Chapter 26

Electromagnetic induction

LEARNING INTENTIONS

In this chapter you will learn how to:

- define magnetic flux as the product of the magnetic flux density and the cross-sectional area perpendicular to the direction of the magnetic flux density
- recall and use $\Phi = BA$
- understand and use the concept of magnetic flux linkage
- understand and explain experiments that demonstrate:
  - that a changing magnetic flux can induce an e.m.f. in a circuit
  - that the direction of the induced e.m.f. opposes the change producing it
  - the factors affecting the magnitude of the induced e.m.f.
- recall and use Faraday's and Lenz's laws of electromagnetic induction.

BEFORE YOU START

- In this chapter, knowledge of magnetic fields is going to be important. Can you work out whether a field is uniform or not from the field pattern? How?
- Physical quantities introduced in this chapter may sound the same, but are very different. Remember the definition for magnetic flux density B and its unit (tesla, T).

GENERATING ELECTRICITY

Most of the electricity we use is generated by electromagnetic induction. This process goes on in the generators at work in power stations, in wind turbines (Figure 26.1) and, on a much smaller scale, in bicycle dynamos. It is the process whereby a conductor and a magnetic field are moved relative to each other to induce, or generate, a current or electromotive force (e.m.f.).

One of the most important principles in physics is the idea of conservation of energy. You cannot just produce electrical energy from nowhere. In the case of a generator or a dynamo, how is the electrical energy produced?

Figure 26.1: This giant wind turbine uses electromagnetic induction to produce electricity. Look for the two engineers at work. (You can identify them by their white helmets.) This gives you an idea of the size of the generator.

26.1 Observing induction

You can carry out some simple experiments to observe features of electromagnetic induction. These are described in Practical Activity 26.1.

PRACTICAL ACTIVITY 26.1: OBSERVING INDUCTION

For each experiment, try to predict what you will observe before you try the experiment.

Experiment 1

Connect a small electric motor to a moving-coil voltmeter (Figure 26.2). Spin the shaft of the motor and observe the deflection of the voltmeter. What happens when you spin the motor more slowly? What happens when you stop? Usually, we connect a motor to a power supply and it turns. In this experiment, you have turned the motor and it generates a voltage across its terminals. A generator is like an electric motor working in reverse.

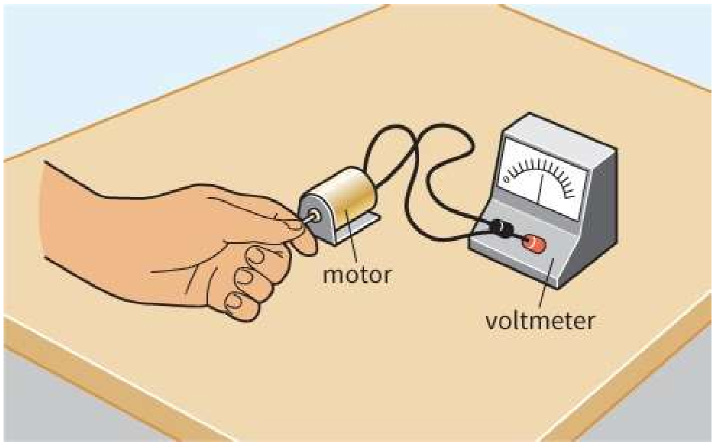

Figure 26.2: A motor works in reverse as a generator.

Experiment 2

Connect a coil to a sensitive microammeter (Figure 26.3). Move a bar magnet in towards the coil. Hold it still, and then remove it. How does the deflection on the meter change? Try different speeds, and the opposite pole of the magnet. Try weak and strong magnets.

With the same equipment, move the coil towards the magnet and observe the deflection of the meter.

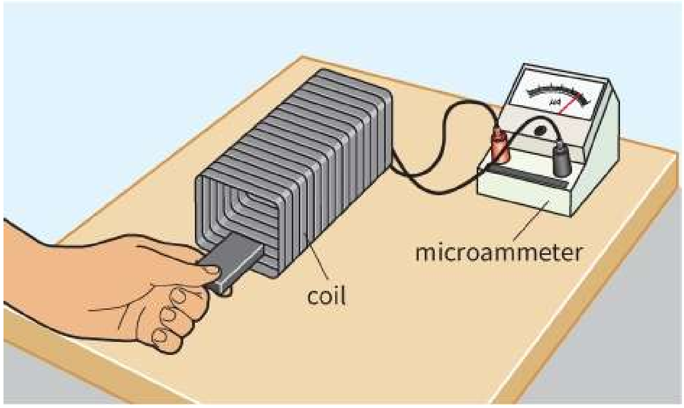

Figure 26.3: A magnet moving near a coil generates a small current.

Experiment 3

Connect a long wire to a sensitive microammeter. Move the middle section of the wire up and down through the magnetic field between the magnets (Figure 26.4). Double up the wire so that twice as much of it passes through the magnetic field. What happens to the meter reading now? How can you form the wire into a loop to give twice the deflection on the meter?

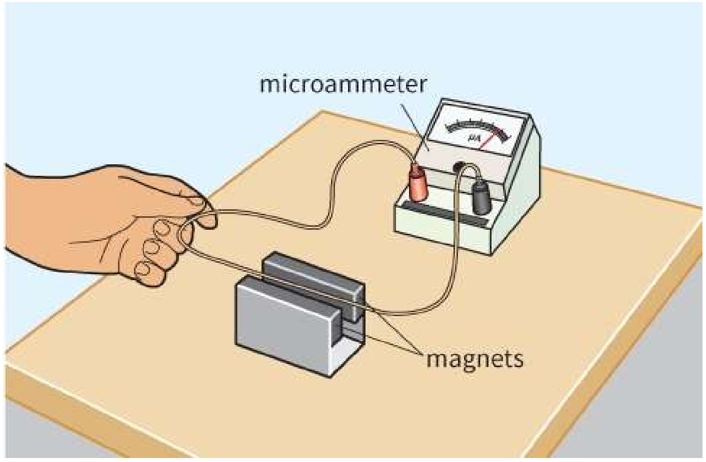

Figure 26.4: Investigating the current induced when a wire moves through a magnetic field.

Factors affecting induced e.m.f

In all the experiments described in Practical Activity 26.1, you have seen an electric current caused by an induced e.m.f. In each case, there is a magnetic field and a conductor. When you move the magnet, or the conductor, there is an induced e.m.f. When you stop, the current stops.

From the three experiments, you should see that the size of the induced e.m.f. depends on several factors.

For a straight wire, the induced e.m.f. depends on the:

- magnitude of the **magnetic flux density**
- length of the wire in the field
- speed of the wire moving across the magnetic field.

For a coil of wire, the induced e.m.f. depends on the:

- magnitude of the magnetic flux density
- cross-sectional area of the coil
- angle between the plane of the coil and the magnetic field
- number of turns of wire
- rate at which the coil turns in the field.

26.2 Explaining electromagnetic induction

You have seen that **relative** movement of a conductor and a magnetic field induces a current in the conductor when it is part of a complete circuit. In the experiments in Practical Activity 26.1, the meter was used to complete the circuit. Now we need to think about how to explain these observations, using what we know about magnetic fields.

Cutting magnetic field lines

Start by thinking about a simple bar magnet. It has a magnetic field in the space around it. We represent this field by magnetic field lines. Now think about what happens when a wire is moved into the magnetic field (Figure 26.5). As it moves, it cuts across the magnetic field. Remove the wire from the field, and again it must cut across the field lines, but in the opposite direction.

We think of this cutting of a magnetic field by a conductor as the effect that gives rise to current caused by induced e.m.f in the conductor. It doesn't matter whether the conductor is moved through the magnetic field or the magnet is moved past the conductor, the result is the same–there will be an induced e.m.f.

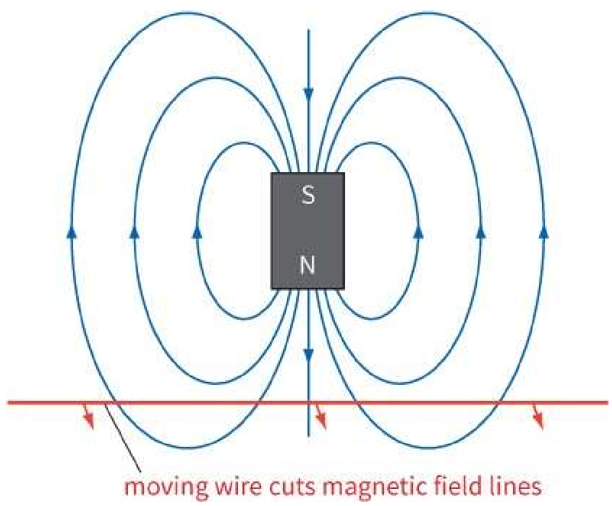

Figure 26.5: Inducing a current by moving a wire through a magnetic field.

The effect is more noticeable if we use a coil of wire. For a coil of N turns, the effect is N times greater than for a single turn of wire. With a coil, it is helpful to imagine the number of field lines linking the coil. If there is a change in the number of field lines that pass through the coil, an e.m.f. will be induced across the ends of the coil (or there will be a current caused by induced e.m.f if the coil forms part of a complete circuit).

Figure 26.6 shows a coil near a magnet. When the coil is outside the field, there are no magnetic field lines linking the coil. When it is inside the field, field lines link the coil. Moving the coil into or out of the field changes this linkage of field lines, and this induces an e.m.f. across the ends of the coil. Field lines linking the coil is a helpful starting point in our understanding of induced e.m.f. However, as you will see later, a more sophisticated idea of magnetic flux is required for a better understanding of how an e.m.f. is generated in a circuit.

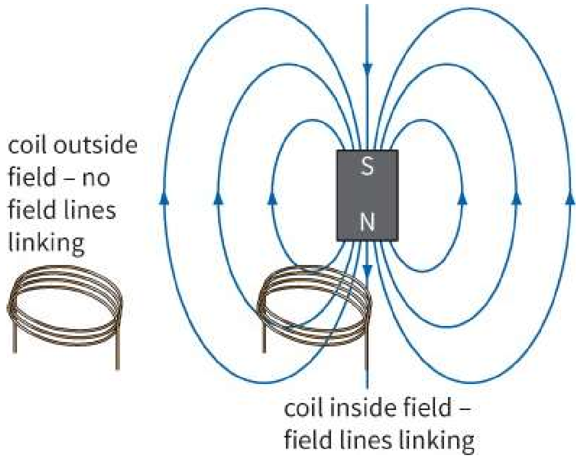

Figure 26.6: The field lines passing through a coil changes as it is moved in and out of a magnetic field.

Question

1 Use the idea of a conductor cutting magnetic field lines to explain how a current is caused by induced e.m.f. in a bicycle generator (Figure 26.7).

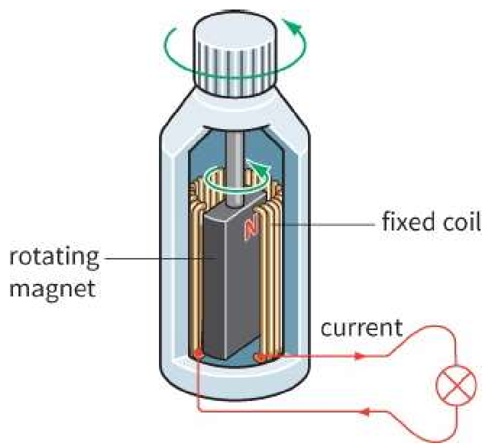

Figure 26.7: In a bicycle generator, a permanent magnet rotates inside a fixed coil of wire. For Question 1.

Current direction (extension)

How can we predict the direction of the current caused by induced e.m.f? For the motor effect in Chapter 24, we used Fleming's left-hand (motor) rule. Electromagnetic induction is like the mirror image of the motor effect. Instead of a current producing a force on a current-carrying conductor in a magnetic field, we provide an external force on a conductor by moving it through a magnetic field and this induces a current in the conductor. So you should not be too surprised to find that we use the mirror image of the left-hand rule: **Fleming's right-hand (generator) rule**.

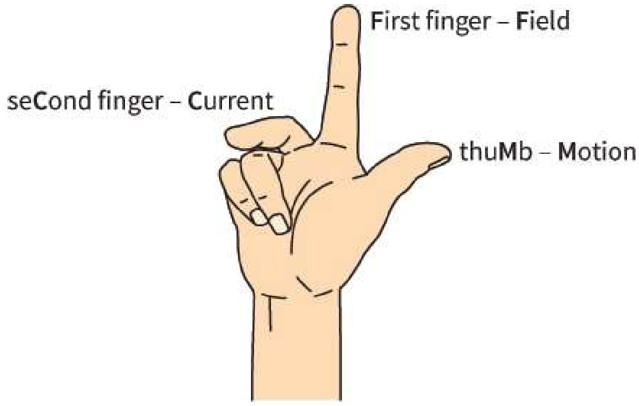

Figure 26.8: Fleming's right-hand (generator) rule.

The three fingers represent the same things again (Figure 26.8):

- thu**M**b–direction of **M**otion
- **F**irst finger–direction of external magnetic **F**ield
- se**C**ond finger–direction of (conventional) **C**urrent caused by induced e.m.f

In the example shown in Figure 26.9, the conductor is being moved downwards across the magnetic field. There is a current caused by induced e.m.f. in the conductor as shown. Check this with your own right hand. You should also check that reversing the movement or the field will result in the current flowing in the opposite direction.

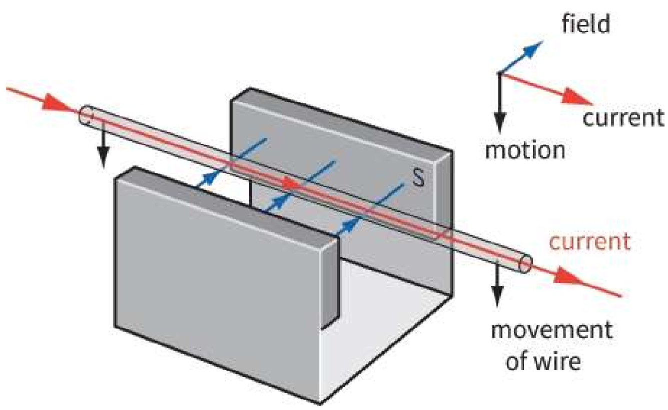

Figure 26.9: Deducing the direction of the current using Fleming's right-hand rule. (The wire shown is a part of a complete circuit or loop.)

Induced e.m.f.

When a conductor is not part of a complete circuit, there cannot be a current induced by e.m.f. Instead, negative charge will accumulate at one end of the conductor, leaving the other end positively charged. We have induced an e.m.f. across the ends of the conductor.

Is e.m.f. the right term? Should it be potential difference (voltage)? In Chapter 8, you saw the distinction between voltage and e.m.f. The term e.m.f. is the correct one here because, by pushing the wire through the magnetic field, work is done and this is transformed into electrical energy. Think of this in another way: since we could connect the ends of the conductor so that there is a current in some other component, such as a lamp, which would light up, it must be an e.m.f. – a source of electrical energy.

Figure 26.10 shows how an e.m.f. is induced. Notice that, within the conductor, conventional current is from negative to positive, in the same way as inside a battery or any other source of e.m.f. In reality, the free electrons within the conductor travel from right to left, making the left-hand side of the conductor negative. What causes these electrons to move? Moving the conductor is equivalent to giving a free electron within the conductor a velocity in the direction of this motion. This electron is in an external magnetic field and hence experiences a magnetic force Bev from right to left. Check this out for yourself.

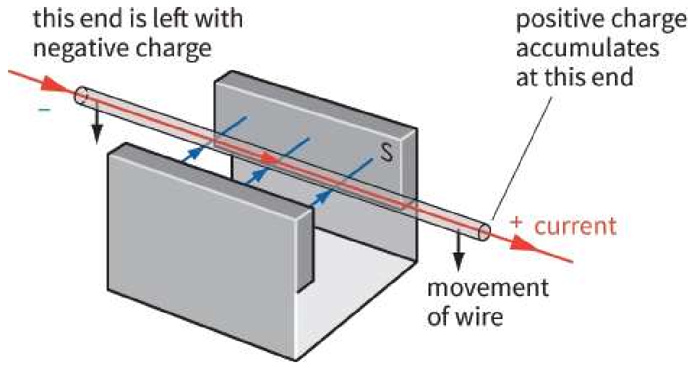

Figure 26.10: An e.m.f. is induced across the ends of the conductor.

Questions

2 The coil in Figure 26.11 is rotating in a uniform magnetic field.

Predict the direction of the current caused by induced e.m.f. in sections AB and CD.

State which terminal, X or Y, will become positive.

3 When an aircraft flies from east to west, its wings are an electrical conductor cutting across the Earth's magnetic flux. In the northern hemisphere, state which wingtip (left or right) will become positive.

State and explain what will happen to this wingtip in the southern hemisphere.

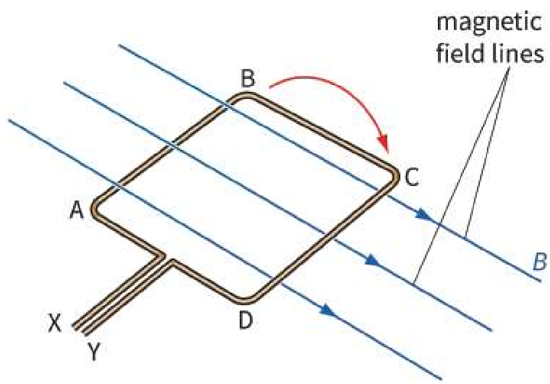

Figure 26.11: A coil rotating in a uniform magnetic field.

Magnetic flux and magnetic flux linkage

So far, in this chapter we have looked at the ideas of electromagnetic induction in a very descriptive manner. Now we will see how to calculate the value of the induced e.m.f. and look at a general way of determining its direction.

In Chapter 24, we saw how magnetic flux density B is defined by the equation

$$B = \frac{F}{IL}$$

Now we can go on to define **magnetic flux** as a quantity. We picture magnetic flux density B as the number of magnetic field lines passing through a region per unit area. Similarly, we can picture magnetic flux as the total number of magnetic field lines passing through a cross-sectional area A. For a magnetic field normal to A, the magnetic flux Φ (Greek letter phi) must therefore be equal to the product of magnetic flux density and the area A (Figure 26.12a).

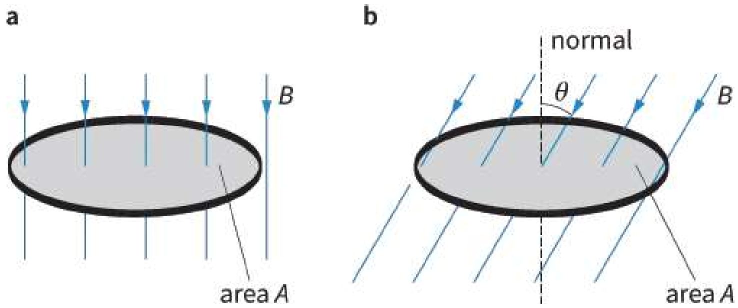

Figure 26.12: a The magnetic flux is equal to BA when the field is normal to the area. **b** The magnetic flux becomes when the field is at an angle θ to the normal of the area.

The magnetic flux Φ through cross-sectional area A is defined as:

$$\Phi = BA$$

where B is the component of the magnetic flux density perpendicular to the area.

KEY EQUATION

Magnetic flux:

$$\Phi = BA$$

KEY EQUATION

$$B \cos \theta$$

The component of the magnetic flux density B perpendicular to the plane of the cross-sectional area, where θ is the angle between the normal to the area and the magnetic field.

How can we calculate the magnetic flux when B is not perpendicular to A? You can easily see that when the field is parallel to the plane of the area, the magnetic flux through A is zero. To find the magnetic flux in general, we need to find the component of the magnetic flux density perpendicular to the cross-sectional area. Figure 28.12b shows a magnetic field at an angle θ to the normal. In this case:

$$\text{magnetic flux } \Phi = (B \cos \theta) \times A$$

or simply:

$$\text{magnetic flux } \Phi = BA \cos \theta$$

(Note that, when $\theta = 90°$, $\Phi = 0$ and when $\theta = 0°$ $\Phi = BA$)

For a coil with N turns, the **magnetic flux linkage** is defined as the product of the magnetic flux and the number of turns; that is:

$$\text{magnetic flux linkage} = N\Phi$$

or

$$\text{magnetic flux linkage} = BAN \cos \theta$$

The unit for magnetic flux, and magnetic flux linkage is the weber (Wb).

One weber (1 Wb) is the magnetic flux that passes perpendicularly through a cross-section of area 1 m^2 when the magnetic flux density is 1 T. 1 Wb = 1 Tm^2.

An e.m.f. is induced in a circuit whenever magnetic flux linking the circuit changes with respect to time. Since magnetic flux is equal to $BA \cos \theta$, there are three ways an e.m.f. can be induced:

- changing the magnetic flux density B
- changing the cross-sectional area A of the circuit
- changing the angle θ.

Now look at Worked example 1.

WORKED EXAMPLE

1 Figure 26.13 shows a solenoid with a cross-sectional area 0.10 m^2. It is linked by a magnetic field of flux density 2.0×10^{-3} T and has 250 turns.

Determine the magnetic flux and flux linkage for this solenoid.

Step 1 We have $B = 2.0 \times 10^{-3}$ T, $A = 0.10$ m^2, $\theta = 0°$ and $N = 250$ turns.

Hence we can calculate the flux Φ.

$$\begin{aligned} \Phi &= BA \\ &= 2.0 \times 10^{-3} \times 0.10 \\ &= 2.0 \times 10^{-4}\,\text{Wb} \end{aligned}$$

Step 2 Now calculate the flux linkage.

$$\begin{aligned} \text{magnetic flux linkage} &= N\Phi \\ &= 2.0 \times 10^{-4} \times 250 \\ &= 5.0 \times 10^{-2}\,\text{Wb} \end{aligned}$$

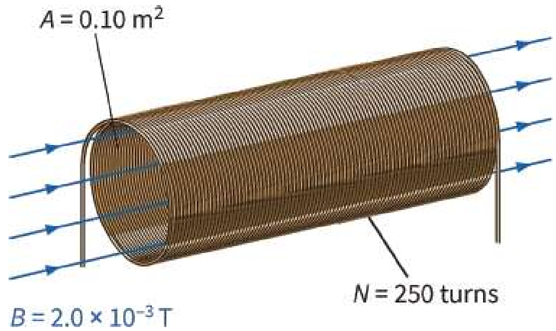

Figure 26.13: A solenoid in a magnetic field.

Questions

4 Use the idea of magnetic flux linkage to explain why, when a magnet is moved into a coil, the e.m.f. induced depends on the strength of the magnet and the speed at which it is moved.

5 In an experiment to investigate the factors that affect the magnitude of an induced e.m.f., a student moves a wire back and forth between two magnets, as shown in Figure 26.14. State why the e.m.f. generated in this way is almost zero.

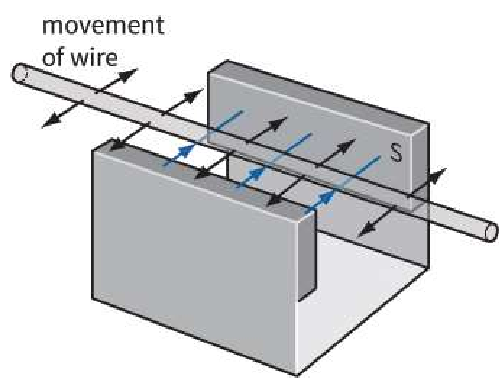

Figure 26.14: A wire is moved horizontally in a horizontal magnetic field. For Question 5.

6 In the type of generator found in a power station (Figure 26.15), a large electromagnet is made to rotate inside a fixed coil. An e.m.f. of 25 kV is induced; this is an alternating voltage of frequency 50 Hz.

a State the factor that determines the frequency.

b Suggest the factors that you think would affect the magnitude of the induced e.m.f.

Figure 26.15: For Question 6. The generators of this power station produce electricity at an induced e.m.f. of 25 kV.

7 At the surface of the north pole of a bar magnet, the magnetic field is uniform with flux density 0.15 T. The pole has dimensions 1.0 cm × 1.5 cm.

Calculate the magnetic flux at this pole.

8 A solenoid has diameter 5.0 cm, length 25 cm and 200 turns of wire (Figure 26.16). A current of 2.0 A creates a uniform magnetic field of flux density 2.0×10^{-5} T through the core of this solenoid.

a Calculate the magnetic flux linkage for this solenoid.

b The diameter of the solenoid is 5.0 ± 0.2 cm. Determine the absolute uncertainty in value calculated in part **a**. You may assume all the other quantities have negligible uncertainties.

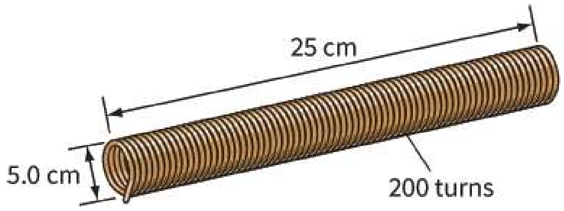

Figure 26.16: A solenoid. For Question 8.

9 A rectangular coil with 120 turns is placed at right angles to a magnetic field of flux density 1.2 T. The coil has dimensions 5.0 cm × 7.5 cm.

Calculate the magnetic flux linkage for this coil.

26.3 Faraday's law of electromagnetic induction

Earlier in this chapter, we saw that electromagnetic induction occurs when magnetic flux linking a circuit changes with time. We can now use **Faraday's law of electromagnetic induction** to determine the magnitude of the induced e.m.f. in a circuit:

The magnitude of the induced e.m.f. is directly proportional to the rate of change of magnetic flux linkage.

Remember that 'rate of change' in physics is equivalent to 'per unit time'. Therefore, we can write this mathematically as:

$$E \propto \frac{\Delta(N\Phi)}{\Delta t}$$

where $\Delta(N\Phi)$ is the change in the magnetic flux linkage in a time Δt. When working in SI units, the constant of proportionality is equal to 1. (At this level of study, you do not need to worry about why this is the case.)

Therefore:

$$E = \frac{\Delta(N\Phi)}{\Delta t}$$

The equation is a mathematical statement of Faraday's law. Note that it allows us to calculate the **magnitude** of the induced e.m.f.; its **direction** is given by Lenz's law, which is discussed later in topic 26.3 Faraday's law of electromagnetic induction.

Now look at Worked examples 2 and 3.

WORKED EXAMPLES

2 A straight wire of length 0.20 m moves at a steady speed of 3.0 m s^{-1} at right angles to a magnetic field of flux density 0.10 T. Use Faraday's law to determine the magnitude of the induced e.m.f. across the ends of the wire.

Step 1 With a single conductor, $N = 1$. To determine the induced e.m.f. E, we need to find the rate of change of magnetic flux; in other words, the change in magnetic flux per unit time.

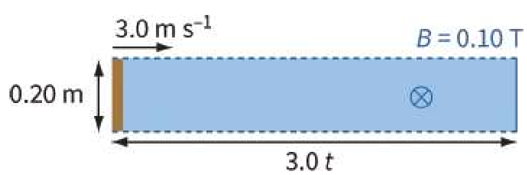

Figure 26.17: A moving wire cuts across the magnetic field.

Figure 26.17 shows that in a time t, the wire travels a distance $3.0t$.

Therefore:

change in magnetic flux = B × change in area

change in magnetic flux = 0.10 × (3.0t × 0.20) = 0.060t

Step 2 Use Faraday's law to determine the magnitude of the induced e.m.f.

E = rate of change of magnetic flux linkage

$$E = \frac{\Delta(N\Phi)}{\Delta t}$$

$\Delta\Phi = 0.060t$, $\Delta t = t$ and $N = 1$

$$\begin{aligned} E &= \frac{0.060t}{t} \\ &= 0.060 \text{ V} \end{aligned}$$

(The t cancels. You could have done this calculation for any time t, even 1.0 s. The results would still be the same.)

The magnitude of the induced e.m.f. across the ends of the wire is 60 mV.

3 This example illustrates one way in which the flux density of a magnetic field can be measured, shown in Figure 26.18. A search coil is a flat-coil with many turns of very thin insulated wire.

A search coil has 2500 turns and cross-sectional area 1.2 cm^2. It is placed between the poles of a magnet so that the magnetic flux passes perpendicularly through the plane of the coil. The magnetic field between the poles has flux density 0.50 T. The coil is pulled rapidly out of the field in a time of 0.10 s.

Calculate the magnitude of the average induced e.m.f. across the ends of the coil.

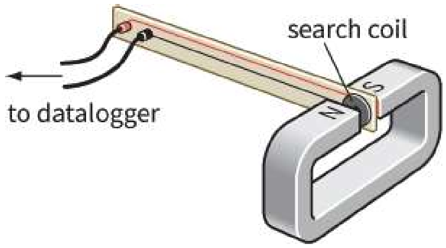

Figure 26.18: An e.m.f. is induced in the search coil when it is moved out of the field between the poles of the magnet. A search coil can be used to detect the presence of magnetic flux.

Step 1 Calculate the change in the magnetic flux linkage, $\Delta(N\Phi)$.

When the coil is pulled out from the field, the final flux linking the coil will be zero. The cross-sectional area A needs to be in m^2. Note: 1 cm^2 = 10^{-4} m^2.

$\Delta(N\Phi)$ = Final $N\Phi$ − initial $N\Phi$

$\Delta(N\Phi) = 0 - [2500 \times 1.2 \times 10^{-4} \times 0.50] = -0.15$ Wb

Step 2 Now calculate the induced e.m.f. using Faraday's law of electromagnetic induction.

$\Delta(N\Phi) = -0.15$ Wb and $\Delta t = 0.10$ s

$$\begin{aligned}\text{magnitude of e.m.f } E &= \frac{\Delta(N\Phi)}{\Delta t} \\ &= \frac{0.15}{0.10} \\ &= 1.5 \text{ V}\end{aligned}$$

(The negative sign is not required; you only need to know the size of the e.m.f.)

Note that, in this example, we have assumed that the flux linking the coil falls steadily to zero during the time interval of 0.10 s. The answer is, therefore, an average value of the induced e.m.f.

Questions

10 A conductor of length L moves at a steady speed v at right angles to a uniform magnetic field of flux density B.

Show that the magnitude of the induced e.m.f. E across the ends of the conductor is given by the equation: $E = BLv$

(You can use Worked example 2 to guide you through Question 10.)

11 A wire of length 10 cm is moved through a distance of 2.0 cm in a direction at right angles to its length in the space between the poles of a magnet, and perpendicular to the magnetic field. The flux density is 1.5 T. If this takes 0.50 s, calculate the magnitude of the average induced e.m.f. across the ends of the wire.

12 Figure 26.19 shows a search coil with 2000 turns and cross-sectional area 1.2 cm^2. It is placed between the poles of a strong magnet. The magnetic field is perpendicular to the plane of the coil. The ends of the coil are connected to a voltmeter. The coil is then pulled out of the magnetic field, and the voltmeter records an average induced e.m.f. of 0.40 V over a time interval of 0.20 s.

Calculate the magnetic flux density between the poles of the magnet.

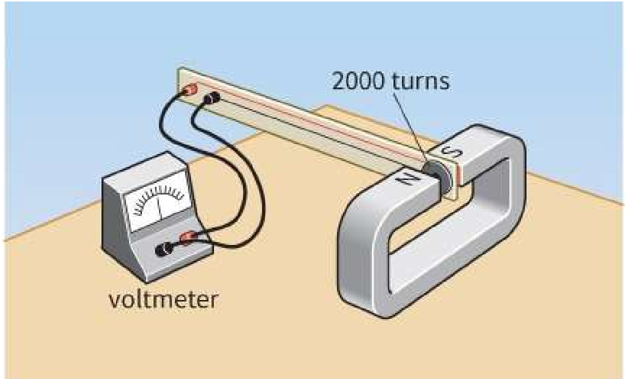

Figure 26.19: Using a search coil to determine the magnetic flux density of the field between the poles of this magnet.

26.4 Lenz's law

We use Faraday's law to calculate the magnitude of an induced e.m.f. Now, we can go on to think about the direction of the induced e.m.f. – in other words, which end of a wire or coil moving in a magnetic field becomes positive, and which becomes negative.

Fleming's right-hand rule gives the direction of a current caused by induced e.m.f. This is a particular case of a more general law, Lenz's law, which will be explained in this topic. First, we will see how the motor effect and the generator effect are related to each other.

The origin of electromagnetic induction

So far, we have not given an explanation of electromagnetic induction. You have seen, from the experiments at the beginning of this chapter, that it does occur, and you know the factors that affect it. But what is the origin of the current?

Figure 26.20 gives an explanation. A straight metal wire XY is being pushed downwards through a horizontal magnetic field of flux density B. Now, think about the free electrons in the wire. They are moving downwards, so they are, in effect, an electric current. Of course, because electrons are negatively charged, the conventional current is flowing upwards.

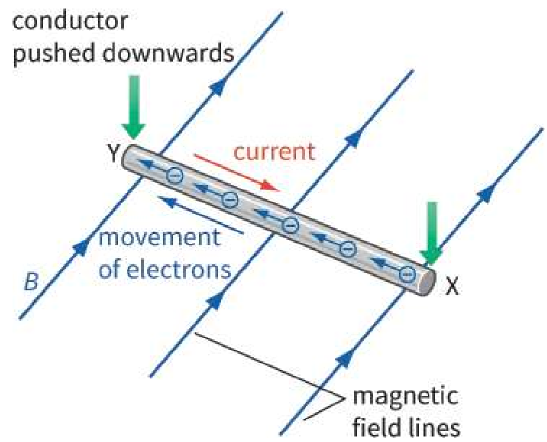

Figure 26.20: Showing the direction of the current caused by the induced e.m.f.

We now have a current flowing across a magnetic field, and the motor effect will, therefore, come into play. Each electron experiences a force of magnitude Bev. Using Fleming's left-hand rule, we can find the direction of the force on the electrons. The diagram shows that the electrons will be pushed in the direction from X to Y. So a current has been induced to flow in the wire; the direction of the conventional current is from Y to X.

Now, we can check that Fleming's right-hand rule gives the correct directions for motion, field and current, which indeed it does.

So, to summarise, there is a current caused by the induced e.m.f. current because the electrons are pushed by the motor effect. Electromagnetic induction is simply a consequence of the motor effect.

In Figure 26.20, electrons are found to accumulate at Y. This end of the wire is thus the negative end of the e.m.f. and X is positive. If the wire was connected to an external circuit, electrons would flow out of Y, round the circuit, and back into X. Figure 26.21 shows how the moving wire is equivalent to a cell (or any other source of e.m.f.).

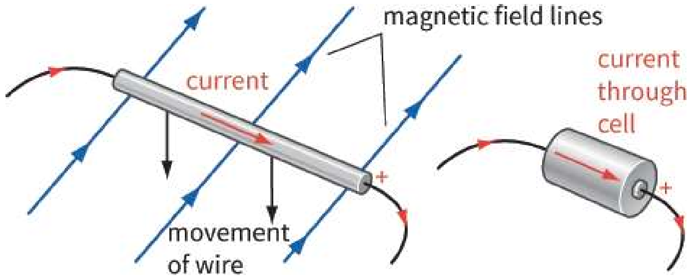

Figure 26.21: A moving wire in a magnetic field is a source of e.m.f. – equivalent to a cell.

Forces and movement

Electromagnetic induction is how we generate most of our electricity. We turn a coil in a magnetic field, and the mechanical energy we put in is transferred to electrical energy. By thinking about these energy transfers, we can deduce the direction of the current.

Figure 26.22 shows one of the experiments from earlier in this chapter. The north pole of a magnet is being pushed towards a coil of wire. There is a current in the coil, but what is its direction? The diagram shows the two possibilities.

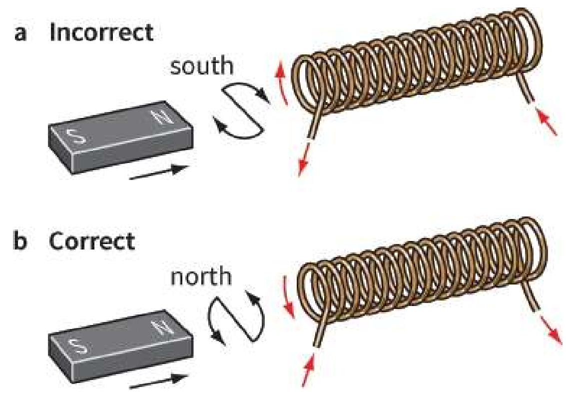

Figure 26.22: Moving a magnet towards a coil: the direction of the current caused by the induced e.m.f. is as shown in **b**, not **a**.

The current in the coil makes it into an electromagnet. One end becomes the north pole, the other the south pole. In Figure 26.22a, if the current is in this direction, the coil end nearest the approaching north pole of the magnet would be a south pole. These poles will attract one another, and you could gently let go of the magnet and it would be dragged into the coil. The magnet would accelerate into the coil, the current caused by induced e.m.f. would increase further, and the force of attraction between the two would also increase.

In this situation, we would be putting no (or very little at the start) energy into the system, but the magnet would be gaining kinetic energy, and the current would be gaining electrical energy. A nice trick if you could do it, but this would violate the principle of conservation of energy!

Figure 26.22b shows the correct situation. As the north pole of the magnet is pushed towards the coil, the current caused by the induced e.m.f. makes the end of the coil nearest the magnet become a north pole. The two poles repel one another, and you have to do work to push the magnet into the coil. The energy transferred by your work is transferred to electrical energy of the current. The principle of energy conservation is not violated in this situation.

Figure 26.23 shows how we can apply the same reasoning to a straight wire being moved in a downward direction through a magnetic field. There will be a current caused by induced e.m.f. in the wire, but in which direction? Since this is a case of a current across a magnetic field, a force will act on it (the motor effect), and we can use Fleming's left-hand rule to deduce its direction.

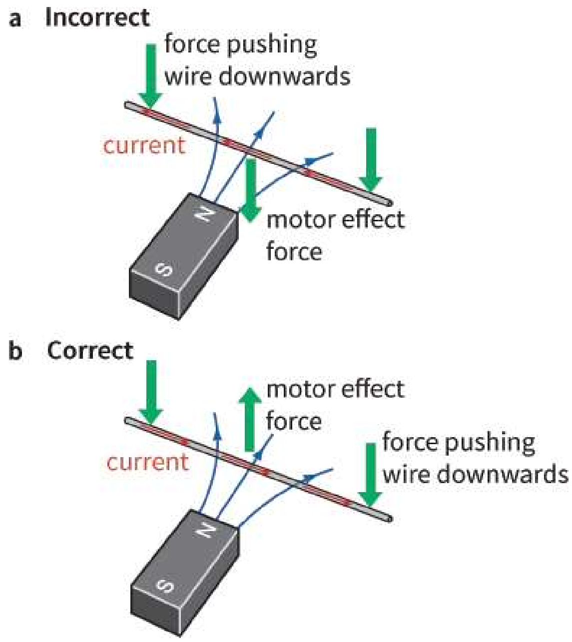

Figure 26.23: Moving a wire through a magnetic field: the direction of the current is as shown in **b**, not **a**.

First, we will consider what happens if the current caused by the induced e.m.f. is in the wrong direction. This is shown in Figure 26.23a. The left-hand rule shows that the force that results would be downward– in the direction in which we are trying to move the wire. The wire would thus be accelerated, the current would increase and again we would be getting both kinetic and electrical energy for no energy input.

The current must be as shown in Figure 26.23b. The force that acts on it due to the motor effect pushes against you as you try to move the wire through the field. You have to do work to move the wire, and hence to generate electrical energy. Once again, the principle of energy conservation is not violated.

Questions

13 Use the ideas in the previous topic to explain what happens if **a** you stop pushing the magnet towards the coil shown in Figure 26.22, and **b** you pull the magnet away from the coil.

14 Draw a diagram to show the directions of the current caused by induced e.m.f. and of the opposing force if you now try to move the wire shown in Figure 26.23 upwards through the magnetic field.

A general law for induced e.m.f.

Lenz's law summarises this general principle of energy conservation. The direction of a current caused by induced e.m.f. or e.m.f is such that it always produces a force that opposes the motion that is being used to produce it. If the direction of the e.m.f were opposite to this, we would be getting energy for nothing.

Here is a statement of Lenz's law:

Any induced e.m.f. will be established in a direction so as to produce effects that oppose the change that is producing it.

This law can be shown to be correct in any experimental situation. For example, in Figure 26.3, a sensitive ammeter connected in the circuit shows the direction of the current as the magnet is moved in and out. If a battery is later connected to the coil to make a larger and constant current in the same direction, a compass will show what the poles are at the end of the solenoid. If a north pole is moved into the solenoid, then the solenoid itself will have a north pole at that end. If a north pole is moved out of the solenoid, then the solenoid will have a south pole at that end.

Faraday's law of electromagnetic induction, and Lenz's law, may be summarised using the equation:

$$E = -\frac{\Delta(N\Phi)}{\Delta t}$$

where E is the magnitude of the induced e.m.f. and the minus sign indicates that this induced e.m.f. causes effects to oppose the change producing it.

The minus sign is there because of Lenz's law – it is necessary to emphasise the principle of conservation of energy.

KEY EQUATION

$$E = -\frac{\Delta(N\Phi)}{\Delta t}$$

Induced electromagnetic force.

Questions

15 A bar magnet is dropped vertically downwards through a long solenoid, which is connected to an oscilloscope (Figure 26.24). The oscilloscope trace shows how the e.m.f. induced in the coil varies with time as the magnet accelerates downwards.

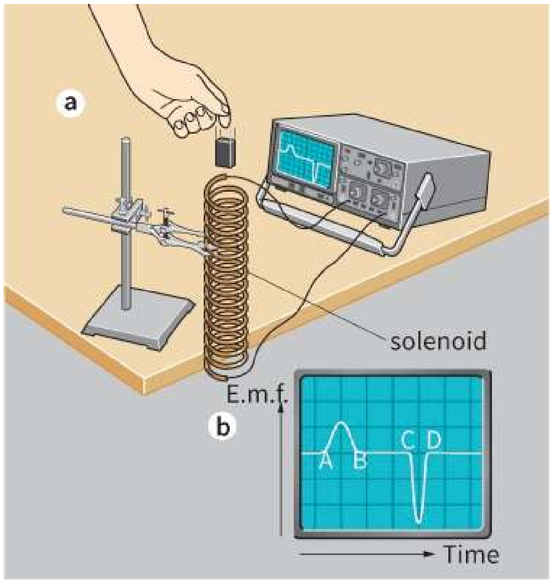

Figure 26.24: **a** A bar magnet falls through a long solenoid. **b** The oscilloscope trace shows how the induced e.m.f. varies with time.

- **a** Explain why an e.m.f. is induced in the coil as the magnet enters it (section AB of the trace).
- **b** Explain why no e.m.f. is induced while the magnet is entirely inside the coil (section BC).
- **c** Explain why section CD shows a negative trace, why the peak e.m.f. is greater over this section, and why CD represents a shorter time interval than AB.

16 You can turn a bicycle dynamo by hand and cause the lamps to light up. Use the idea of Lenz's law to explain why it is easier to turn the dynamo when the lamps are switched off than when they are on.

26.5 Everyday examples of electromagnetic induction

An induced e.m.f. can be generated in a variety of ways, but can be explained in terms of Faraday's and Lenz's laws. An e.m.f. will be induced whenever there is a rate of change of magnetic flux linkage for a circuit or device. In this topic, we will examine the physics behind two devices – a generator and a transformer.

Generators

We can generate electricity by spinning a coil in a magnetic field. This is equivalent to using an electric motor backwards. Figure 26.25 shows such a coil in three different orientations as it spins.

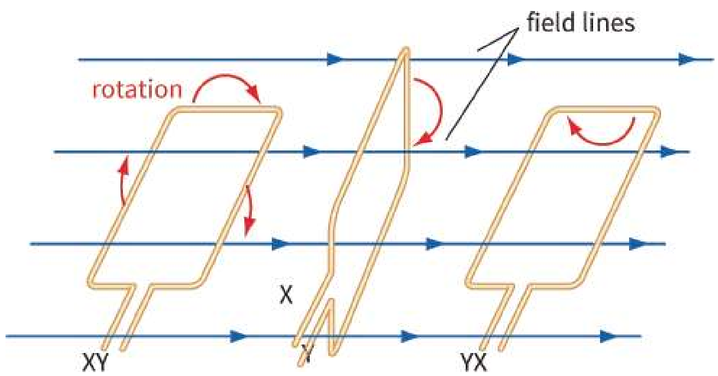

Figure 26.25: A coil rotating in a magnetic field.

Notice that the rate of change of magnetic flux linkage is maximum when the coil is moving through the **horizontal** position. In this position, we get a large induced e.m.f. As the coil moves through the **vertical** position, the rate of change of magnetic flux is zero and the induced e.m.f. is zero.

Figure 26.26 shows how the magnetic flux linkage varies with time for a rotating coil.

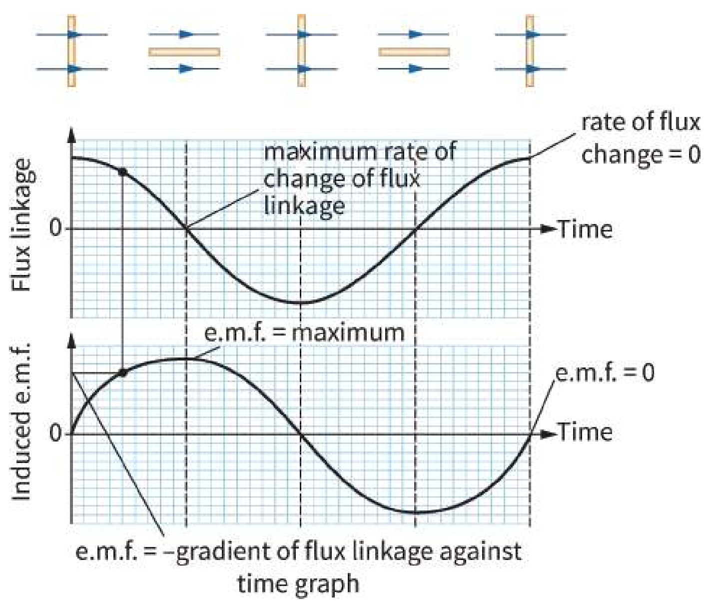

Figure 26.26: The magnetic flux linking a rotating coil as it changes. This gives rise to an alternating e.m.f. The orientation of the coil is shown above the graphs.

According to Faraday's and Lenz's laws, the induced e.m.f. is equal to minus the **gradient** of the flux linkage against time graph:

$$E = -\frac{\Delta(N\Phi)}{\Delta t}.$$

When the flux linking the coil is:

- maximum, the rate of change of flux linkage is zero and hence the induced e.m.f. is zero
- zero, the rate of change of flux linkage is maximum (the graph is steepest) and hence the induced e.m.f. is also maximum.

Hence, for a coil like this, we get a varying e.m.f. – this is how alternating current is generated. In practice, it is simpler to keep the large coil fixed and spin an electromagnet inside it (Figure 26.27). A bicycle generator is similar, but in this case a permanent magnet is made to spin inside a fixed coil.

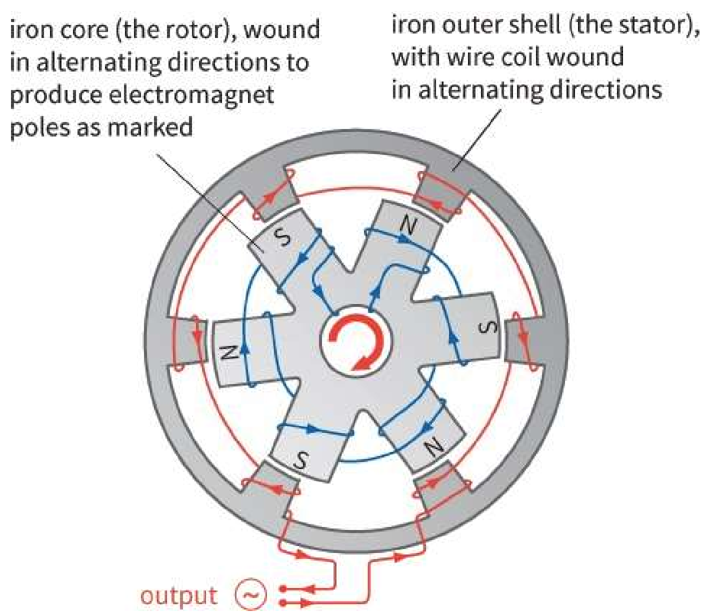

Figure 26.27: In a generator, an electromagnet rotates inside a coil.

Transformers

You may have studied transformers before your study of this course.

A simple transformer has a primary coil and a secondary coil, both wrapped around a soft iron core (ring). An alternating current is supplied to the primary coil. This produces a varying magnetic flux in the soft iron core (see Figure 26.28). The secondary coil is linked by the same changing magnetic flux in the soft iron core, so an e.m.f. is induced at the ends of this coil. According to Faraday's law, you can increase the induced e.m.f. at the secondary coil by increasing the number of turns of the secondary coil. Having fewer turns on the secondary will have the reverse effect.

Transformers are used to transport electrical energy using overhead cables.

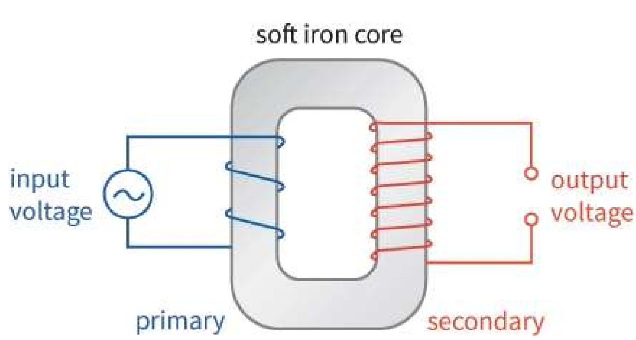

Figure 26.28: Faraday's law can be used to explain the output from a transformer.

Questions

17 Figure 26.29 represents a coil of wire ABCD being rotated in a uniform horizontal magnetic field.

Copy and complete the diagram to show the direction of the current caused by induced e.m.f. in the coil, and the directions of the forces on sides AB and CD that oppose the rotation of the coil.

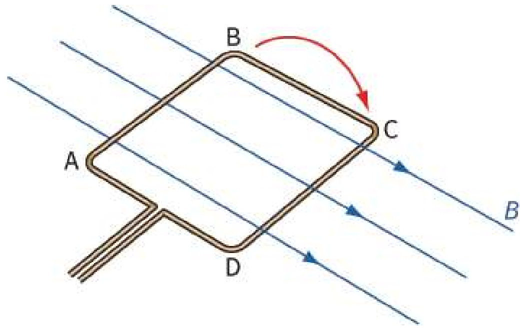

Figure 26.29: A coil rotating in a magnetic field.

18 Does a bicycle generator (Figure 26.7) generate alternating or direct current? Justify your answer.

19 The peak e.m.f. induced in a rotating coil in a magnetic field depends on four factors: magnetic flux density B, area of the coil A, number of turns N and frequency f of rotation. Use Faraday's law to explain why the magnitude of the induced e.m.f. must be proportional to each of these quantities.

20 Explain why, if a transformer is connected to a steady (d.c.) supply, no e.m.f. is induced across the secondary coil.

REFLECTION

Without looking at your textbook, summarise the factors that affect the e.m.f. induced in a circuit. Compare your summary with a fellow learner.

Make a deck of cards with all the physical quantities in this chapter. Do the same for the units for each quantity. Ask a fellow learner to match the quantities with their units.

How can you better support and encourage your classmates on future activities and questions?

SUMMARY

In a magnetic field of magnetic flux density B, the magnetic flux Φ passing through a cross-sectional area A is given by:

$$\Phi = BA$$

Magnetic flux linkage = N × magnetic flux = $N\Phi$

Magnetic flux and magnetic flux linkage are both measured in webers (Wb). 1 Wb = 1 T m^2.

An e.m.f. is induced in a circuit whenever there is a change in the magnetic flux linkage.

Faraday's law states that the magnitude of the induced e.m.f. is equal to the rate of change of magnetic flux linkage:

$$E = \frac{\Delta(N\Phi)}{\Delta t}$$

Lenz's law states that the induced current or e.m.f. is in a direction so as to produce effects that oppose the change that is producing it.

The equation for both Faraday's and Lenz's laws may be written as:

$$E = -\frac{\Delta(N\Phi)}{\Delta t}$$

EXAM-STYLE QUESTIONS

1 Which of the following units is **not** correct for magnetic flux? **[1]**

A kg m^2 s^{-2} A^{-1}

B T

C T m^2

D Wb

2 A student thinks that electrical current passes through the core in a transformer to the secondary coil. Describe how you might demonstrate that this is not true and explain how an electrical current is actually induced in the secondary coil. Use Faraday's law in your explanation. **[3]**

3 A square coil of 100 turns of wire has sides of length 5.0 cm. It is placed in a magnetic field of flux density 20 mT, so that the flux is perpendicular to the plane of the coil.

a Calculate the flux through the coil. **[2]**

b The coil is now pulled from the magnetic field in a time of 0.10 s. Calculate the average e.m.f. induced in it. **[3]**

[Total: 5]

4 An aircraft of wingspan 40 m flies horizontally at a speed of 300 ± 10 m s^{-1} in a region where the vertical component of the Earth's magnetic field is 5.0 × 10^{-5} T.

Calculate the magnitude of the e.m.f. induced between the aircraft's wingtips; in your answer, include the absolute uncertainty. **[5]**

5 Figure 28.26 shows the magnetic flux linkage and induced e.m.f. as a coil rotates. Explain why the induced e.m.f. is a maximum when there is no flux linkage and the induced e.m.f. is zero when the flux linkage is a maximum. **[4]**

6 **a** Explain what is meant by a magnetic flux linkage of 1 Wb. **[2]**

b This is a graph of magnetic flux density through a 240 turn coil with a cross-sectional area 1.2 × 10^{-4} m^2 against time.

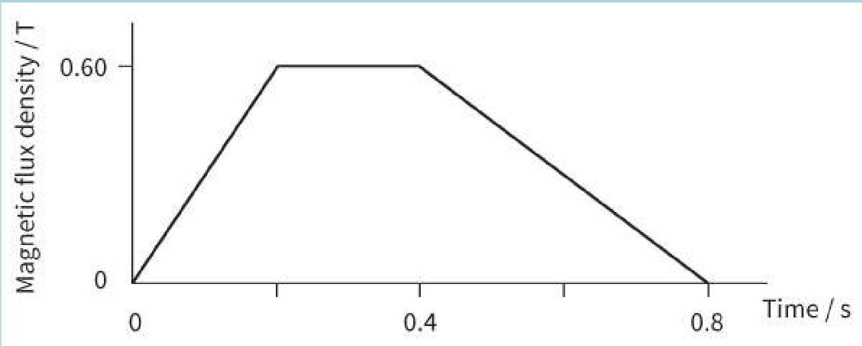

Figure 26.30

i Determine the maximum rate of change of flux in the coil. **[2]**

ii Determine the maximum magnitude of the induced e.m.f. in the coil. **[2]**

iii Sketch a diagram to show the induced e.m.f. varies with time. Mark values on both the e.m.f. and time axes. **[2]**

[Total: 8]

7 This diagram shows a square coil about to enter a region of uniform magnetic field of magnetic flux density 0.30 T. The magnetic field is at right angles to the plane of the coil. The coil has 150 turns and each side is 2.0 cm in length. The coil moves at a constant speed of 0.50 m s^{-1}.

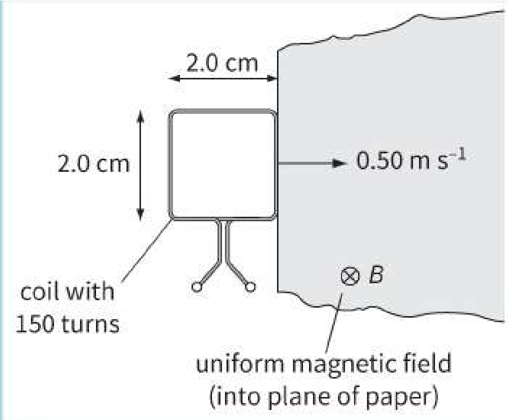

Figure 26.31

a **i** Calculate the time taken for the coil to completely enter the region of magnetic field. **[1]**

ii Determine the magnetic flux linkage through the coil when it is all within the region of magnetic field. **[2]**

b Explain why the magnitude of the induced e.m.f. is constant while the coil is entering the magnetic field. **[1]**

c Use your answer to part a to determine the induced e.m.f. across the ends of the coil. **[4]**

d Explain the induced e.m.f. across the ends of the coil when it is completely within the magnetic field. **[2]**

e Sketch a graph to show the variation of the induced e.m.f. with time from the instant that the coil enters the magnetic field. Your time axis should go from 0 to 0.08 s. **[2]**

[Total: 12]

8 **a** State Faraday's law of electromagnetic induction. **[2]**

b A circular coil of diameter 200 mm has 600 turns is shown. It is placed with its plane perpendicular to a horizontal magnetic field of uniform flux density 50 mT. The coil is then rotated through 90° about a vertical axis in a time of 120 ms.

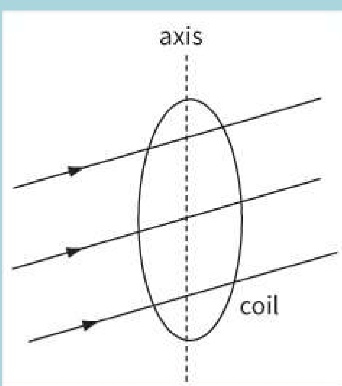

Figure 26.32

Calculate:

i the magnetic flux passing through the coil before the rotation **[2]**

ii the change of magnetic flux linkage produced by the rotation **[2]**

iii the average magnitude of the induced e.m.f. in the coil during the rotation. **[2]**

[Total: 8]

9 A bicycle wheel is mounted vertically on a metal axle in a horizontal magnetic field, as shown in the diagram. Sliding connections are made to the metal edge of the wheel and to the metal axle.

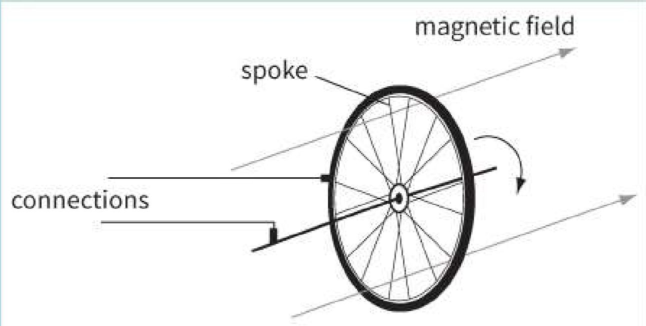

Figure 26.33

a **i** Explain why an e.m.f. is induced when the wheel rotates. **[2]**

ii State and explain two ways in which this e.m.f. can be increased. **[2]**

b The wheel rotates five times per second and has a radius of 15 cm. The magnetic flux density may be assumed to be uniform and of value 5.0×10^{-3} T.

Calculate:

i the area swept out each second by one spoke **[2]**

ii the induced e.m.f. between the contacts. **[2]**

[Total: 8]