

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

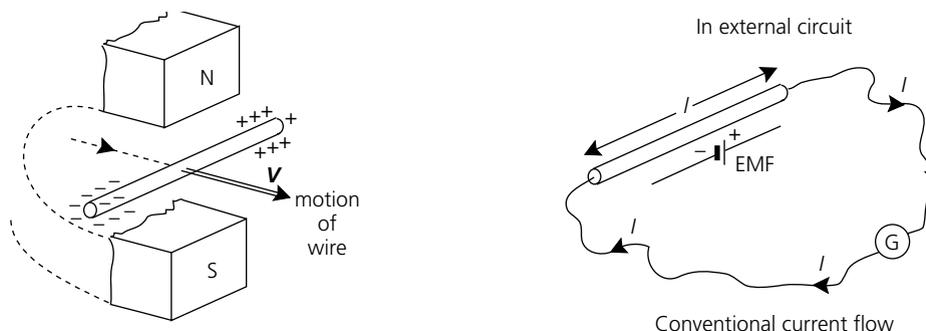
— Faraday's law

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.



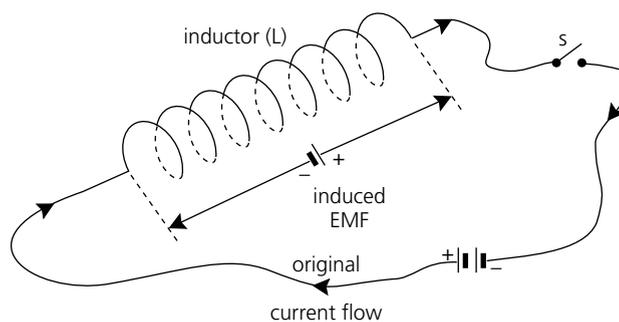
Notice in Figure 26.1 that for a maximum induced EMF and its consequent induced current, the conductor needs to be moved perpendicular to the lines of magnetic flux. We say that the magnetic flux lines are being cut in a perpendicular direction for maximum induced voltage. Alternatively, there will be 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.

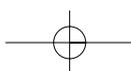
An easy way to visualise this rule in terms of the separation of charge is to imagine a small test positive charge sitting within the conductor. As the conductor is moved this test charge moves in a direction as given by the thumb in the RH motor rule. The extended fingers point in the direction of the 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.

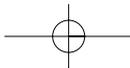
— Self-induction

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

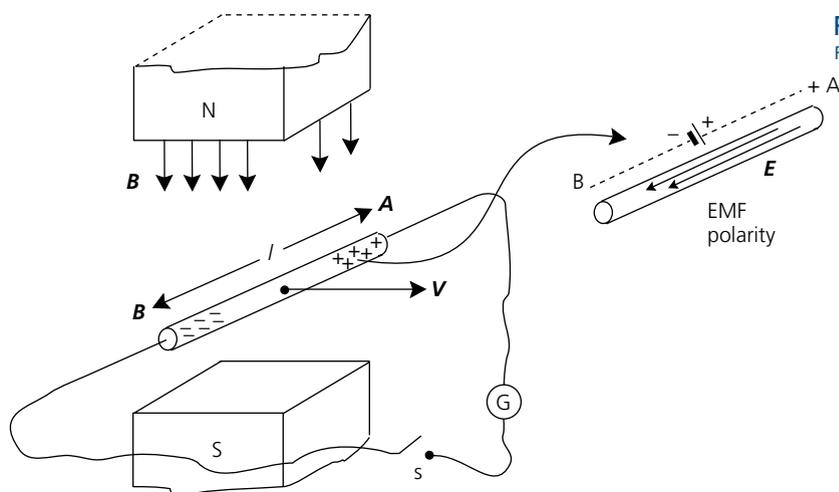


Figure 26.3
Faraday's law.

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 v . The magnetic force acting on each moving electron is given by: where B = magnetic field strength in teslas; q = charge on the electron in coulombs; v = velocity of motion in m s^{-1} .

$$F_B = qvB$$

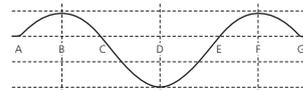
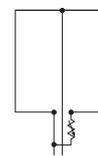
This force has a direction such that the electrons are pushed towards end B as the conductor is moved. This leaves end A equally charged but positive. As the charges build up at each end, AB, of the conductor, an electric field E is set up within the conductor, which begins to oppose the free flow of 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:

$$F_E = F_B$$

$$F_E = qE$$

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 through 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'.

