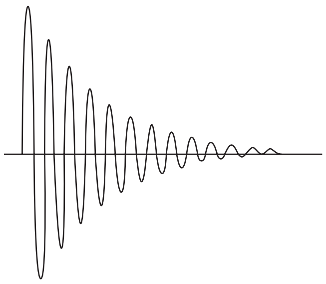
(d) Could you use this sort of pickup on a guitar with nylon strings? Explain.

(e) Another way musicians can change the sound of electric guitars is by using an 'effects pedal', which is plugged into an amplifier and activated by the tap of a foot. Three major types are described below:

- **Big muff** — produces a guitar note of relatively constant amplitude, drawing out the sound until it eventually decays. It does so by clipping off the high and low peaks.
- **Delay** — the effects box stores information about the notes and feeds them to the amplifier a few milliseconds later. Often used in rockabilly music.
- **Wah-wah** — uses a filtering device that changes the volume of different frequencies as the sound decays. For example, as the sound decays the high frequency notes are reduced quickly whereas the lower frequency notes are allowed to predominate to produce the muffled 'wah-wah' sound.

If the guitar produces a note as shown in Figure 26.26, match the three output waveforms (Figure 26.27) with the three types of effects.

Figure 26.26



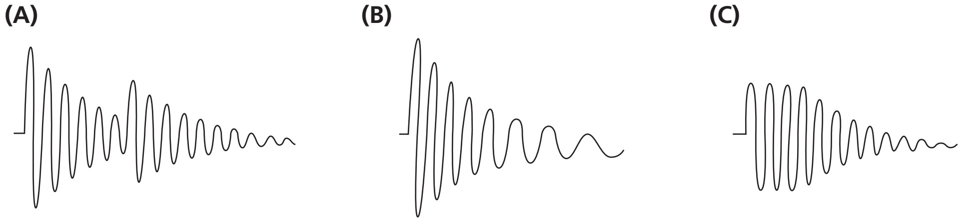


Figure 26.27