UNIT 14

.....Electromagnetic induction.....

After studying this chapter students will be able to:

- describe the production of electricity by magnetism.
- explain that induced emf's can be generated in two ways.
  - (i) by relative movement (the generator effect).
  - (ii) by changing a magnetic field (the transformer effect).
- infer the factors affecting the magnitude of the induced emf.
- state Faraday's law of electromagnetic induction.
- account for Lenz's law to predict the direction of an induced current and relate to the principle of conservation of energy.
- apply Faraday's law of electromagnetic induction and Lenz's law to solve problems.
- explain the production of eddy currents and identify their magnetic and heating effects.
- explain the need for laminated iron cores in electric motors, generators and transformers.
- explain what is meant by motional emf. Given a rod or wire moving through a magnetic field in a simple way, compute the potential difference across its ends.
- define mutual inductance (M) and self-inductance (L), and their unit henry.
- describe the main components of an A.C generator and explain how it works.
- describe the main features of an A.C electric motor and the role of each feature.
- explain the production of back emf in electric motors.
- describe the construction of a transformer and explain how it works.
- identify the relationship between the ratio of the number of turns in the primary and secondary coils and the ratio of primary to secondary voltages.

- describe how step-up and step-down transformers can be used to ensure efficient transfer of electricity along cables.

Electricity and magnetism are two aspects of a single electromagnetic force. Moving electric charges produce magnetic forces and moving magnets produce electric forces. The interplay of electric and magnetic forces is the basis for electric motors, generators, and many other modern technologies.

Figure 14.1: electric motor is the heart of domestic appliances such as vacuum cleaners, washing machines, electric trains, lifts, and cars etc.,

The essential feature of an electric motor is the supply of electrical energy to a coil in a magnetic field causing it to rotate. The generation of electrical power requires relative motion between a magnetic field and a conductor. In a generator, mechanical energy is converted into electrical energy while the opposite occurs in an electric motor. The electric motor is a simple device in principle. It converts electric energy into mechanical energy. In this chapter we will discuss these basic motor principles.

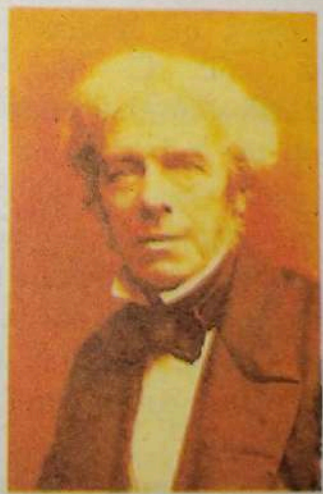


Fig: 14.2: Michael Faraday

In 1831, English scientist Michael Faraday discovered that when the magnetic flux linking a conductor changes, an e.m.f is induced in the conductor. This phenomenon is known as electromagnetic induction. In this chapter, we will study the various aspects of electromagnetic induction.

14.1 ELECTROMAGNETIC INDUCTION

When the magnetic flux linking a conductor changes, an e.m.f is induced in the conductor this phenomenon is known as electromagnetic induction. The basic requirement for electromagnetic induction is the change in flux linking the conductor (or coil).

Activity :

In order to demonstrate the phenomenon of electromagnetic induction, consider a coil C of wire connected to a galvanometer as shown in Fig14.3(a). Near the coil is a stationary bar magnet. When the magnet is stationary the galvanometer shows no current so there is no source of e.m.f. in the circuit.

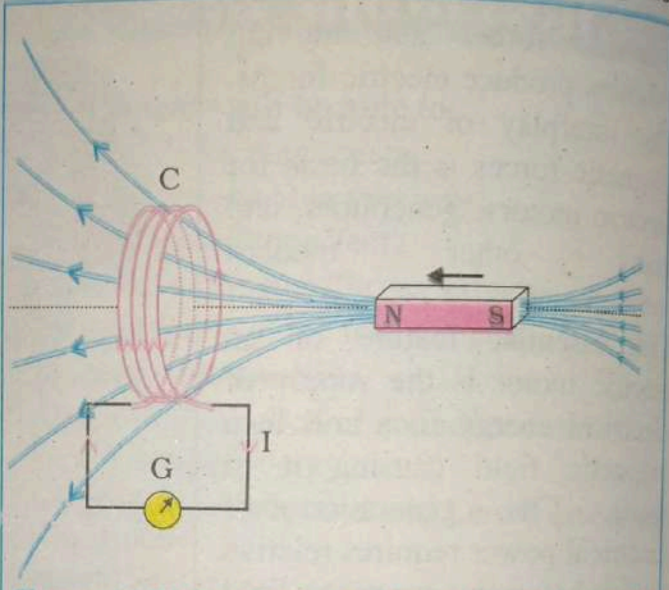


Figure 14.3(a): When the bar magnet is pushed towards the coil, the pointer in the galvanometer G deflects.

Now if we move the magnet towards the coil C, the galvanometer will show deflection in one direction. If we move the magnet away from the coil, the galvanometer again shows deflection but in the opposite direction. In either case, the deflection will persist so long as the magnet is in motion. The production of e.m.f. and hence current in the coil *C* is due to the fact that when the magnet is in motion (towards or away from the coil), the amount of flux linking the coil changes-the basic requirement for inducing e.m.f. in the coil. If the movement of the magnet is stopped, though the flux is linking the coil there is no change in flux so no e.m.f is induced in the coil therefor galvanometer shows zero deflection.

The product of number of turns (N) of the coil and the magnetic flux (Φ) linking the coil is called flux linkages i.e.

$$\text{Flux linkages} = N\Phi$$

The phenomenon of electromagnetic induction may be demonstrated in another way as when the current carrying primary coil is moved away or towards

the stationary coil. The current in the primary coil set up a magnetic field that links the stationary coil. Again it is the relative mótion of the primary coil which causes induced emf in the coil, and the voltmeter shows deflection.
The e.m.f and current will persist in the coil as long as flux through the coil is changing.

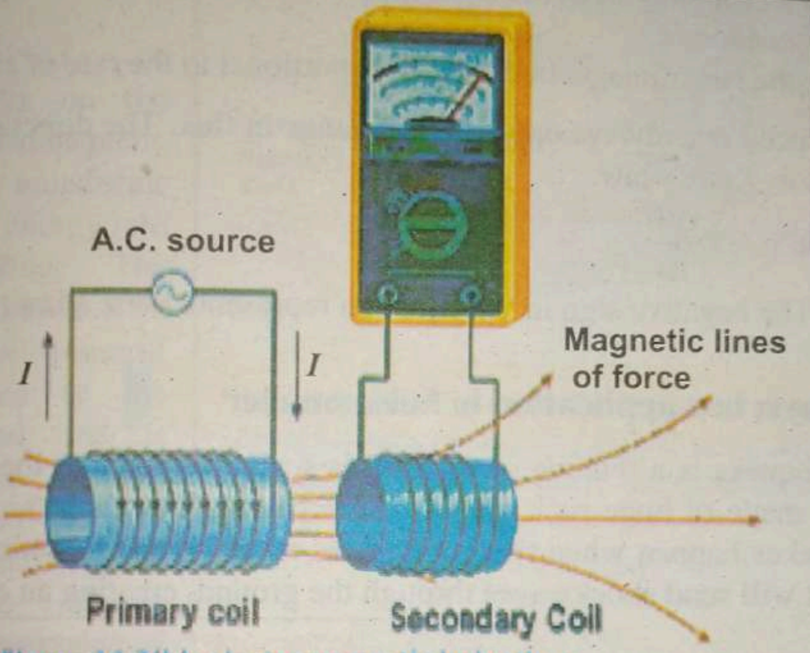


Figure 14.3(b): electromagnetic induction

14.2 FARADAY'S LAWS OF ELECTROMAGNETIC INDUCTION

As the magnitude of e.m.f. induced in a coil is directly proportional to the rate of change of flux linkages. If N is the number of turns of the coil and the magnetic flux linking the coil changes from Φ_1 to Φ_2 in t seconds, then,
Induced e.m.f., $\mathcal{E} \propto$ rate of change of flux linkages

Induced emf , $\mathcal{E} \propto N \dfrac{\Delta\Phi}{\Delta t}$

$$\mathcal{E} = k N \frac{\Delta\Phi}{\Delta t}$$

Where k is constant and its value is $k = 1$

$$\mathcal{E} = N\frac{\Delta\Phi}{\Delta t}$$

Above equation is called Faraday law of induction.

Faraday proposed two laws of electromagnetic induction:

(1) a changing magnetic field induces an electromagnetic force in a conductor;

(2) the electromagnetic force is proportional to the rate of change of the field

The induced emf always opposes the change in flux. The direction of induced emf is given by Lenz's law.

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

The negative sign in the equation represents Lenz's law.

Faradays; law application in Seismometer

An earthquake is a shaking of the earth's surface, known as the crust. The earth's crust is made of huge rock plates, which can shift to cause an earthquake. Most earthquakes happen when two rock plates meet, creating friction. The force is so strong it will send shockwaves through the ground, creating an earthquake.

There are millions of earthquakes every day! Most earthquakes are very small, so no one can feel it. Earthquakes can happen anywhere: land, mountains and oceans. To measure the earthquakes we use a device which is called seismometer.

It's used by seismologists in order to detect earthquakes. One kind of seismometer is called inertial because it is based on Newton's 1st Law. It consists of spring mass system which records the vibrations in the earth's surface and will pick up even the slightest vibration.

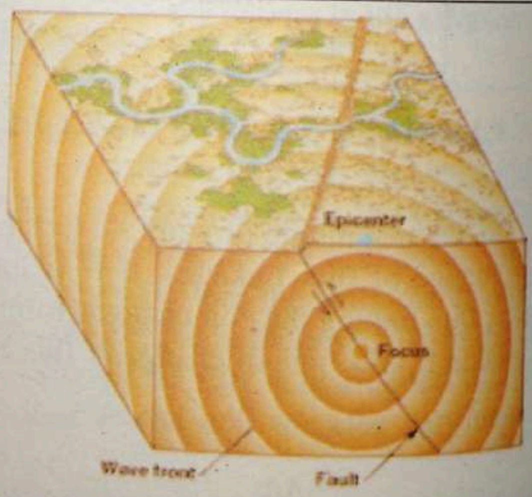


Figure 14.4(a): The focus of an earthquake is the location where rupture begins and energy is released. The place on the surface vertically above the focus is the epicenter. Seismic wave fronts move out in all directions from their source, the focus of an earth.

This is recorded on a sheet of paper under the seismograph needle that writes it. When there are vibrations, the needle sways, causing bigger lines to be drawn. As shown in figure.

The other kind of seismometer works on the principle of electromagnetic induction. It transforms received vibration energy into an electrical voltage. The relative motion between a magnet and a coil (one of which is attached to the inertial mass and one is attached to the frame) induces an emf in the coil that is proportional to the velocity of the relative motion. The magnitude of emf is also proportional to the strength of the magnet used and the number of turns in the coil.

In practice either the magnet or the coil can be attached to the inertial mass (in commercial systems the magnet is itself often used as the inertial mass).

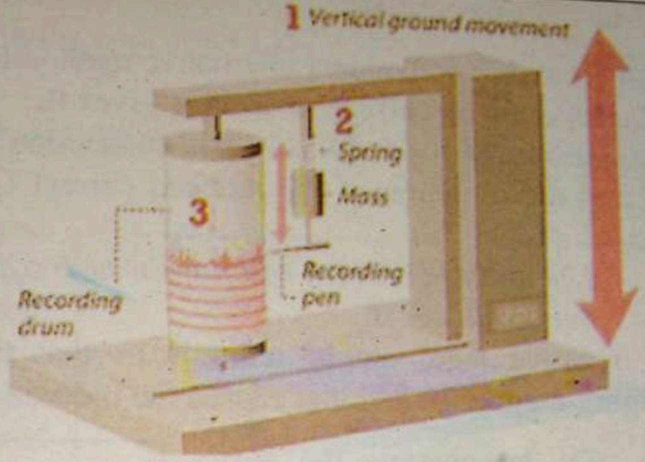


Figure 14.4(b): A vertical-motion seismograph. This seismograph operates on the same principle as a horizontal-motion instrument and records vertical ground movement.

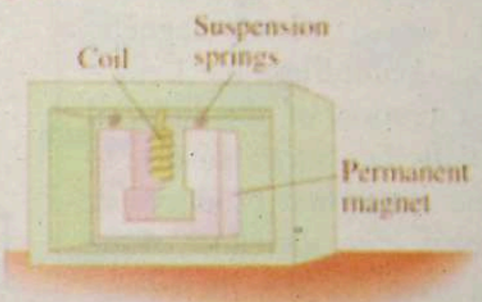


Figure 14.4(c) : electromagnetic seismometer has a coil fixed to the case and moves with the earth. The magnet suspended by spring has inertia and does not move instantaneously with the coil (and case), so there is relative motion between magnet and coil.

14.3 Lenz's Law:

Lenz's law is a convenient alternative method for determining the direction of an induced e.m.f or current. It always gives the same results as the sign rules we have introduced for $\mathcal{E}$ and $\Delta\Phi/\Delta t$ in connection with Faraday's law.

To find the direction of the induced current German scientist Lenz's proposed that:

The induced current will flow in such a direction so as to oppose the cause that produces it.

The negative sign simply reminds us that the induced current opposes the changing magnetic field that caused the induced current. $\mathcal{E} = -\Delta\Phi/\Delta t$.

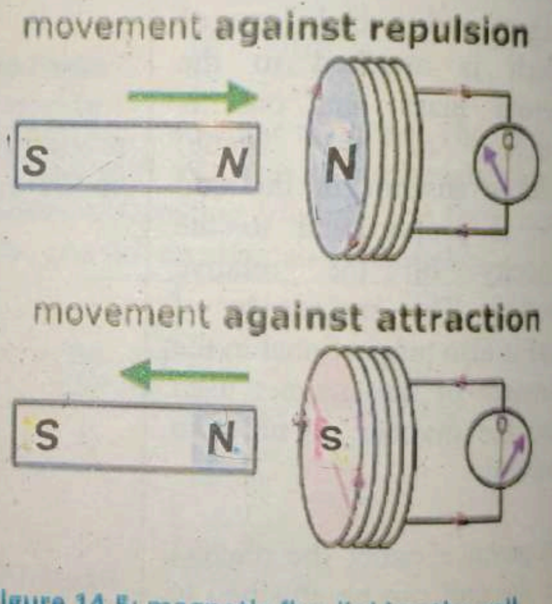


Figure 14.5: magnetic flux linking the coil

To demonstrate the lenz's law consider the *N*-pole of the magnet towards the coil as shown in fig. As the *N*-pole of the magnet moves towards the coil, the magnetic flux linking the coil produces electromagnetic induction. According to Lenz's law, the direction of the induced current will be such so as to oppose the cause that produces it. In the present case, the cause of the induced current is the increasing magnetic flux linking the coil. So the induced current will set up magnetic flux that opposes the increase in flux through the coil. This is possible only if the left hand face of the coil become *N*-pole. Once we know the magnetic polarity of the coil face, the direction of the induced current can be easily determined by applying right-hand rule for the coil.

Lenz's law and conservation of energy

Lenz's law is a consequence of the law of conservation of energy. In the above case, for example, when the *N*-pole of the magnet is approaching the coil, the induced current will flow in the coil in such a direction that the left-hand face of the coil becomes *N*-pole. The result is that the motion of the magnet is opposed. The mechanical energy spent in overcoming this opposition is converted into electrical energy which appears in the coil. Thus Lenz's law is consistent with the law of conservation of energy.

Fleming's Right-Hand Rule and direction:

To find the direction of the induced e.m.f. and hence current, Fleming's right-hand rule may also be used. When the conductor moves at right angles to a stationary magnetic field then the direction of induced current is from right to left as shown in fig. If the motion of the conductor is downward, then the direction of induced current will be from left to right.

It may be stated as under:

Stretch out the **forefinger, middle finger** *and* **thumb** *of your right hand so that they are at right angles to one another. If the forefinger points in the direction of magnetic field, thumb in the direction of motion of the conductor, then the middle finger will point in the direction of induced current.*

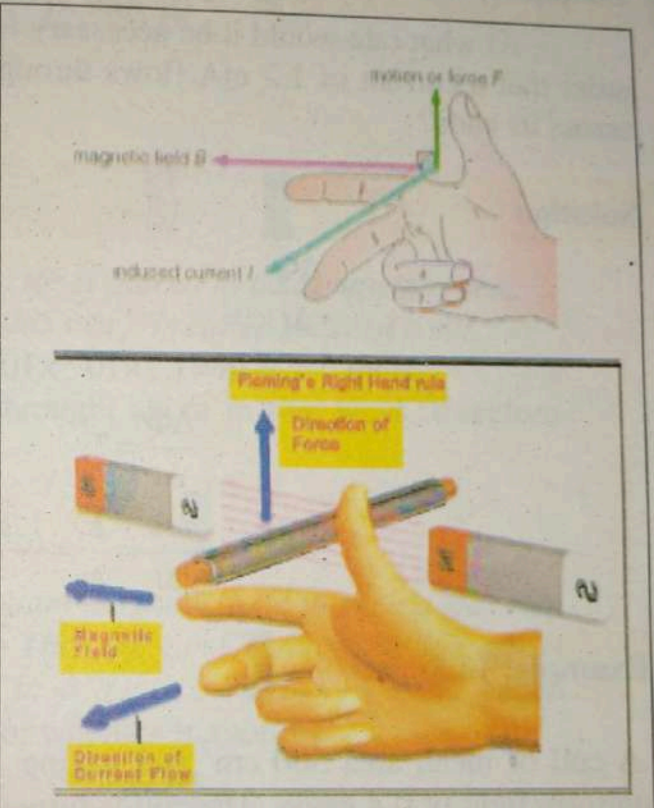


Figure 14.6 : Fleming's right hand rule shows the relative directions of Current (second finger), Magnetic Field (first finger) and the direction of motion or force (thumb).

Example: 14.1.

A coil of 100 turns is linked by a flux of 20 m Wb. If this flux is reversed in a time of 2 ms, calculate the average e.m.f. induced in the coil.

Solution.

Change in flux, $\Delta\Phi = 20 - (-20) = 40\ \text{mWb} = 40 \times 10^{-3}\ \text{Wb}$

Time taken for the change, $\Delta t = 2\text{ ms} = 2 \times 10^{-3}$ s

$$\mathcal{E} = N\frac{\Delta\Phi}{\Delta t} = 100\times\frac{40\times10^{-3}}{2\times10^{-3}}$$

$$= 2000\text{ V}$$

Example: 14.2.

At what rate would it be necessary for a single conductor to cut the flux in order that a current of 1.2 mA flows through it when 10 Ω resistor is connected across its ends?

Solution

$$\mathcal{E} = N\frac{\Delta\Phi}{\Delta t}$$

Here $\mathcal{E} = IR = 1.2\times10^{-3}\times10 = 1.2\times10^{-2}$ V;

$$\frac{\Delta\Phi}{\Delta t} = ?$$

$$\frac{\Delta\Phi}{\Delta t} = \frac{\mathcal{E}}{N} = \frac{1.2\times10^{-2}}{1}$$

$$= 1.2\times10^{-2}\text{ Wb/s}$$

Example: 14.3.

A coil of mean area 500 cm^2 and having 1000 turns is held perpendicular to a uniform field of 0.4 gauss. The coil is turned through 180^0 in 1/10 s. Calculate the average induced e.m.f.

Solution.

$$\Phi = NBA\cos\theta$$

When the plane of the coil is perpendicular to the field, $\theta = 0^0$. When the coil is turned though 180^0, $\theta = 180^0$.

Therefore, initial flux linked with the coil is $\Phi_1 = NBA\cos\theta = NBA$

Flux linked with coil when turned through 180^0 = -NBA

Change in flux linking the coil is

$$\Delta\Phi = \Phi_2 - \Phi_1 = (-NBA) - (NBA) = -2\,NBA$$

$\therefore$ Average induced e.m.f., $\mathcal{E}=\frac{\Delta\Phi}{\Delta t}=\frac{2NBA}{\Delta t}$

Here $N=1000$; $B=0.4$ G$=0.4\times10^{-4}$ T

$;A=500\times100^{-4}m^{2};$

$\Delta t=0.1$s

$$\mathcal{E}=\frac{2\times1000\times(0.4\times10^{-4})\times500\times10^{-4}}{0.1}$$

$=0.04$V

14.4 INDUCED E.M.F

By Faraday's law *whenever a conductor is placed in a varying magnetic field, EMF is induced in the conductor and this e.m.f. is called induced e.m.f.*

But as the varying magnetic field can be brought about in two ways, therefore induced e.m.f. is of two types

1. Dynamically induced e.m.f.

When the conductor is moved in a stationary magnetic field in such a way that the flux linking it changes in magnitude. Then the e.m.f. induced in this way is called dynamically induced e.m.f. (as in a d.c. generator). It is so called because e.m.f. is induced in the conductor which is in motion.

2. Statically induced e.m.f.

When the conductor is stationary and the magnetic field is moving or changing. Then the e.m.f. induced in this way is called statically induced e.m.f. (as in a transformer). It is so called because the e.m.f. is induced in a conductor which is stationary.

14.4.1 Motional e.m.f.

In order to study the dynamically induced e.m.f. in details, consider a conductor NM moving in a magnetic field. Fig: 14.7 shows a conductor of length l in a uniform magnetic field $\vec{B}$ perpendicular to the plane of the figure, directed into the page.

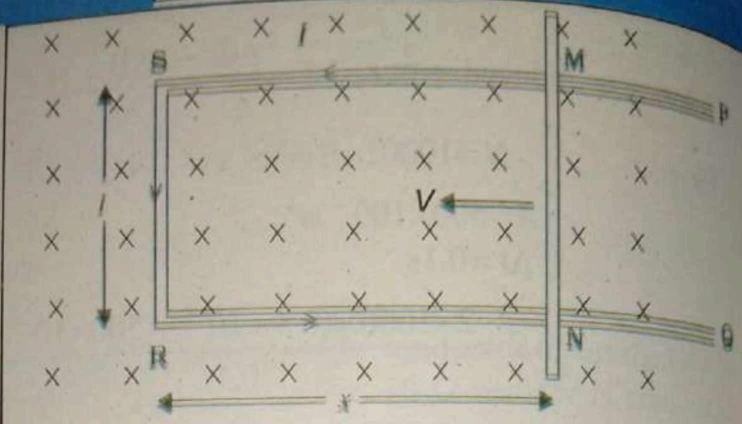


Figure 14.7 The arm MN is moved to the left side, thus decreasing the area of the rectangular loop. This movement induces a current I as shown.

Suppose that the conductor is a part of a closed circuit so that induced current I flows in it. When the conductor is moved towards left with constant velocity $\vec{v}$ then the charge particle q in the conductor experiences a force equal to $qv \times B$. Since the conductor is carrying current and is in the uniform magnetic field, it will experience a force of magnitude BIl. By Fleming right hand rule, the direction of this force is towards right, *i.e.* it opposes the applied force F.

$$\therefore \quad F = BIl$$

The applied force is doing work against the force BIl.

$$\therefore \quad \text{Rate of work done} = Fv = (BIl)v = BIlv$$

The work being done is converted into electrical energy.

Rate of production of electrical energy = $\mathcal{E}\ I$

Where $\mathcal{E}$ = e.m.f. induced in the conductor.

The e.m.f. produced induced in this case is an example of dynamically induced e.m.f.

According to the principle of conservation of energy, the rate of work done is equal to the rate of production of electrical energy *i.e.*

$$\mathcal{E}\, I = BIlv$$

or

$$\mathcal{E} = Blv$$

The above equation is valid as long as B, l and v are mutually perpendicular. If they are not, then their mutually perpendicular components are used.

Example:14.4

A loop of resistance 0.1Ω is placed in a magnetic field of 2T. If a conductor of length 0.2m is sliding along a loop with a velocity of 0.2ms^{-1}. Find (a) the e.m.f. produced in the conductor if the motion of a conductor is perpendicular to the field (b) the current through the loop (c) the electrical power generated (d) the input mechanical power.

Solution:

(a) The motional e.m.f $\mathcal{E}$

$vBL = 0.2 \times 2 \times 0.2 = 0.08\text{V}$

(b) The current through the loop is $= I = \mathcal{E}/R$

$$= \frac{0.08\text{V}}{0.1\Omega} = 0.8\text{A}$$

(c) Electrical power generated is $= P = IV =$

$$= 0.08 \times 0.8 = 0.064\text{W}$$

The magnetic force exerted on the current carrying loop of length L is

$F = BIL = 2 \times 0.8 \times 0.2 = 0.32$ N

The power necessary to move the loop against magnetic force F is

$P = F\,v = 0.32 \times 0.2 = 0.064\text{W}$

14.4.2 Self-induced e.m.f.

We have already studied that when the conductor is stationary and the field is changing then the e.m.f. induced in the conductor is called statically induced e.m.f. Self-induced e.m.f. is an example of statically induced e.m.f. Fig14.8: shows current carrying coil and magnetic field established through that coil. If current in the coil changes, then the flux linking the coil also changes. Hence an e.m.f. $(= N\,\Delta\Phi / \Delta t)$ is induced in the coil. This is known as self-induced e.m.f. The direction of this e.m.f. (By Lenz's law) is such so, as to oppose the cause

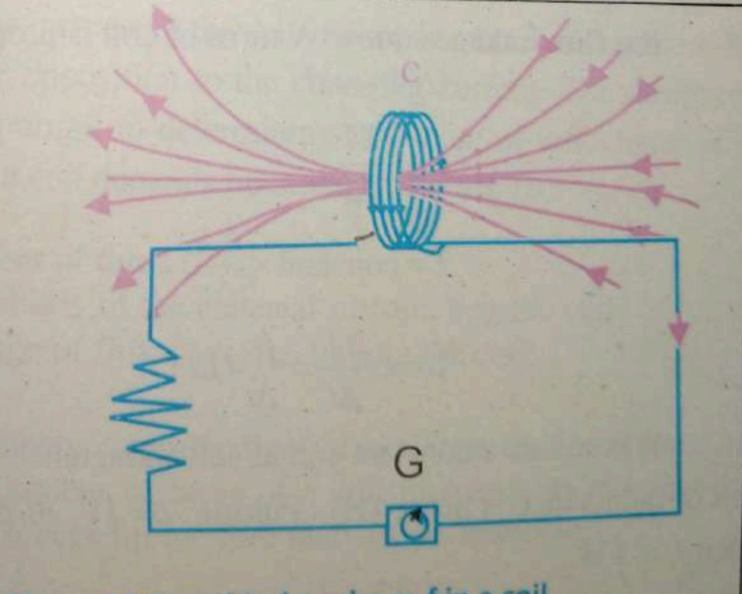


Figure 14.8: self-induced e.m.f in a coil

producing it, namely the change of current (and hence field) in the coil. The self-induced e.m.f. will persist so long as the current in the coil is changing. So it is concluded that when current in a coil changes, the self-induced e.m.f. opposes the change of current in the coil which is known as self-inductance or inductance.

The e.m.f. induced in a coil due to the change of its own flux linked with it is called self-induced e.m.f.

14.4.3 Self-Inductance

The inductance of a coil can be demonstrated by changing current in it. For example, if a steady direct current (d.c.) is flowing in a circuit, there will be no inductance. However, when alternating current is flowing in the same circuit, the current is constantly changing and hence the circuit exhibits inductance.

The property of a coil that opposes any change in the amount of current flowing through it is called its self-inductance or *inductance*.

This property (*i.e.* inductance) is due to the self-induced e.m.f. in the coil itself by the changing current. In order to find the expression for magnitude of self-induced e.m.f. and self-inductance consider a coil of N turns carrying a current of I. When the current in the coil changes then, the flux linking of the coil will also change. This will set up a self-induced e.m.f. $\mathcal{E}$ in the coil given by;

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

The flux linkages due to N turns of coil is proportional to current I

$$(N\Phi) \propto I$$

$$\mathcal{E} \propto \frac{\Delta I}{\Delta t}$$

$$\mathcal{E} = \text{constant} \times \frac{\Delta I}{\Delta t}$$

$$\mathcal{E} = L\frac{\Delta I}{\Delta t} = \frac{\Delta}{\Delta t}(LI) \qquad (1)$$

Where L is a constant called self-inductance or inductance of the coil. The unit of inductance is henry (H). Putting $\mathcal{E} = 1V$, $\Delta I/\Delta t = 1$ A/s, in Eq. (1) then $L = 1$ H.

Hence a coil (or circuit) has an inductance of 1 henry if an e.m.f. of 1 volt is induced in it when current through it changes at the rate of 1 ampere per second.

Also we know that

$$\mathcal{E} = \frac{\Delta}{\Delta t}(N\Phi) \qquad (2)$$

Comparing Eq(1) and Eq (2) we have

$$LI = N\Phi$$

$$\text{or } L = \frac{N\Phi}{I}$$

14.4.3.1 Factors affecting inductance:

Inductors play a great role in electronic, electrical, electromechanical, wireless circuits etc. To study the properties of inductance let us consider a coil of N turns.

When an induced emf is produced in a coil due to increasing current then its direction is always opposite to the increasing current i.e., direction of self-induced e.m.f. is opposite to that of the applied voltage. On the other hand when an emf is produced in a coil due to decreasing current then its direction is always opposite to the decreasing current i.e., direction of self-induced e.m.f. will be same as that of the applied voltage. Thus by increasing the self-induced emf, increases the self-inductance of the coil and the opposition to the changing current. The design of the inductor also plays an important in determining the value of inductance of a coil. Hence, the inductance of a coil depends upon the following factors, *viz:*

(i) Shape and number of turns (N).
(ii) Relative permeability of the material surrounding the coil.
(iii) The rate of change of flux $(\Delta\Phi / \Delta t)$ linking the coil.

In fact, anything that affects magnetic field also affects the inductance of the coil. Thus, increasing the number of turns of a coil increases its inductance. Similarly, by substituting an iron core for air core increase its inductance.

14.4.3.2 Mutually Induced e.m.f.

The property of two neighbouring coils to induce voltage in one coil due to the change of current in the other is called mutual inductance.

In order to demonstrate the phenomenon of mutually induced e.m.f. let us place two coils A and B adjacent to each other as shown in Fig14.9: When the current flows in the coil A then there will be magnetic field produced around it. A part of the magnetic flux produced by coil A passes through or links with coil B. This flux which is common to both the coils A and B is called mutual flux (Φ_m). If current in coil A is varied, the mutual flux also varies and hence e.m.f. is induced in both the coils. The e.m.f. induced in coil A is called self-induced e.m.f. as already discussed. The e.m.f. induced in coil B is known as mutually induced e.m.f. The mutually induced e.m.f. in coil B persists so long as the current in coil A is changing. If current in coil A becomes steady, the mutual flux also becomes steady and mutually induced e.m.f. drops to zero.

The magnitude of mutually induced e.m.f. is given by Faraday's laws i.e., $\mathcal{E} = N_B \Delta\Phi_m / \Delta t$ where N_B is the number of turns of coil B and $\Delta\Phi_m / \Delta t$ is the rate of change of mutual flux *i.e.* flux common to both the coils. The direction of mutually induced e.m.f. (by Lenz's law) is always such so as to oppose the cause producing it. The cause producing the mutually induced e.m.f. in coil B is the changing mutual flux produced by coil A.

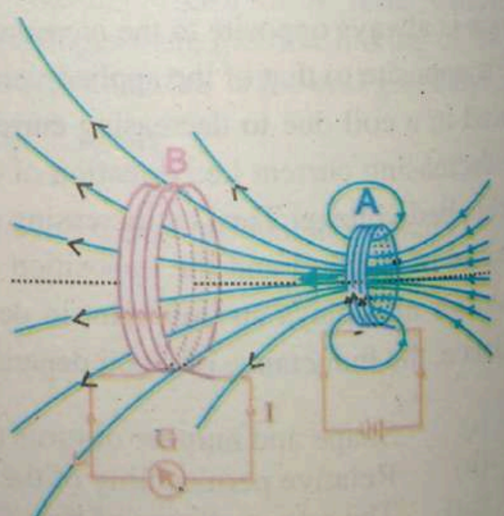


Figure 14.9: Current is induced in coil B due to motion of the current carrying coil A.

Hence the direction of induced current (when the circuit is completed) in coil B will be such that the flux set up by it will oppose the changing mutual flux produced by coil A.

The e.m.f. induced in a coil due to the changing current in the neighbouring coil is called mutually induced e.m.f.

14.4.3.3 MUTUALLY INDUCTANCE

When the two coils are placed near each other then, changing current in one coil will induce an e.m.f. in the other coil. Fig14.10: shows two coils A and B placed near each other. If a current I_1 flows in the coil A, a flux is set up and a part of this flux links the coil B. The two coils being magnetically linked. When the current in the coil A, changes, the flux linking the coil B also changes and e.m.f. is induced in the coil B. The e.m.f. induced in coil B is termed as mutually induced e.m.f.

According to Faraday's laws of electromagnetic induction, induced voltage in a coil depends upon the number of turns (N) and the rate of change of flux $(\Delta\Phi / \Delta t)$ linking the coil. The larger the rate of change of current in coil A, the greater is the e.m.f induced in coil B. In other words, mutually induced e.m.f. in coil B is directly proportional to the rate of change of current in coil A i.e.,

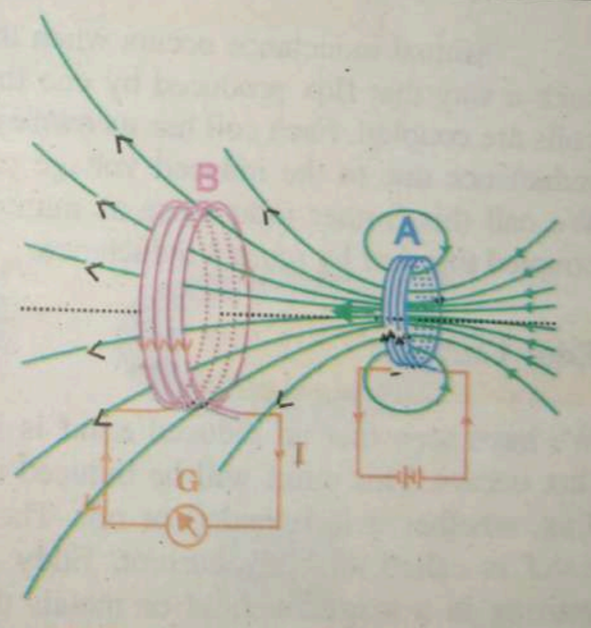


Figure 14.10: Current is induced in coil B due to motion of the current carrying coil A.

Mutually induced e.m.f. in coil B $\propto$ rate of change of current in coil A

$$\mathcal{E} \propto \frac{\Delta I}{\Delta t}$$

$$\mathcal{E} = M\frac{\Delta I}{\Delta t} = \frac{\Delta}{\Delta t}(MI) \qquad (1)$$

Where M is a constant called mutual inductance between the two coils. The unit of mutual inductance is henry (H).

Putting $\mathcal{E} = 1\text{V}$, $\Delta I/\Delta t = 1$ A/s, in Eq. (1) then $M = 1$ H.

Hence mutual inductance between two coils is 1 henry *if current changing at the rate of 1 A/s in one coil induces an e.m.f. of 1 V in the other coil.*

Also we know that

$$\mathcal{E} = \frac{\Delta}{\Delta t}(N\Phi) \qquad (2)$$

Comparing Eq(1) and Eq (2) we have

$$MI = N\phi \qquad or \; M = \frac{N\Phi}{I}$$

Mutual inductance occurs when the two coils are placed close together in such a way that flux produced by one links the other. We say then that the two coils are coupled. Each coil has its own inductance but in addition, there is further inductance due to the induced voltage produced by coupling between the coils. We call this further inductance as mutual inductance. We say the two coils are coupled together by mutual inductance.

Eddy Currents

We have seen that an induced e.m.f is induced whenever a change of magnetic flux occurs. This e.m.f will be induced in any conductor experiencing change of flux, whether it is intended or not. The current that is induced because of this e.m.f is called an eddy current. Eddy currents are currents induced in metals moving in a magnetic field or metals that are exposed to a changing magnetic field. Consider a solid metallic cylinder rotating in a magnetic-field as shown:

1. A force resisting the rotation would be generated as shown.
2. Heat would be generated by the induced current in cylinder

To reduce eddy currents, the solid cylinder could be replaced with a stack of "coins" with insulation between one another. The insulation between the coins increases resistance and reduces eddy current, thus reducing friction or heating.

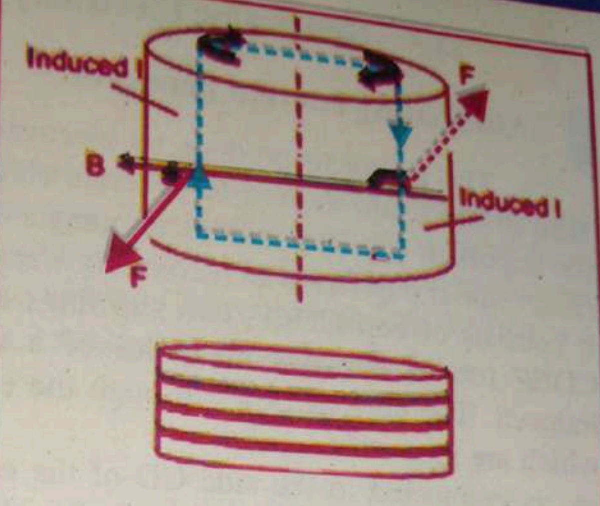
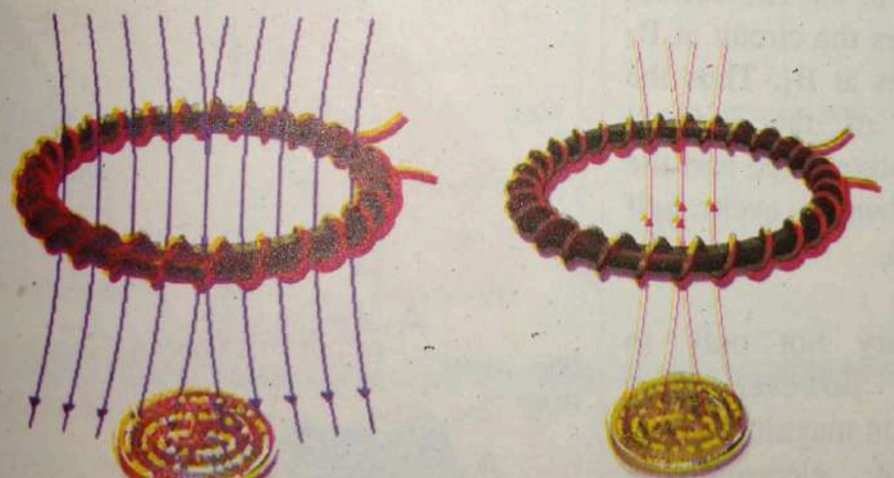


Figure 14.11: eddy current

For your information

Applications of eddy currents in metal detectors



A pulsing current is applied to the coil, which then induces a magnetic field shown. When the magnetic field of the coil moves across metal, such as the coin in this illustration, the field induces electric currents (called eddy currents) in the coin. The eddy currents induce their own magnetic field, which generates an opposite current in the coil, which induces a signal indicating the presence of metal.

14.5 Generating Electricity

Alternating current generator

The ability to produce an electromotive force by changing the magnetic field inside a coil is used to generate electricity. The generation of electricity is the important application of electromagnetic induction.

Generator is a device which converts Mechanical energy into electrical energy.

It consists of coil CDEF, two slip rings and two carbon brushes. When the coil CDEF rotates between the poles of a magnet and an electromotive force is induced. The current flows through the external circuit by slip rings A_1 and A_2 which are made of copper.

A_1 is connected to the side CD of the coil and A_2 to the side EF as shown in fig14.12: A_1 is always in contact with the brush B_1 and A_2 with the brush B_2. When the side CD moves upwards Fleming's Right-hand Rules shows that the direction of the current is from C to D and E to F. Thus the current enters the circuit at B_1 and leaves at B_2. Half a revolution later FE will be in the position previously occupied by CD and the current direction is reversed, i.e. it is from F to E and D to C. The current now enters the circuit at B_2 and leaves at B_1. Thus the direction of the induced electromotive force and the current changes every half revolution.

These vary not only in direction; however, they also vary in magnitude. The graph of electromotive force against time is shown in Fig14.13: The time taken for one revolution T is called the period and frequency f, is the number

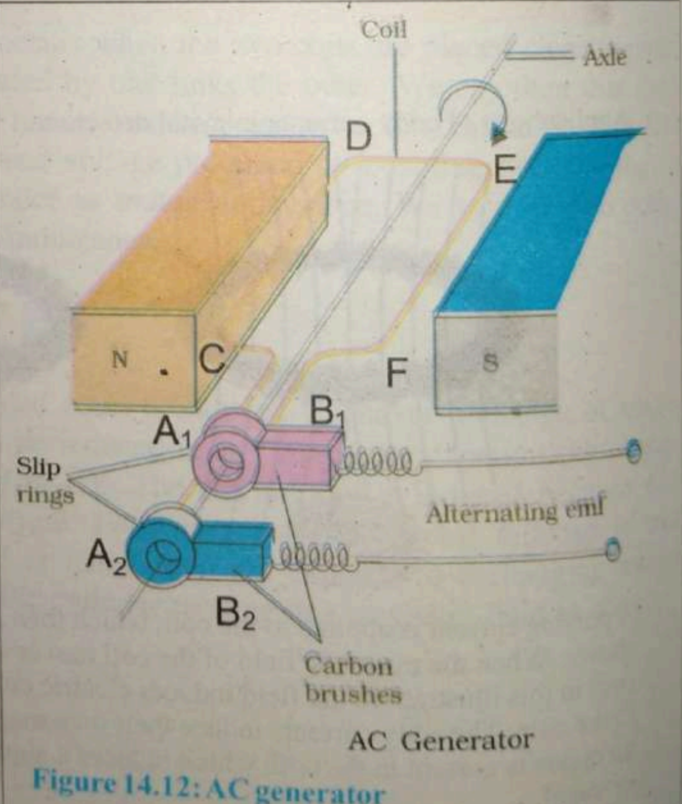


Figure 14.12: AC generator

of revolutions per second. Hence

$$f = \frac{1}{T}$$

The domestic electricity supply has a frequency of 50 hertz, which means that the generator makes fifty revolutions each second. The graph of current against time has the same shape as that of electromotive force against time, but the magnitude of the current depends upon the resistance of the external circuit. Fig14.13 shows the positions of the coil that correspond to various points on the graph.

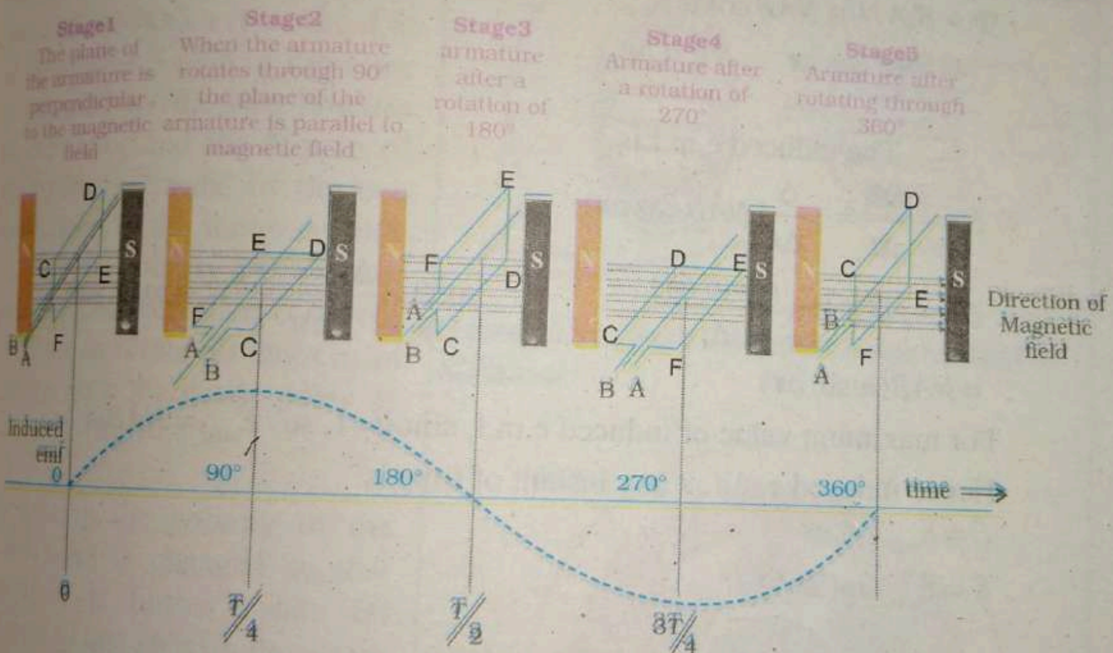


Figure 14.13 An alternating emf is generated by a loop of wire rotating in a magnetic field.

The coil has the maximum number of lines of force passing through it when it is in vertical position, and hence the maximum number of flux linkages. Therefore the induced electromotive force is a maximum when the coil is horizontal and a minimum when the coil is vertical. The induced electromotive force, is determined by the rate at which the number of flux linkages changes. From Fig14.13: it is clear that there is very little change in the number of flux linkages when the coil is near the vertical position and consequently no, or very little induced electromotive force. Another way of looking at the problem is to consider the sides CD and EF of the coil which are responsible for the induced electromotive force. When the coil is horizontal sides CD and EF are moving perpendicular to the magnetic field and so the induced electromotive force is a maximum; when the coil is perpendicular to the field sides CD and EF are moving parallel to the magnetic field and so the induced electromotive force is zero.

The magnitude of induced e.m.f can be determined by finding the rate of change of flux through the coil. Suppose the coil is rotating with angular velocity ω and at any instant t, θ be the angle which the coil makes with the field B. If N is the number of turns in the coil then the flux through the coil of area A is

$$\Phi = B.A\,N = NAB\cos\theta$$

$$= NAB\cos\omega t \qquad \therefore \theta = \omega t$$

The induced e.m.f is

$$\mathcal{E} = -\frac{\Delta\Phi}{\Delta t} = -\frac{\Delta}{\Delta t}(NAB\cos\omega t)$$

$$\mathcal{E} = -NAB\lim_{\Delta t\to 0}\frac{\Delta(\cos\omega t)}{\Delta t} \qquad \text{As } \lim_{\Delta t\to 0}\frac{\Delta(\cos\omega t)}{\Delta t} = -(\omega\sin\omega t)$$

$$= NAB(\omega\sin\omega t)$$

For maximum value of induced e.m.f. $\sin\omega t = 1$, so $\mathcal{E}_{max} = NAB\omega$

Hence induced e.m.f at any instant of time is:

$$\mathcal{E} = \mathcal{E}_{max}\sin\omega t$$

$$\mathcal{E} = \mathcal{E}_{max}\sin(2\pi f t)$$

14.6 AC Motor

An AC motor has two basic electrical parts: a "stator" and a "rotor" as shown in Fig14.14: The stator is the stationary part of the motor while rotor is the rotating part of the motor. The stator consists of a group of individual electro-magnets arranged in such a way that they form a hollow cylinder, with one pole of each magnet facing toward the center of the group. It also consists of a group of electro-magnets arranged around a cylinder, with the poles facing toward the stator poles. The rotor, obviously, is located inside the stator and is mounted on the motor's shaft. The objective of these motor components is to make the rotor rotate which in turn will rotate the motor shaft. The rotor consists of coils wound on a laminated iron armature mounted on an axle. The rotor coils are not connected to the external power supply, and an induction motor has neither commutator nor brushes. An induction motor is so named because eddy currents are induced in the rotor coils by the rotating magnetic field of the stator.

The eddy currents produce magnetic fields which interact with the rotating field of the stator to exert a torque on the rotor in the direction of rotation of the stator field.

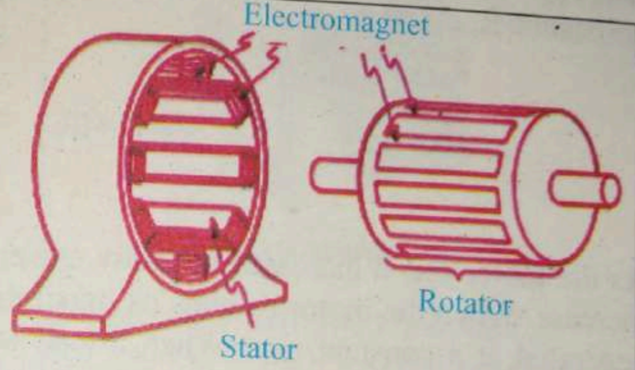


Figure 14.14 : Basic electrical components of an AC motor.

In order to understand the principle on which it works. Let at time t_1 the S-pole of the rotor is attracted by the two N-poles of the stator and the N-pole of the rotor is attracted by the two south poles of the stator. At time t_2, when the polarity of the stator poles is changed then it forces the rotor to rotate 60 degrees to line up with the stator poles as shown in fig 14.15.

At time t_3, the polarity of the stator poles is changed so that the rotor is further rotate 60 degrees to line up with the stator poles. Similarly at time t_4 it further rotates 60 degrees.

As each change is made, the poles of the rotor are attracted by the opposite poles on the stator. Thus, as the magnetic field of the stator rotates, the rotor is also forced to rotate with it.

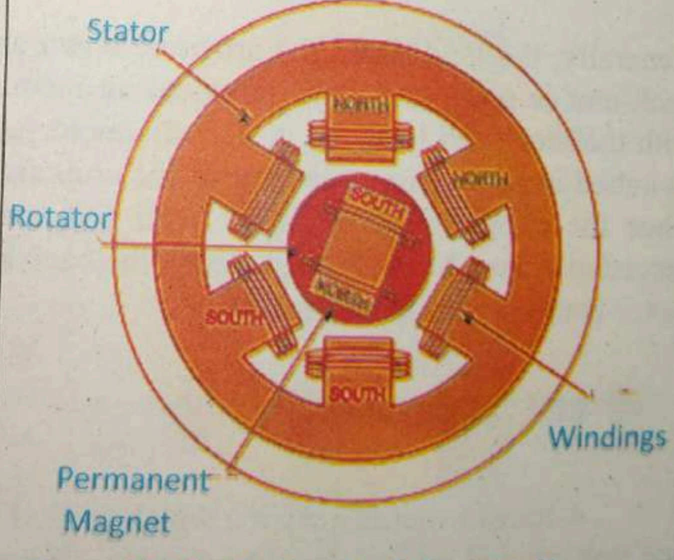


Figure 14.15 : the S-pole of the rotor is attracted by the two N-poles of the stator and the N-pole of the rotor is attracted by the two south poles of the stator.

14.6.1 Back emf

When the coil of electric motor rotates in a magnetic field by applying it with a battery of potential difference V an induced emf $\mathcal{E}$ is produced. This induced emf is produced in such a direction so as to oppose the emf V of battery which is known as back emf.

The applied voltage is equal to back emf $\mathcal{E}$ plus the voltage drop across the resistance R.

$$V = \mathcal{E} + IR$$

As the motor speed increases the eddy currents and the resulting back EMF also increase. When the motor reaches its maximum operating speed back emf will be generated at a constant rate. When a load is applied, the speed of the motor is reduced, which reduces the back emf and hence increases current in the motor. If the load stops the motor from moving then the current may be high enough to burn out the motor coil windings.

Generally, the load slows the armature down and so the current increases as the back emf is decreased. This produces an increase in current and torque to cope with the increased load. To protect the motor at low speeds a resistor in series is switched in to the circuit to protect the coils from burning out. It is switched out when the current drops to a set level and switches back in when this level is exceeded again. At the higher speeds the back emf reduces the current and so the motor continues to operate safely.

14.7 Transformers

A transformer is a device which is used to transform electrical power from one voltage and current level to another. The transformer depends on the use of alternating current. There are three main parts to a transformer: two coils of wire (called the primary and secondary) and a laminated iron core connecting them:

The primary coil is connected to the input electrical supply, which has to be AC to work properly. An AC current through the coil creates a changing magnetic field which is concentrated through the iron core.

The transformer is based on two principles: first, that an electric current can produce a magnetic field (electromagnetism), and, second that a changing magnetic field within a coil of wire induces a voltage across the ends of the coil (electromagnetic induction). Changing the current in the primary coil changes the magnetic flux that is developed. The changing magnetic flux induces a voltage in the secondary coil.

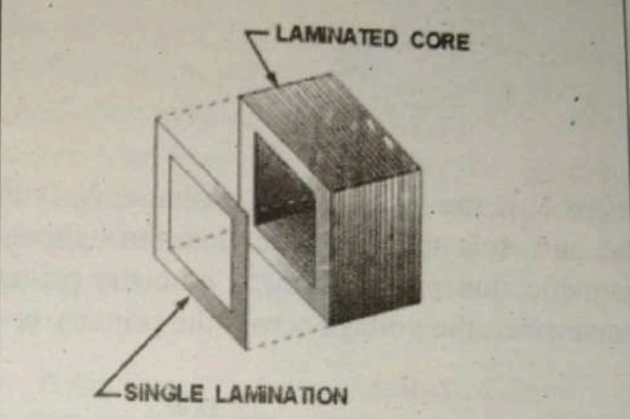


Figure 14.16: laminated iron core

14.7.1 Induction law

Current passing through the primary coil creates a magnetic field. The primary and secondary coils are wrapped around a core of high magnetic permeability, such as iron, so that most of the magnetic flux passes through both the primary and secondary coils. So the flux through the primary and secondary coil is same. The changing magnetic flux through the primary coil gives rise to an induced emf V_s in the secondary coil.

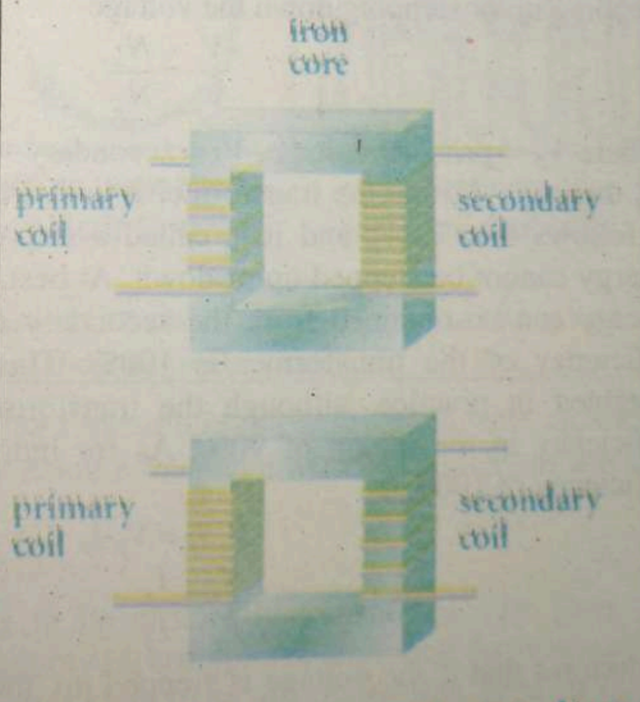


Figure 14.17: step up and step down transformer

The voltage induced across the secondary coil is given by Faraday's law of induction, which states that:

$$V_s = N_s \frac{d\Phi}{dt}$$

where V_s is the instantaneous voltage, N_s is the number of turns in the secondary coil and Φ is the magnetic flux through one turn of the coil. Since the same magnetic flux passes through both the primary and secondary coils in an ideal transformer, the voltage across the primary is

$$V_P = N_P \frac{d\Phi}{dt}$$

Taking the ratio of the two equations for V_s and V_P gives the basic equation for stepping up or stepping down the voltage

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

Where V_p = primary voltage, V_s = secondary voltage, N_p = primary turns. If $N_s > N_p$ then $V_s > V_p$ and the transformer is called a step-up transformer. When $N_s < N_p$ it follows that $V_s < V_p$ and it is called a step-down transformer. The amount of energy cannot be stepped up or down. At best, as with the induction coil, as such energy can be obtained from the secondary as is put into the primary, i.e. the efficiency of the transformer is 100%. This theoretical efficiency cannot be obtained in practice, although the transformer is a very good machine with efficiency in the region of 90%. As for induction coil (assuming a theoretical efficiency of 100%),

$$V_s I_s = V_p I_p$$

$$\frac{V_s}{V_p} = \frac{I_s}{I_p}$$

It follows that if the voltage is stepped up, the current is stepped down and vice versa. If a high voltage is required a step-up transformer is used, whereas if a high current is required a step-down transformer is used.

14.7.2 Energy losses in transformers:

(i) Flux Leakage: There is always some flux leakage; that is, not all of the flux due to primary passes through the secondary due to poor design of the core or the air gaps in the core. It can be reduced by winding the primary and secondary coils one over the other.

(ii) **Resistance of the windings:** The wire used for the windings has some resistance and so, energy is lost due to heat produced in the wire (I^2R). In high current, low voltage windings, these are minimised by using thick wire.

(iii) **Eddy currents:** A transformer has an iron core to concentrate the magnetic field to achieve the maximum possible inductive coupling between the primary and secondary coils. As the changing flux intersects the core, eddy currents are induced in the iron. Heating occurs because of the rather high resistance of the iron to the eddy currents.

Transformer cores are made of laminated iron, that is, many thin sheets of iron pressed together but separated by thin insulating layers. This limits the circulation of any eddy currents to the thickness of one lamina, rather than the whole core, thus reducing the overall heating effect.

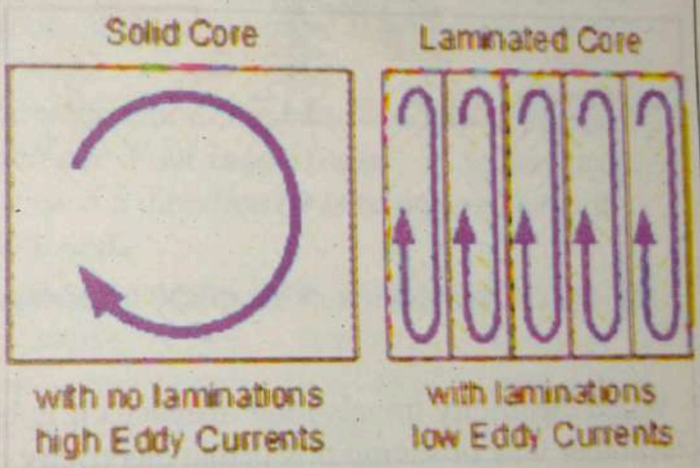


Figure 14.18: Eddy currents in an ordinary iron core, and a laminated iron core.

(iv) **Hysteresis:** The magnetisation of the core is repeatedly reversed by the alternating magnetic field. The resulting expenditure of energy in the core appears as heat and is kept to a minimum by using a magnetic material which has a low hysteresis loss.

The transformer allowed electricity to be efficiently transmitted over long distances. This made it possible to supply electricity to homes and businesses located far from the electric generating plant. The electricity first goes to a transformer at the power plant that boosts the voltage up to 400,000 volts.

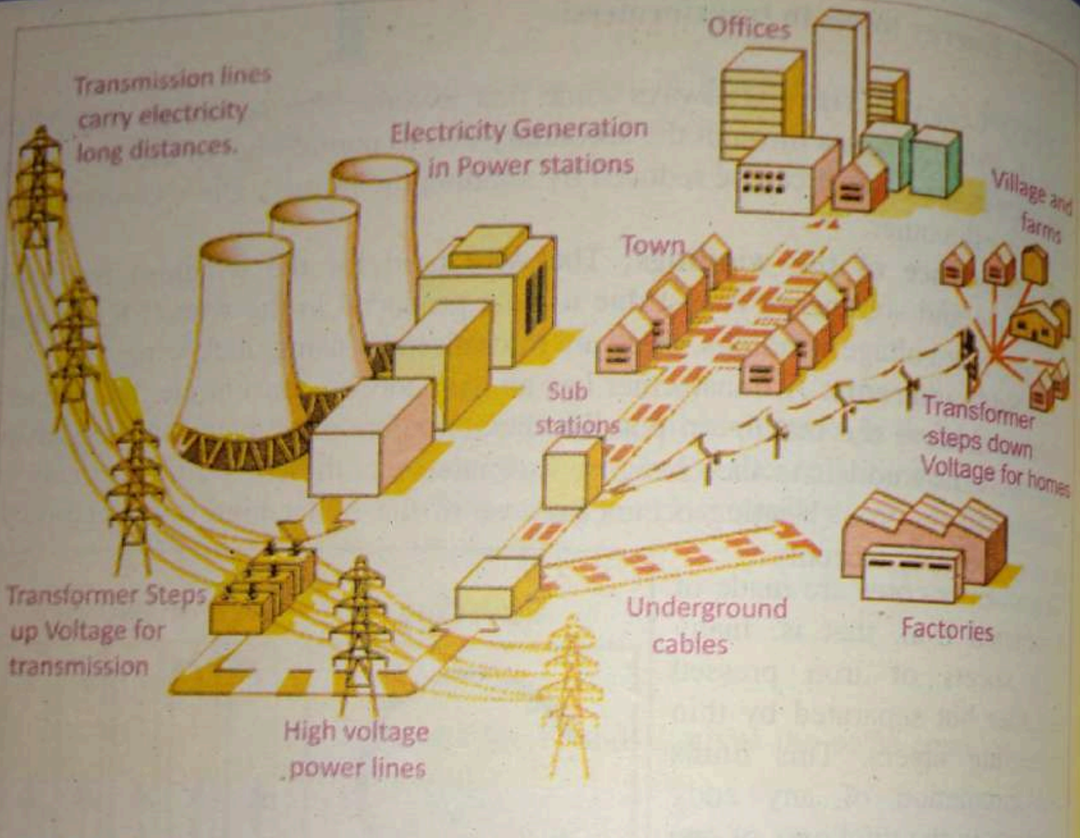


Fig 14.19: Illustrations of electricity transmission from power station to homes

When electricity travels long distances it is better to have it at higher voltages. Another way of saying this is that electricity can be transferred more efficiently at high voltages. The long thick cables of transmission lines are made of copper or aluminum because they have a low resistance. Some of the electrical energy is lost because it is changed into heat energy. High voltage transmission lines carry electricity long distances to a substation. The power lines go into substations near businesses, factories and homes. Here transformers change the very high voltage electricity back into lower voltage electricity.

From these substations, electricity in different power levels is used to run factories, streetcars and mass transit etc., In your neighborhood, another small transformer mounted on pole or in a utility box converts the power to even lower levels to be used in your house. The voltage is eventually reduced to 220 volts for larger appliances, like stoves and clothes dryers, and 110 volts for lights, TVs and other smaller appliances.

Key points

- When the magnetic flux linking a conductor changes, an e.m.f is induced in the conductor this phenomenon is known as electromagnetic induction.
- The basic requirement for electromagnetic induction is the change in flux linking the conductor (or coil).
- The e.m.f and hence the current in this conductor (or coil) will persist so long as this change is taking place.
- If the change of magnetic flux is due to a variation in the current flowing in the same circuit, the phenomenon is known as self-induction; if it is due to a change of current flowing in another circuit it is known as mutual induction.
- When the coil of electric motor rotates in a magnetic field by applying it with a battery of potential difference V an induced emf $\mathcal{E}$ is produced. This induced emf is produced in such a direction so as to oppose the emf V of battery which is known as back emf.
- Lenz's proposed that the induced current will flow in such a direction so as to oppose the cause that produces it.
  When the conductor is moved in a stationary magnetic field in such a way that the flux linking it changes in magnitude. The e.m.f. induced is called dynamically induced e.m.f.
- When the conductor is stationary and the magnetic field is moving or changing. The e.m.f. induced is called statically induced e.m.f.
- The ability to produce an electromotive force by changing the magnetic field inside a coil is used to generate electricity. *Generator is a device which converts Mechanical energy into electrical energy.*
- A transformer is a device which is used to transform electrical power from one voltage and current level to another.
- The transformer is based on two principles: first, that an electric current can produce a magnetic field, and, second that a changing magnetic field within a coil of wire induces a voltage across the ends of the coil.
- One of the best ways to overcome difficulties of heating in transformers is to reduce the size of the eddy currents.

Exercise ?

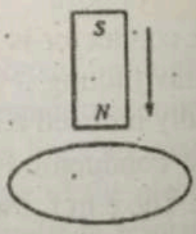
Multiple choice questions:

Each of the following questions is followed by four answers. Select the correct answer in each case.

1. For inducing emf in a coil the basic requirement is that
   (a) Flux should link the coil
   (b) change in flux should link the coil
   (c) coil should form a closed loop
   (d) both (b) and (c) are true

2. The device in which induced emf is statically induced emf is
   (a) transformer (b) ac generator
   (c) alternator (d) dynamo.

3. The north pole of a magnet is brought near a metallic ring as shown in the fig. The direction of induced current in the ring will be



   (a) anticlockwise
   (b) clockwise
   (c) first anti-clockwise and then clockwise
   (d) first clockwise and then anti-clockwise

4. What is the coefficient of mutual inductance, when the magnetic flux changes by 2×10^{-2} Wb, and change in current is 0.01 A?
   (a) 2 H (b) 3H
   (c) 1/2 H (d) zero

5. The induced emf in a coil is proportional to
   (a) magnetic flux through the coil
   (b) rate of change of magnetic flux through the coil
   (c) area of the coil
   (d) product of magnetic flux and area of the coil

6. In a coil current change from 2 to 4 A in .05 s. If the average induced emf is 8V then coefficient of self-inductance is
(a) 0.2 henry (b) 0.1 henry
(c) 0.8 henry (d) 0.04 henry

7. Whic.. of the following quantities remain constant in step up transformer?
(a) current (b) voltage (c) power (d) heat

8. Step-up transformer has a transformation ratio of 3:2. What is the voltage in secondary, if voltage in primary is 30 V?
(a) 45 V (b) 15 V
(c) 90 V (d) 300 V

9. Eddy current is produced when
(a) a metal is kept in varying magnetic field
(b) a metal is kept in steady magnetic field
(c) a circular coil is placed in a steady magnetic field
(d) a current is passed through a circular coil.

Conceptual question's

1. Make list of similarities and differences between the motor effect and electromagnetic induction in a moving wire (the dynamo effect).
2. For a simple motor, why must the back e.m.f. always be smaller than the applied potential difference?
3. What factors limit the size of the back e.m.f.?
4. Why does back e.m.f. tend to decrease as the rate of doing work increases?

5. Explain from $\mathcal{E} = -\frac{\Delta\Phi}{\Delta t}$ why it possible to say that $\mathcal{E} \propto \frac{\Delta I}{\Delta t}$

6. Show that the relationship $\mathcal{E} = -\frac{\Delta\Phi}{\Delta t}$ is dimensionally correct.

7. Give the formulae for the flux linkage in terms of angular orientation.

8. Explain the eddy current in terms of Lenz's law. Also by drawing a suitable diagram show the direction of eddy current and the polarity produced in the sheet as a result of magnetic field.

9. How electromagnetic brake works? Explain.

10. A bar magnet is dropped inside a long vertical tube. If the tube is made of metal, the magnet quickly approaches a terminal speed, but if the tube is made of cardboard, the magnet falls with constant acceleration. Explain why the magnet falls differently in the metal tube than it does in the cardboard tube.

11. The transformer suffers from Eddy current loss (a) Explain how eddy currents arise. (b) State the features of transformer designed to minimize eddy currents.

12. Analyse information to explain how induction is used in cook tops in electric ranges?

13. (a) Explain what is meant by the term back e.m.f. in any electric motor operation.

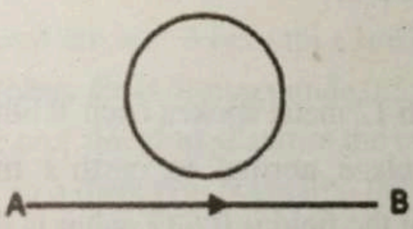
(b) Explain why it is an advantage for the armature to rotate in a radial magnetic field rather than a uniform one?

17.

14. If the armatures rotating freely then explain, in terms of electromagnetic principles (a) why the current in the armatures progressively decreases as 18 the angular velocity of the armature increases (b) why a maximum angular velocity is eventually reached?

15. Transformer cores can be made from a variety of materials. What are the 19 main features that you would require of material to make a good transformer core? Suggest how well each of the following materials would perform; iron, solid soft iron, laminated soft iron, aluminum.

16 20. Current is increasing in magnitude from A to B as shown in fig:. What is the direction of induced current, if any, in the loop?



Comprehensive question's

1. Describe electromagnetic induction with simple experiments. Explain the factors effecting magnitude and direction of induced emf.
2. State faradays law of electromagnetism. Also explain statically and dynamically induced emf with experiments.
3. Describe lenses law. Show that this law is a manifestation of conservation of energy.
4. Explain the phenomenon of mutual induction. Define the coefficient of mutual induction and units.

5. Explain the phenomenon of self-induction. Define the coefficient of self-induction and units.
6. Explain motional emf. Show that motional induced emf is $\mathcal{E} = Blv$.
7. What is dc generator? Explain how alternating emf is generated by a loop of wire rotating in a magnetic field.
8. What is AC motor? Explain the construction and working of AC motor.
9. What is transformer? Give its principle, mathematical relationship. Also explain why laminated iron core is used instead of solid one.
10. Explain the back emf in an electric motor.
11. Explain eddy current with suitable example. How eddy current can be minimized.

Numerical problems

1. Two identical coils A and B of 500 turns each has on parallel planes such that 70% of flux produced by one coil links with the other. A current of 6 A flowing in coil A produces a flux of 0.06 mWb in it. If the current in coil A changes from 10A to -10 A in .03s, calculate (a) the mutual inductance and (b) the e.m.f. induced in coil B.

(a. 3.5×10^{-3}mH, b. 2.33V)

2. A wheel with 12 metal spokes each 0.6m long is rotated with a speed of 180 r.p.m in a plane normal to earth's magnetic field at a place. If the magnitude of the field is 0.6 G, what is the magnitude of induced e.m.f. between the axle and rim of the wheel? (2.035×10^{-4} V)

3. A circuit has 1000 turns enclosing a magnetic circuit 20cm^2 in section with 4A current, the flux density is 1 Wbm^{-2} and with 9A current, it is 1.4Wbm^{-2}. Find the mean value of the inductance between these current limits and the induced e.m.f. if the current falls from 9A to 4A in .05s.

(.16H, 16V)

4. A coil of resistance 100Ω is placed in a magnetic field of 1mWb. The coil has 100 turns and a galvanometer of 400Ω resistance is connected in series

with it: find the average emf and the current if the coil is moved in 1/10th s from the given field to a field of 0.2mWb.

(1.6 mA)

5. A horizontal straight wire 10 m long extending from east to west is falling with a speed of 5.0 m s^{-1}, at right angles to the horizontal component of the earth's magnetic field, 0.30×10^{-4} Wb m^{-2} (a) what is the instantaneous value of the emf induced in the wire?

(b) What is the direction of the emf ?

(c) Which end of the wire is at the higher electrical potential?

(1.5×10^{-3} V)

6. Current in a circuit falls from 5.0 A to 0 A in 0.1 s. If an average emf of 200 V induced, give an estimate of the self-inductance of the circuit.

(4 H)

7. A long solenoid with 15 turns per cm has a small loop of area 2.0 cm^2 placed inside the solenoid normal to its axis. If the current carried by the solenoid changes steadily from 2.0 A to 4.0 A in 0.1 s, what is the induced emf in the loop while the current is changing?

(7.54×10^{-6} V)

8. A rectangular wire loop of sides 8 cm and 2 cm with a small cut is moving out of a region of uniform magnetic field of magnitude 0.3 T directed normal to the loop. What is the emf developed across the cut if the velocity of the loop is 1 cm s^{-1} in a direction normal to the (a) longer side, (b) shorter side of the loop? For how long does the induced voltage last in each case?

(2.4×10^{-4} V, 2 s, & 0.6×10^{-4} V, 8 s)

9. A 90-mm length of wire moves with an upward velocity of 35 ms^{-1} between the poles of a magnet. The magnetic field is 80 mT directed to the right. If the resistance in the wire is 5.00 m Ω, what are the magnitude and direction of the induced current?

(50.4 A)

10. A pair of adjacent coils has a mutual inductance of 1.5 H. If the current in one coil changes from 0 to 20 A in 0.5 s, what is the change of flux linkage with the other coil?

(30 Wb)

11. The back emf in a motor is 120V when the motor is turning at 1680 rev/min. What is the back emf when the motor turns at 3360 rev/min?

(240 V)