Unit 14

ELECTROMAGNETIC INDUCTION

Major Concepts

(18 PERIODS)

- Induced e.m.f.
- Faraday's law
- Lenz's law
- Eddy currents
- Mutual Inductance
- Self-inductance
- Energy stored by an inductor
- Motional e.m.f.
- A.C. Generator
- A.C. motor and Back e.m.f.
- Transformer

Conceptual Linkage

This chapter is built on Electromagnetism Physics X

Students Learning Outcomes

After studying this unit, the students will be able to:

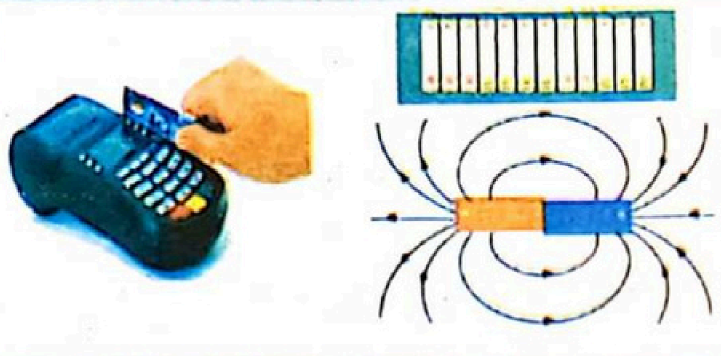
- describe the production of electricity by magnetism.
- explain that induced e.m.f.'s can be generated in two ways.
  (i) by relative movement (the generator effect).
  (ii) by changing a magnetic field (the transformer effect).
- infer the factors affecting the magnitude of the induced e.m.f..
- state 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 of laminated iron cores in electric motors, generators and transformers.
- explain what is meant by motional e.m.f.. 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 e.m.f. 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.

INTRODUCTION

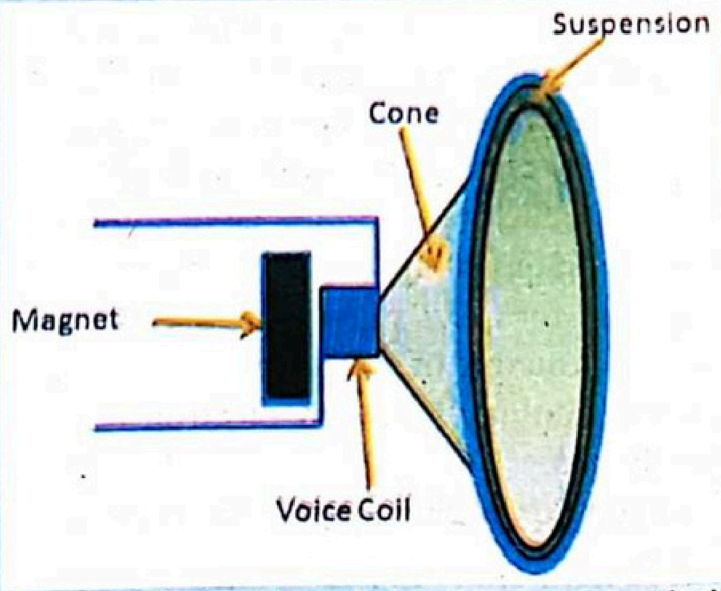
In the previous unit, we have studied that a flow of electric current produces a magnetic field. This is a the link between electricity and magnetism. Such link was discovered by Oersted in 1820. Now a question arises that can a magnetic field also produce current or electric field? A few years later, the answer of this question was sounded Yes, when the reverse effect was discovered. i.e., a changing magnetic field can also produce a current in a nearby circuit. This effect was studied by Michelson Faraday in England and Joseph Henry in America in the year 1831. The effect of inducing voltage or electromotive force due to a change in the magnetic field is known as electromagnetic induction. Induced e.m.f. can be generated either by generator effect (by relative motion between changing magnetic field and the conductor) or by transformer effect (changing B). The changing magnetic field forces the electrons

INTERESTED INFORMATION



Electronic Card Swiping System based on electromagnetic induction theory

FOR YOUR INFORMATION



When an A.C. signal is applied, a changing current in the coil of the loudspeaker produce a magnetic field in it. This magnetic field interacts with the field of permanent magnetic of the loudspeaker and it causes the magnetic force that exerts on the coil which results in vibration of the cone. This vibration produces sound waves.

to move in any conductor within the field producing an induced e.m.f. or current. The great discovery of electromagnetic induction by Faraday through his fundamental law has brought a revolution in the field of science and technology. Most of the electrical devices such as motors, generators, transformer etc. are working on the basis of principle of Faraday's law. In this unit, we will not only explain the various aspect of electromagnetic induction but also discuss its practical applications.

14.1 INDUCED E.M.F.

It has been observed experimentally that when a changing magnetic flux passes through a circuit or conductor, an e.m.f. is induced in it. This phenomena is known as induced e.m.f.. Which is explained by the an example.

Consider a coil connected with a sensitive galvanometer and it is placed near a stationary bar magnetic, such that the magnetic flux from its N-pole is linked with the coil as shown in Fig.14.1(a). Initially, when both are at rest i.e., there is no relative motion between coil and magnet, so the deflection of the galvanometer is zero. Now when we move the bar magnet towards the coil, the magnetic flux across the coil is increased,

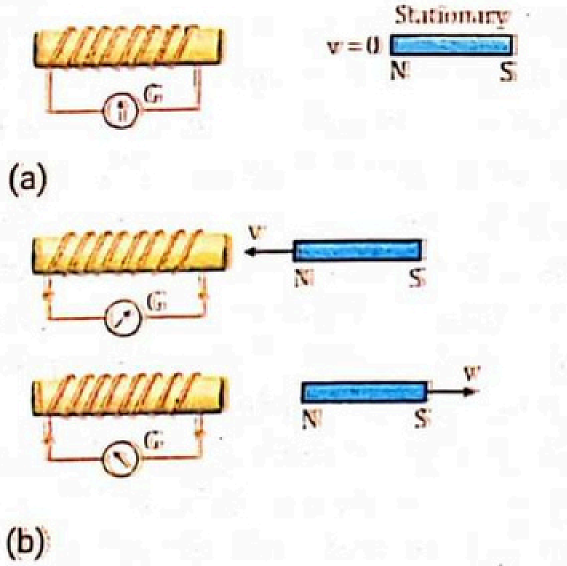


Fig.14.1(a) Magnetic bar is at rest and meter deflection is zero. (b) Magnetic bar is moving towards and away from the coil and meter shows deflection

and galvanometer shows deflection in one side as shown in Fig.14.1(b). Similarly, when the bar magnet is moved away from the coil, this time the magnetic flux is decreased, and the galvanometer again shows deflection but on the opposite side. The same result of deflection will be observed when the bar magnet is at rest, while the coil is moved either towards or away from the magnet. It is important to notice that the deflection can be observed only when there is a relative motion between bar magnet and the coil. However, no deflection will be observed when they are stationary no matter how close they are to each other.

The deflection of the galvanometer indicates that a current is induced in the circuit in the absence of a battery or any other source of e.m.f., it is observed only due to changing magnetic flux linked the coil. Such current is called induced current. Its corresponding voltage is called induced e.m.f.. The analysis shows that the induced current depends upon the following factors:

i. Number of turns of the coil.

ii. Magnetic flux linked to the coil.
iii. Relative speed between bar magnet and coil.

There are number of methods that produce induced current, but we are going to explain two of them.

Method I: Consider a coil of uniform area connected with a galvanometer such that the coil is placed in a uniform magnetic field as shown in Fig.14.2(a). Initially, when the coil is at rest, there is no deflection in the coil. However, when the coil is rotated, the magnetic flux linked the coil changes by its rotation and galvanometer shows deflection as shown in Fig. 14.2(b). This indicates that the current is induced by the rotation of coil in uniform magnetic field. This principle is being used in electric generator.

Method II Similarly, we have another method to induce current. This method consists of two coils placed side by side. One coil is connected to a battery with a switch and is called primary coil P. The other is connected to a galvanometer and is called secondary coil S.

Initially, when the switch is open and there is no current in the primary circuit, then the deflection on the galvanometer in the secondary circuit is zero as shown in Fig.14.3(a). Now when the switch is closed then the current increases in the primary coil and it causes increasing magnetic flux in the secondary coil S linked with primary coil and thus galvanometer shows deflection as shown in Fig.14.3(b). Similarly, when the switch is again made open then the current decreases in the primary coil which causes decreasing magnetic flux in the

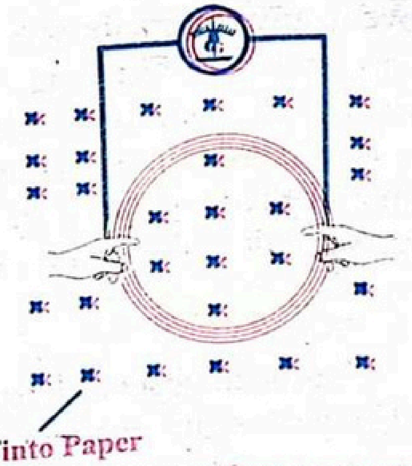


Fig.14.2(a) A coil of uniform area connected with a galvanometer in uniform magnetic field.

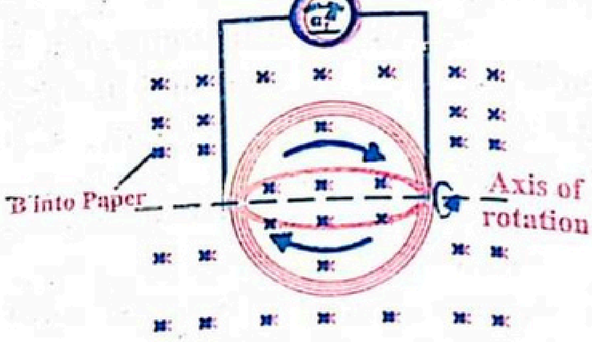


Fig.14.2(b) Induced current due to rotation of a coil in uniform magnetic field.

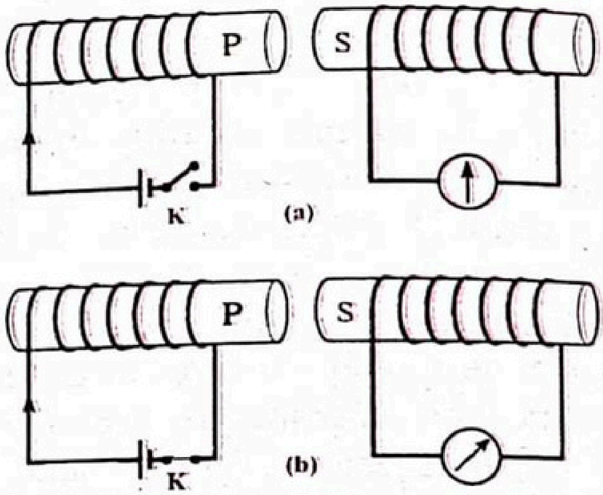


Fig.14.3(a) When the switch is opened and current is zero in the primary circuit, the deflection in meter is also zero in the secondary circuit (b) when switch K is closed current increases in primary coil and flux increases in secondary coil thus meter shows deflection.

secondary coil 'S'. Again the galvanometer shows deflection but in the opposite direction. In this process, the e.m.f. induces due to the mutual link of two coils through magnetic flux, so it is named as mutual induction. A transformer's working is based on principle of such mutual induction.

14.2 MOTIONAL E.M.F.

In the previous section, we have studied the production of induced e.m.f. by different methods. In this section, we describe **the e.m.f. induced in a conductor due to its motion across a uniform magnetic field and it is called motional e.m.f..**

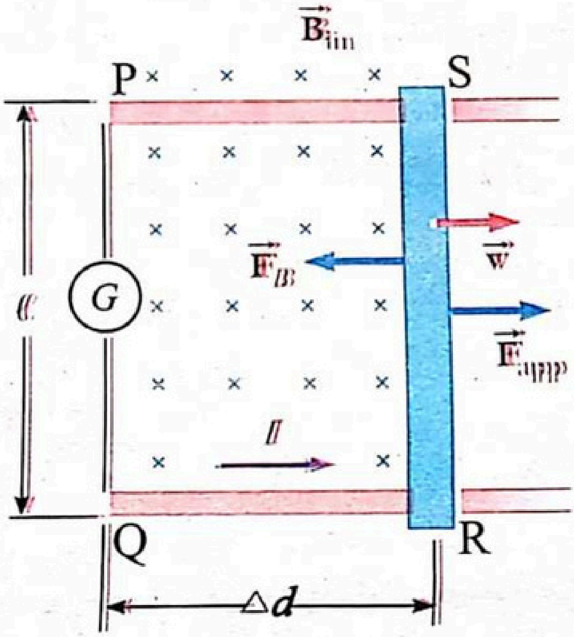


Fig.14.4(a) A conducting rod sliding with velocity v along two parallel rails produces a motional e.m.f..

The motional e.m.f. can be explained by an experimental setup which consists of two parallel conducting rails, separated by a distance 'ℓ' and a galvanometer is connected between their two ends P and Q. Let a conducting rod RS of length 'ℓ' is placed on the two parallel rails. In this way, we have a closed conducting loop PQRS as shown in Fig.14.4(a). A uniform magnetic field is also applied which directed into the page.

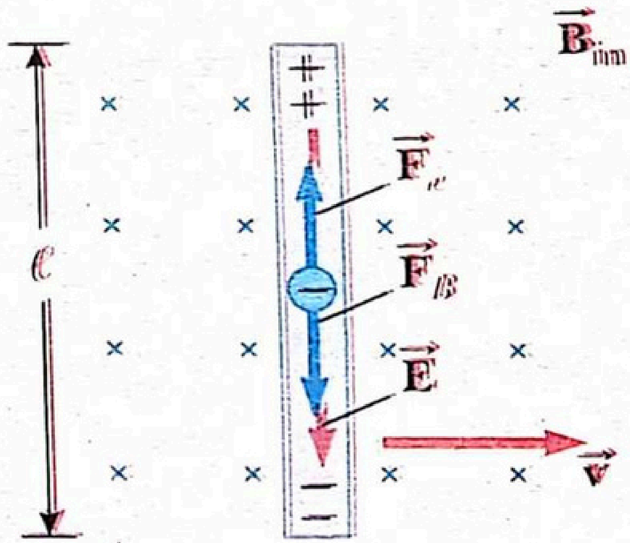


Fig.14.4(b) Separation of charges causes of electric field as well as electric potential across the ends of conductor.

Initially, when the rod is stationary, the galvanometer shows zero current in the closed loop. However when the conducting rod is pulled to the right with velocity 'v' under the action of an applied force ($\vec{F}_{app}$), the free charges (electron) of the rod experience a magnetic force $\vec{F}_B$. As a result, the free charges start to flow along the conductor and then in the closed loop thus galvanometer shows the current in the loop. This result shows that the current is induced in the closed loop due to the motion of the rod across the magnetic field.

The force that experience by the charges of the rod is given by

$$\vec{F}_B = q\left(\vec{v}\times\vec{B}\right) = qvB\sin\theta\hat{n}$$

In scalar notation

$$F_B = qvB\sin\theta$$

As the velocity 'v' is perpendicular to the magnetic field 'B' and angle θ between them is 90°. Therefore,

$$F_B = qvB\sin 90^\circ$$

$$F_B = qvB \quad ......(14.1)$$

The magnetic force causes the electrons (–ve charges) to accumulate at the one end of the rod and leaving a net the positive charge at the other end as shown in Fig.14.4(b). This separation of charges produces an electric field in the conductor where the electric force ($F_e = qE$) on the charges equals to the magnetic force ($F_B = qvB$). i.e., they are same in magnitude but in opposite direction. Thus according to Newton's third law:

$$F_e = -F_B$$

$$qE = -qvB$$

$$E = -vB \quad ......(14.2)$$

The separation of charges in the conductor also causes a potential difference (ΔV) across the ends of conductor and it is related to the induced e.m.f. (ε) in the loop. That is,

Wireless charging mobile works under the principle electromagnetic induction.

$$\varepsilon = \Delta V$$

But $$E = \frac{\Delta V}{\ell}$$

Or $$\Delta V = E\ell$$

∴ $$\varepsilon = E\ell$$

$$E = \frac{\varepsilon}{\ell}$$

Thus eq. 14.2 becomes

$$\frac{\varepsilon}{\ell} = -vB$$

$$\varepsilon = -vB\ell \quad ......(14.3)$$

This is the maximum value of motional e.m.f. when the velocity of the rod is perpendicular to the applied magnetic field. But, when there is some angle 'θ' between $\vec{V}$ and $\vec{B}$ then Eq.14.3 can be expressed as;

$$\varepsilon = B\ell v\sin\theta \quad ......(14.4)$$

This result shows that the motional e.m.f. depends upon length of the rod, speed of the rod and angle 'θ' between $\vec{v}$ and $\vec{B}$.

Example 14.1

A conducting rod of length 40cm is moving at a speed of 50 m s^{-1} in a uniform magnetic field of strength 2T. Calculate the e.m.f. induced in the rod when **(a)** the direction of motion of the rod is perpendicular to the magnetic field **(b)** and the rod moves at an angle of 60^0 to the field.

Solution:

Length of the rod = ℓ = 40cm = 0.4m

Speed of the rod = v = 50 m s^{-1}

Strength of the field = B = 2T

e.m.f. = ε = ?

(a) Angle between v and B = $\theta_1 = 90^0$

(b) Angle between v and B = $\theta_2 = 60^0$

By definition of motional e.m.f.

(a)
$$\varepsilon_1 = vB\ell \sin\theta_1$$
$$= (50\ m\ s^{-1})(2T)(0.4m)\ \sin 90^o$$
$$\varepsilon_1 = 40V$$

(b)
$$\varepsilon_2 = vB\ell \sin\theta_2$$
$$= (50ms^{-1})(2T)(0.4m)\ \sin 60^o$$
$$\varepsilon_2 = 35V$$

14.3 FARADAY'S LAW OF ELECTROMAGNETIC INDUCTION

In motional e.m.f., we studied the induced e.m.f. by moving a conducting rod with constant velocity perpendicular to the magnetic field. Now the same phenomenon under the same experimental setup was explained by Faraday in terms of changing magnetic flux. Again considering a conducting rod of length ($RS = \ell$) which is placed on two parallel conducting rails and a galvanometer is connected between the two ends P and Q. So there is closed

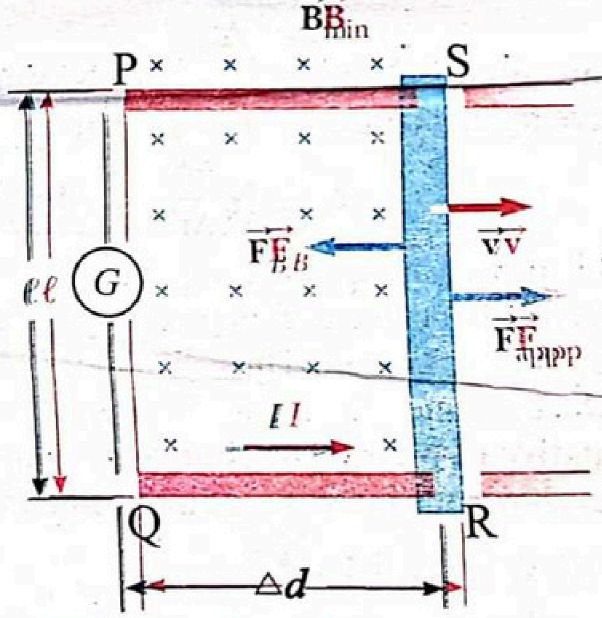


Fig.14.5 Induced e.m.f. due to changing of magnetic flux through the area of the loop PQRS.

conducting loop PQRS as shown in Fig.14.5. A magnetic field is also applied perpendicular to the plane of the conducting loop. If the rod moves through a distance Δd in time Δt then its velocity is given by:

$$v = \frac{\Delta d}{\Delta t} \quad \text{......(14.5)}$$

Due to motion of the rod, the area of the conducting loop changes continuously. This changing area is related with the changing of magnetic flux through the loop. Thus, by definition of magnetic flux

$$\Delta\phi = B \cdot \Delta A$$

The direction of area of the loop is parallel to the direction of B and angle θ between them is 0°. So

$$\Delta\phi = BA\cos 0^\circ = B\Delta A$$

$$\Delta\phi = B\ell\Delta d$$

Or $$B = \frac{\Delta\phi}{\ell\Delta d} \quad \text{......(14.6)}$$

> ***POINT TO PONDER***
>
> By neglecting the resistance, can a constant current in a coil setup a potential difference across the coil?

Now by definition of motional e.m.f.

$$\varepsilon = -vB\ell \quad \text{......(14.7)}$$

Putting the value of v and B from eq. 14.5 and eq. 14.6 in eq. 14.7

$$\varepsilon = \left(\frac{\Delta d}{\ell\Delta d}\right)(\ell)$$

$$\varepsilon = -\frac{\Delta\phi}{\Delta t}$$

This result can be extended for 'N' number of loops instead of a single loop and we have indeed e.m.f. 'N' times. That is,

$$\varepsilon = -N\frac{\Delta\phi}{\Delta t} \quad \text{......(14.8)}$$

This is the mathematical form of Faraday law of electromagnetic induction. It shows that the induced e.m.f. depends upon the rate at which the magnetic flux through the the coil is changed. Thus, Faraday law of electromagnetic induction states that **the induced e.m.f. in a coil having 'N' number of loops is equal to N times the negative of the rate of change of magnetic flux linked with the coil.** The negative sign shows the direction of induced e.m.f. and it will be studied in Lenz's law.

14.4 LENZ'S LAW

We have studied that the magnitude of induced e.m.f. can be determined by using Faraday law of induction. i.e., the magnitude of induced e.m.f. is directly proportional to the rate of change of magnetic flux. The direction of this induced current was pointed out by a Russian Scientist H.F.E. Lenz in 1834 which states as: **"the direction of induced current is always such as to oppose the cause (direction of the action) that produces the induced current".** Thus, Lenz's law can be expressed same as that the Faraday's law but with negative sign.

$$\varepsilon = -N\frac{\Delta\phi}{\Delta t} \qquad \ldots\ldots(14.9)$$

The negative sign in the Eq.14.3 implies that the induced e.m.f. opposes the rate of change of magnetic flux linked with the coil. It is further explained by an example;

Consider a coil which consists of a number of turns. When the N-pole of the bar magnet moves toward the coil, magnetic flux linking the coil increases. According to Faraday's law the induced current is setup in the circuit. Similarly, according to Lenz's law, this induced current opposes the further increase in flux through the coil. It is therefore, when the magnetic flux across the coil is changed then like a bar magnet, the one end of the coil acts as a N-pole while the other end acts as a S-pole. Hence, if the N-pole of the bar magnet move towards the coil. Now the two N-poles will then repel each other. Thus, by applying right hand rule, the direction of induced current in the circuit is anti-clockwise as shown in Fig.14.6(a).

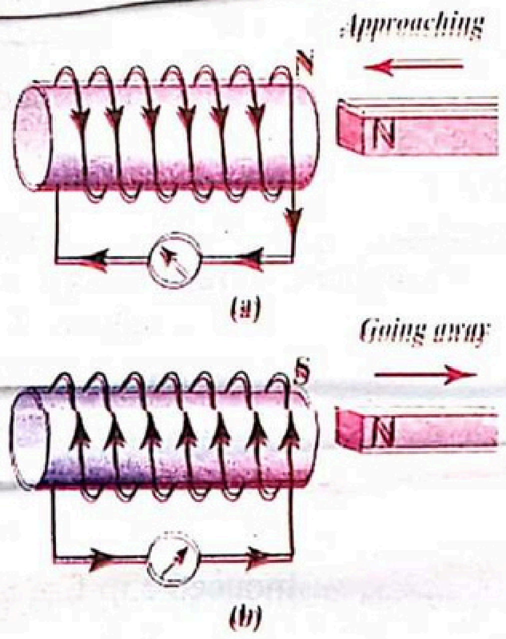


Fig.14.6(a) The induced current flows anticlockwise.
(b) The induced current flows clockwise.

If the N-pole of bar magnet moves away from the coil, the flux linking the coil decreases. The induced current in the circuit again opposes the decrease in flux. This time the end of the coil toward the magnet becomes S-pole. Now the two opposite poles will then attract each other and the direction of the induced current in the circuit is clockwise, to oppose the cause i.e., decrease in flux as shown in Fig.14.6(b).

Lenz's law is not only provided the direction of the induced current but it is also given the principle of law of conservation of energy. It is explained by considering again Fig.14.6. When N-pole of bar magnet is approaching the coil, the magnetic flux linking the coil increases and the end of the coil towards the bar magnet becomes N-pole. Now the two N-poles oppose each other. Due to this opposition, the mechanical energy is converted into electrical energy. Thus, Lenz's law is consistent with the law of conservation of energy. If the magnetic flux linking the coil increases, the direction of current in the coil will be such that it will oppose the further increase in flux and hence the induced current will be anticlockwise. If at this instant the direction of current would be clockwise then it will become self-perpetuating and this is the violation of law of conservation of energy.

Similarly, when the N-pole of the magnet moves away from the coil, the magnetic flux linking the coil decreases which induce current in the coil in such a direction that the end of coil towards the magnet becomes S-pole. Now the attraction of two unlike poles opposes the decrease in flux of the coil. This opposition to the cause of change in flux is again in accordance with the law of conservation of energy.

Example 14.2

A coil of 150 loops is pulled in 0.06s from the poles of the magnet, which decreases the magnetic flux linked with the coil from 6×10^{-4}Wb to 2×10^{-4}Wb. Determine the average e.m.f. induced in the coil due to changing of flux.

Solution:

Number of turns of coil $= N = 150$

Time taken $= t = 0.06s$

Initial flux $= \phi_1 = 6\times10^{-4}$ Wb

Find flux $= \phi_2 = 2\times10^{-4}$ Wb

Changing in flux $= \Delta\phi = \phi_2 - \phi_1$

$$\Delta\phi = 2\times10^{-4} - 6\times10^{-4} = -4\times10^{-4}\,\text{Wb}$$

Induced e.m.f. $= \varepsilon = ?$

According to Faraday Law,

$$\varepsilon = -N\frac{\Delta\phi}{\Delta t}$$

$$\varepsilon = \frac{-150(-4\times10^{-4}\,\text{Wb})}{0.06s}$$

$$\varepsilon = (10000)\times10^{-4}\,\text{V}$$

$$\varepsilon = 1\text{V}$$

14.5 MUTUAL INDUCTION

When a changing current in one coil induces an e.m.f. in another nearly coil then such phenomenon is known as mutual induction. It is explained as: Consider two coils which are placed side by side and close to each other as shown in Fig.14.7. The coil which is connected to a battery, a switch and a rheostat is called primary coil P and the other coil which is connected to a sensitive galvanometer is called secondary coil S. When the switch is closed the current increases from zero to its maximum value in the primary coil P and it produces a changing magnetic flux which links with the secondary coil S and we observe momentarily deflection. After some time the magnetic field becomes steady i.e. there is no more changing flux and deflection on galvanometer becomes zero. If the current in the primary coil P is changed by changing the resistance of the rheostat, then the magnetic flux linked with secondary coil S is also changed. Hence, according to Faraday's law, the changing magnetic flux produces an induced e.m.f. in the secondary coil 'S' and galvanometer shows deflection. Since the induced e.m.f. in the secondary circuit is due to the mutual link of coil S with the coil P through magnetic flux, such induction is termed as mutual induction. The magnitude and direction this induced e.m.f. can be determined by Faraday's law and Lenz's law and its value is given by:

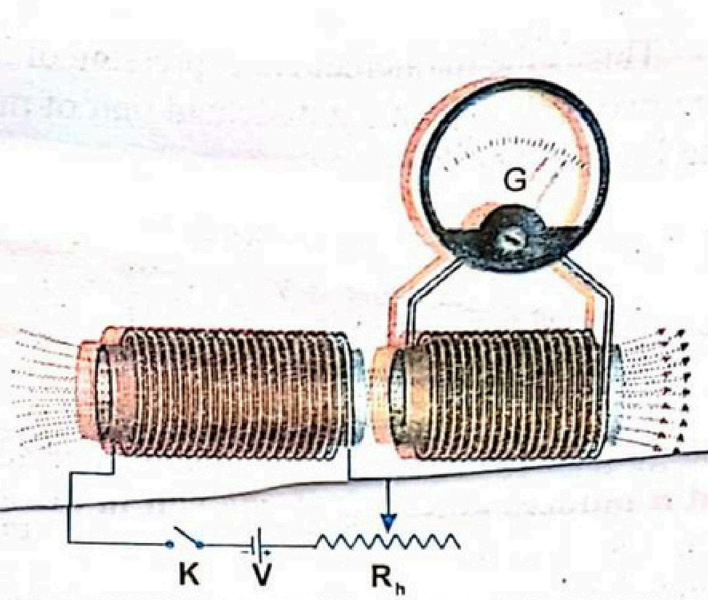


Fig.14.7 The changing current in primary coil P, the changing flux through secondary coil S produces an e.m.f. in it.

$$\varepsilon_s = -N_s \frac{\Delta\phi_s}{\Delta t} \quad ......(14.10)$$

where N_s is the number of turns of the secondary coil S. The analysis shows that the total flux $N_s\phi_s$ through the secondary coil S which causes the induced e.m.f. is directly proportional to the current I_P in the primary circuit. i.e.,

$$N_s\phi_s \propto I_P$$

$$N_s\phi_s = MI_P \quad ......(14.11)$$

where M is the constant of proportionality known as mutual inductance of the two coils. It depends upon the rate of changing of current in the primary coil, number of turns of coils, cross sectional area of the coils and closeness of the coils. Substitute the value of ϕ_s from Eq.14.11 in Eq.14.10, we get,

$$\varepsilon_s = -N_s \frac{\Delta}{\Delta t}\left(\frac{MI_P}{N_s}\right)$$

$$\varepsilon_s = -M\frac{\Delta I_P}{\Delta t} \quad ......(14.12)$$

This is the mathematical expression of induced e.m.f. due to mutual induction of the two coils. The magnitude and unit of mutual inductance can be calculated by using Eq.14.12 as;

$$M = \frac{\varepsilon_s}{\frac{\Delta I_P}{\Delta t}} \quad ......(14.13)$$

The unit of mutual inductance is Henry denoted by H. That is, **if the current in a coil P is changing at the rate of one ampere per second and it induces an e.m.f. of one volt in the coil S, then the mutual inductance is said to be one henry**, i.e.

$$H = \frac{V}{As^{-1}}$$

Swiping Induction Card acts as a key opening and closing the door.

Example 14.3

When the current in the primary coil is changing at a rate of $6As^{-1}$, it is observed that an e.m.f. of 14mV is induced in the nearby secondary coil. What is the mutual inductance of the combination?

Solution:

Rate of change of current in primary coil $= \frac{\Delta I}{\Delta t} = 6As^{-1}$

Induced e.m.f. in the secondary coil $= \varepsilon = 14mV = 1.4 \times 10^{-2}V$

Mutual inductance = M = ?

According to the relation of mutual induction

$$\varepsilon = M\frac{\Delta I}{\Delta t}$$

$$M = \frac{\varepsilon}{\left(\frac{\Delta I}{\Delta t}\right)}$$

$$M = \frac{1.4 \times 10^{-2} V}{6As^{-1}} = 2.3 \times 10^{-3} H$$

$$M = 2.3mH$$

14.6 SELF INDUCTION

It was first suggested by Henry that changing current in a coil induces an e.m.f. in itself. This is known as self-induction which is explained as:

Consider a coil is connected in series with a battery, a switch S and a rheostat as shown in Fig.14.8. When the switch S is closed, current flows through the coil and a magnetic field is set up in it. Now if the current is changed by adjusting the resistance of the rheostat, the magnetic flux linked with the coil also changes. This changing magnetic flux causes an induced e.m.f. in the same coil.

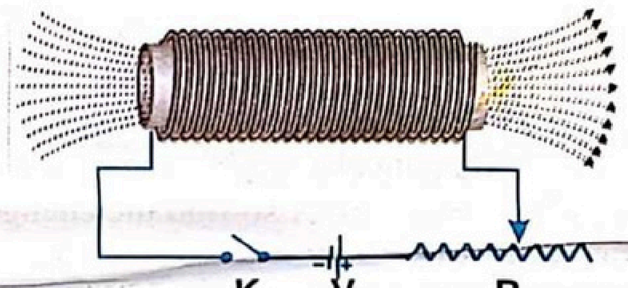


Fig.14.8 Changing current in the coil causes an induced e.m.f. in the same coil.

Such induced e.m.f. is termed as self-induced e.m.f. whose magnitude can be calculated by using Faraday's law of induction.

$$\varepsilon = -N\frac{\Delta\phi}{\Delta t} \quad ......(14.14)$$

where 'N' is the number of turns of the coil, ϕ be the flux through a single loop of the coil. So, the total flux through the coil is $N\phi$ and the experiment shows that the total flux is directly proportional to the changing current. i.e.,

$$N\phi \propto I$$

$$N\phi = LI \quad ......(14.15)$$

where 'L' is constant of proportionality called self-inductance. The value of self-inductance depends upon number of turns of the coil, size or shape of the coil and the type of material on which coil is wound.

Substituting the value of magnetic flux ϕ from Eq.14.15 in Eq.14.14 we have,

$$\varepsilon = -N\frac{\Delta}{\Delta t}\left(\frac{LI}{N}\right)$$

$$\varepsilon = -L\frac{\Delta I}{\Delta t} \quad ......(14.16)$$

This is a mathematical expression of a self-induction. The magnitude and unit of self-inductance can be determined by using Eq.14.16 in the form;

$$L = \frac{\varepsilon}{\left(\frac{\Delta I}{\Delta t}\right)} \quad ......(14.17)$$

The SI unit of self-inductance is henry 'H'. It is defined as; **if the current in a coil is changing at the rate of one ampere per second and an e.m.f. of one volt is induced in the same coil then self-inductance 'L' is said to be one henry**, i.e.

$$H = \frac{V}{As^{-1}}$$

Example 14.4

Calculate change in current in an inductor of 6H in which the e.m.f. of 220V is induced in 0.09s. Also find the change in flux in the same inductor.

Solution:

Change in current = ΔI = ?

Self-inductance = L = 6H

Induced e.m.f. = ε = 220V

Time taken = Δt = 0.09s

Change in magnetic flux = $\Delta\phi$ = ?

> ***POINT TO PONDER***
> Which law of Physics tells us that if a current carrying conductor produces a force on the magnet, then a magnet must produce a force on a current carrying the conductor?

According to the equation of self-inductance

$$\varepsilon = L\frac{\Delta I}{\Delta t}$$

$$\Delta I = \frac{\varepsilon \Delta t}{L}$$

$$\Delta I = \frac{(220V)(0.09s)}{6H}$$

$$\Delta I = 3.3A$$

Also

$$\varepsilon = \frac{\Delta\phi}{\Delta t}$$

$$\Delta\phi = \varepsilon \Delta t$$

$$\Delta\phi = 220V \times 0.09s$$

$$\Delta\phi = 19.8Wb$$

14.7 ENERGY STORED IN AN INDUCTOR :

Like a capacitor which stores energy in its electric field, an inductor also stores energy in its magnetic field. It is explained as:

Consider an inductor of inductance 'L' which is connected with a battery through a switch as shown in Fig.14.9. When switch is closed then there is a growth of current from zero to its maximum value I_o in time t. This increasing of current causes of changing magnetic flux (magnetic field) linked the coil. According to Faraday's law, "this changing magnetic flux produces an induced e.m.f.". Similarly, according to Lenz's law, "the induced e.m.f. opposes the growth of current, therefore, work is needed to be done against the induced e.m.f. in the inductor during the growing current until it attains its maximum value. This work done is stored in the magnetic field of the inductor in terms of magnetic potential energy and it is calculated as under;

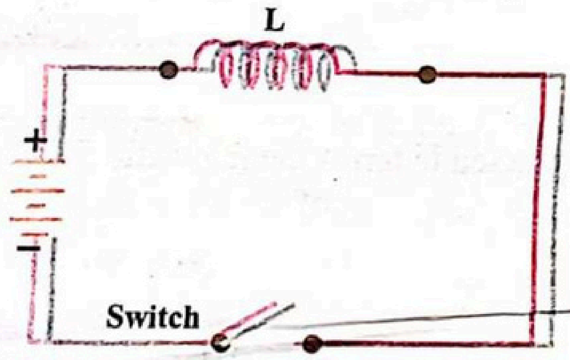


Fig.14.9 Magnetic potential energy stores in the magnetic field of an inductor.

By the definition of work on the charges to flow in the given circuit,

$$W = F \cdot d$$

But $$F = (\Delta q)E = (\Delta q)\left(\frac{V}{d}\right) \qquad \therefore E = \frac{V}{d}$$

Hence $$W = \Delta q \frac{V}{d} \cdot d = \Delta q V$$

But according to self-inductance, the magnitude of induced e.m.f. ε or V is given as:

$$V = L\frac{\Delta I}{\Delta t}$$

So $$W = \Delta q L \frac{\Delta I}{\Delta t}$$

$$W = \frac{\Delta q}{\Delta t} L \Delta I = LI\Delta I$$

where $I = \dfrac{0 + I_0}{2}$

and ΔI = change in current $= I_0 - 0$

Thus $$W = L\frac{I_0}{2} I_0$$

$$W = \frac{1}{2} L I_0^2 \quad \text{......(14.18)}$$

FOR YOUR INFORMATION

Shake flash light needs no battery. Shake the light for 30 second and generates upto 5 minutes of light. Electromagnetic induction occurs as a built in magnetic slides to and fro between coils that charge capacitor. When the brightness diminishes, shake again. You provide the energy to charge the capacitor.

This work is stored in the form of magnetic potential energy in the magnetic field of the inductor. Thus, according to work – energy principle, work done equals the change in energy

$$\Delta U = \text{Work}$$

$$\Delta U = \frac{1}{2} L I_0^2 \quad \ldots\ldots(14.19)$$

As the energy is stored in the magnetic field of the inductor, Eq.14.19 can be expressed in terms the magnetic field B.

By the definition of magnetic field inside the solenoid,

$$B = \mu_0 n I_0 = \frac{\mu_0 N I_0}{\ell} \quad \ldots\ldots(14.20) \qquad \therefore n = \frac{N}{\ell}$$

$$I_0 = \frac{B\ell}{\mu_0 N} \quad \ldots\ldots(14.21)$$

Now changing magnetic flux through an inductor of cross section area 'A' having 'N' number of turns;

$$\Delta\phi = B \cdot A$$

$$\Delta\phi = \left(\frac{\mu_0 N I}{\ell}\right) A \quad \ldots\ldots(14.22)$$

POINT TO PONDER

What would be the value of stored energy in an inductor if the applied current is doubled?

According to Faraday's law of induction

$$\varepsilon = -L\frac{\Delta I}{\Delta t} = -N\frac{\Delta\phi}{\Delta t}$$

$$L(I_0 - 0) = N\Delta\phi$$

$$L = \frac{N\left(\frac{\mu_0 N I_0}{\ell}\right)A}{I_0}$$

$$L = \frac{\mu_0 N^2 A}{\ell} \quad \ldots\ldots(14.23)$$

Thus, substituting the values of I and L from Eq.14.21 and 14.23 in Eq.14.19. We get,

$$\Delta U = \frac{1}{2}\frac{\mu_0 N^2 A}{\ell} \cdot \frac{B^2 \ell^2}{\mu_0^2 N^2}$$

$$\Delta U = \frac{1}{2}\frac{B^2}{\mu_0}(\ell A) \quad \ldots\ldots(14.24)$$

$$\Delta U = \frac{1}{2}\frac{B^2}{\mu_0}(\text{Volume})$$

DO YOU KNOW

- A capacitor stores energy in its electric field.
- An inductor stores energy in its magnetic field.

Now magnetic potential energy (U_m) per unit volume of the inductor is given by

$$U_m = \frac{\Delta U}{\text{Volume}} = \frac{\frac{1}{2}\frac{B^2}{\mu_0}(\text{Volume})}{\text{Volume}}$$

$$U_m = \frac{1}{2}\frac{B^2}{\mu_0} \quad \text{......(14.25)}$$

This is the energy density or magnetic potential energy per unit volume in the magnetic field of an inductor.

Example 14.5

A steady current of 4A in an inductor of 1000 turns causes a flux of 0.001 Wb to link the loops of the inductor. Calculate (a) the e.m.f. induced in the inductor if the current is stopped in 0.06s (b) the inductance of the inductor and (c) the energy stored in the coil.

Solution:

Changing current = $\Delta I = 4 - 0 = 4A$

Number of turns = $N = 1000$

Changing flux = $\Delta\phi = 0.001 Wb$

Time taken = $\Delta t = 0.06s$

(a) Back e.m.f. = ε = ?

(b) Inductance = L = ?

(c) Energy stored = U_m = ?

DO YOU KNOW

A steady D.C current cannot induce an induced e.m.f. because magnetic flux due to such current does not change.

According to Faraday's Law:

(a)

$$\varepsilon = N\frac{\Delta\varphi}{\Delta t}$$

$$\varepsilon = 1000\frac{(0.001Wb)}{0.06s}$$

$$\varepsilon = 16.7V$$

(b) Using the relation of self-inductance:

$$\varepsilon = L\frac{\Delta I}{\Delta t}$$

$$L = \frac{\varepsilon \Delta t}{\Delta I}$$

$$L = \frac{16.7V(0.06s)}{4A}$$

$$L = 0.25H$$

(c)

$$U_m = \frac{1}{2}LI^2$$

$$U_m = \frac{1}{2}(0.25H)(4A)^2$$

$$U_m = 2J$$

14.8 A.C. GENERATOR

An A.C. generator is a device that converts mechanical energy into electrical energy. The conversion of energy is based on the principle of induced motional e.m.f. The essential parts of an A.C. generator are as under:

Armature

It is a rectangular coil abcd of length 'ℓ' and width x having 'N' number of turns of insulated copper wire wounded on a soft iron core. It is capable of rotating about an axis perpendicular to the magnetic field, as shown in Fig.14.10(a).

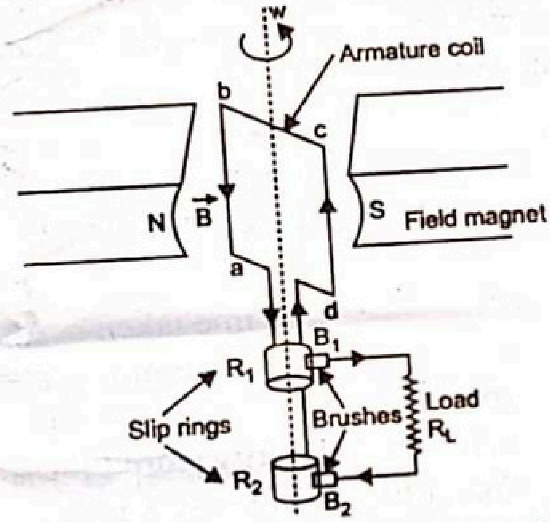


Fig.14.10(a) A schematic diagram of an A.C.

Magnetic Field

A strong uniform magnetic field exists between north and south poles of the magnets such that the armature rotates in it.

Slip Rings

The ends of the armature are connected with two slip rings R_1 and R_2. These rings rotate with the rotation of the armature.

Brushes

Two stationery carbon brushes B_1 and B_2 in contact with the slip rings are responsible to provide the induced current from the armmature to the external circuit.

Working

When the armature is rotated at constant angular speed 'ω' in the applied magnetic field between north and south poles, the magnetic flux that linked with the armature changes. This changing magnetic flux induces an e.m.f. in the armature i.e.,

$$\varepsilon = vB\ell$$

where '$\vec{v}$' is perpendicular to '$\vec{B}$'. In order to determine a general expression for such induced e.m.f., we consider the clockwise rotation of the armature. The side ab and cd are moving at velocity 'v' making angle 'θ' with magnetic field 'B', such that, the vertical component of velocity ($v\sin\theta$) is perpendicular to 'B' as shown in Fig.14.10(b). The charges in these two sides experience force along the sides of the wire, causing induced e.m.f., while the e.m.f. due to the side ad and bc is zero, because the force experience by charges in these two sides is perpendicular, not along the sides of the wires. Thus, the value of resultant e.m.f. induced in the armature having 'N' number of turns is given by

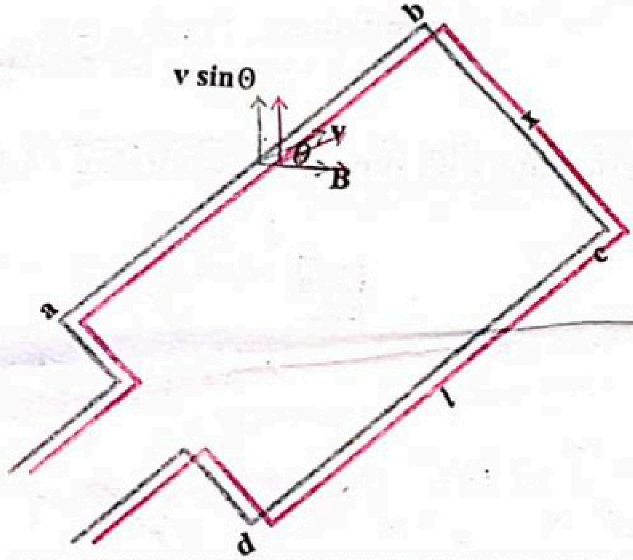


Fig.14.10(b) The plane of armature at an angle 'θ' with the magnetic field B.

$$\varepsilon = \varepsilon_{ab} + \varepsilon_{bc} + \varepsilon_{cd} + \varepsilon_{da}$$

$$\varepsilon = NvB\ell\sin\theta + 0 + NvB\ell\sin\theta + 0$$

$$\varepsilon = 2NvB\ell\sin\theta \quad ......(14.26)$$

If the armature rotates with constant angular velocity 'ω' then according to the relationship between linear velocity and angular velocities is given as

$$v = r\omega$$

$$v = \frac{x}{2}\omega \quad \text{and} \quad \theta = \omega t$$

where 'x' is the width of the armature. Thus Eq.14.26 becomes

$$\varepsilon = 2N\frac{x}{2}\omega B\ell\sin\omega t$$

As $x\ell = A$ (area of the armature)

$$\varepsilon = NAB\omega\sin\omega t \quad ......(14.27)$$

If angle 'θ' between A and B is 90^0 then ε is maximum (ε_m) and Eq.14.27 becomes

$$\varepsilon_m = NAB\omega\sin 90^\circ$$

$$\varepsilon_m = NAB\omega$$

Eq.(14.27) becomes

$$\varepsilon = \varepsilon_m\sin\omega t \quad ......(14.28)$$

Since $\omega = \frac{2\pi}{T} = 2\pi f$

Hence Eq.14.28 becomes

$$\varepsilon = \varepsilon_m\sin 2\pi f\,t \quad ......(14.29)$$

DO YOU KNOW

An electric generator is an electric motor with its input and output reversed.

This result shows that the e.m.f. induced in the armature varies periodically with time. If a graph between e.m.f. and time is drawn then we have a sinusoidal wave of frequency 'f'. The wave form of one cycle of A.C. due to different positions of the armature with time is shown in Fig.14.11.

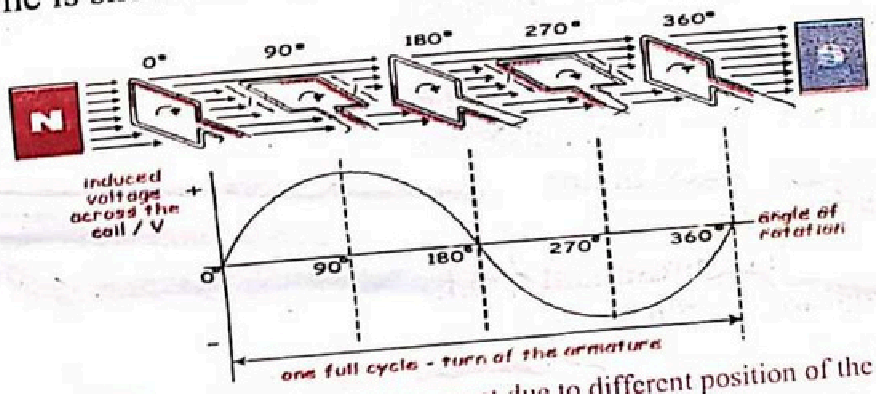


Fig.14.11 A wave cycle of alternating current due to different position of the armature.

Example 14.6

The armature of a generator has 150turns and its area is $200cm^2$. If it rotates with frequency 60Hz in 0.15T magnetic field, calculate the maximum e.m.f. induced in the coil.

Solution:

Number of turns of the coil = N = 150

Area of the coil = $A = 200cm^2 = 0.02m^2$

Frequency of the coil = f = 60Hz

Magnetic field = B = 0.15T

By definition of angular frequency:

$$\omega = 2\pi f$$

$$\omega = 2(3.14)(60Hz)$$

$$\omega = 377 rad\,s^{-1}$$

Now peak value of induced e.m.f. is given by

$$\varepsilon_m = NAB\omega$$

$$= (150)(0.02m^2)(0.15T)(377rads^{-1})$$

$$\varepsilon_m = 170volt$$

14.9 A.C. MOTOR

An A.C. motor is an electrical machine that converts electrical energy into mechanical energy. It works on the basis of principle of mutual induction, i.e., the applied alternating current in the stator winding induces current in the rotor. The magnetic field due to this induced current in the motor interacts with the stator field. This interaction between the two fields produce rotation in rotor. An A.C. motor may be either single phase or three phase. A single-phase A.C. motor converts a small amount of electric energy into mechanical energy, while, the three phase motor converts a bulk amount of electrical energy into mechanical energy.

An induction motor consists of two main parts as shown in Fig.14.12. One is the outer side called stator having coils supplied with alternating current source to produce a rotating magnetic field. While the other is rotor which rotates inside stator. The rotor is attached to the output shaft producing a second rotating magnetic field. The stator and the rotor are designed in such a way that there is a small gap between them known as air gap. Now we explain various parts of an A.C. motor.

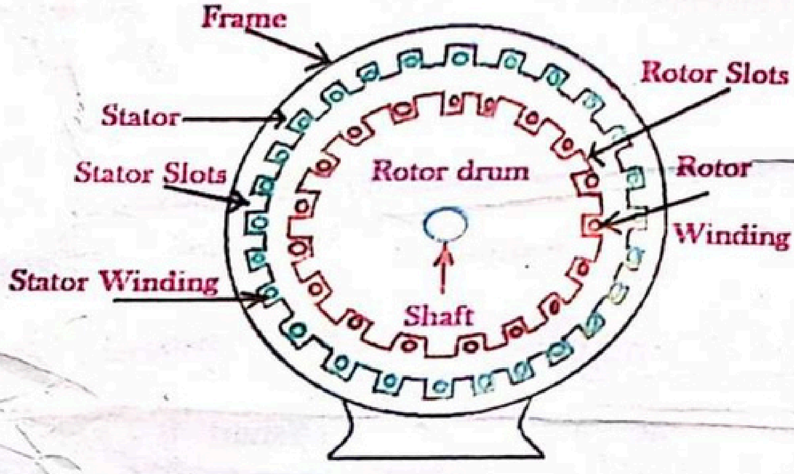


Fig.14.12 A schematic diagram of an A.C. motor with its different parts.

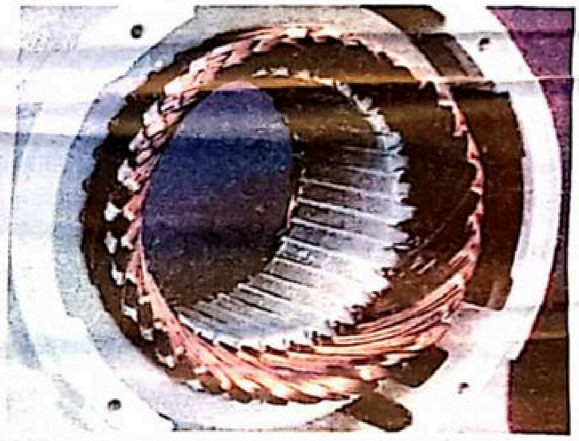


Fig.14.13 A stator winding of an A.C. motor

Stator

The word 'stator' has been derived from static, means stationary. The stator is made up of a number of stampings which are slotted to receive the winding. It is wound for a definite number of poles as shown in Fig.14.13. The number of poles are inversely related to the speed of the motor, i.e. greater the number of poles, lesser the speed and vice versa. An A.C. motor does not have any brushes, but the stator is connected directly to the A.C. source where the current alternates through the poles and it causes a rotating magnetic field.

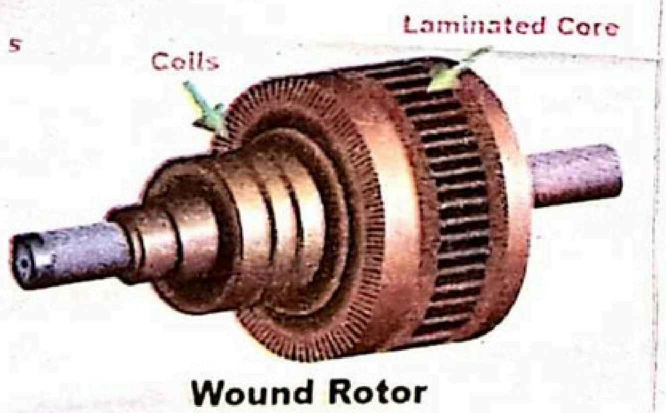


Fig.14.14 A rotor of an A.C. motor.

Rotor

The word rotor has been derived from rotation means rotational motion. A rotor is the central component of the motor. It is inserted into the stator and fixed to the shaft. The rotor consists of a cylindrical terminated core with parallel slots for carrying the rotor conductor. The rotor conductors are not simple wires, but these are heavy bars of copper or aluminum such that one bar is placed in each slot as shown in Fig.14.14. This configuration is called a squirrel-cage rotor, such rotor has the simplest and most rugged construction imaginable.

Bearings and Fan

Bearings are mounted on the shaft which supports the rotor, minimizes the friction and increases the efficiency of the motor as shown in Fig.14.15(a). A fan is also mounted on the shaft of the rotor for cooling the motor when the shaft is rotating as shown in Fig.14.15(b).

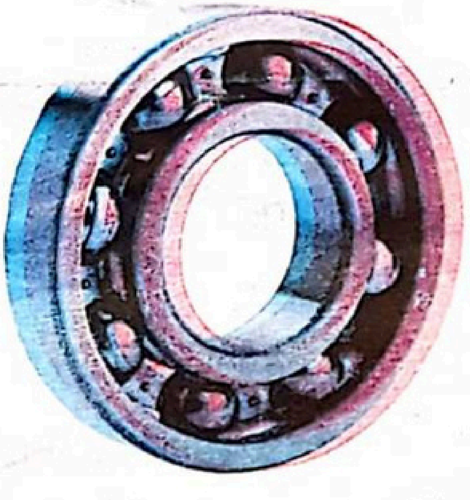


Fig.14.15(a) A bearing of an A.C. Motor

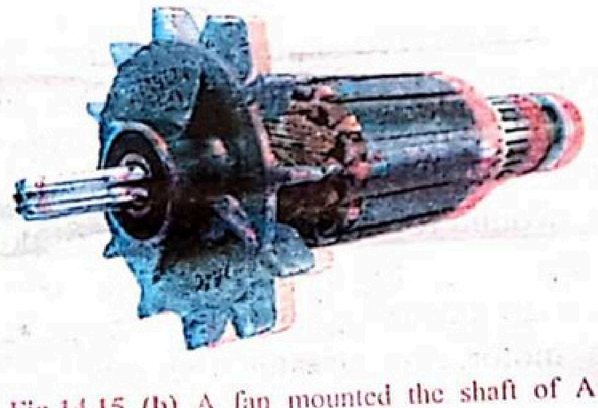


Fig.14.15 (b) A fan mounted the shaft of A.C.

Working of Motor

An A.C. motor works using the principle of electromagnetic induction. When A.C. power from a source is applied to the stator of the motor, it produces a rotational magnetic field. According to Faraday's law, this magnetic field induces a current in the rotor of motor without any physical connection between the stator and the rotor. The frequency of the induced current is same as that of applied current. The induced current in the rotor produces another magnetic field in the rotor that reacts against the stator field. Now these two magnetic fields interact with each other, their interaction produces torque and hence the rotor starts to rotate in the direction of the stator rotational magnetic field. The speed of the motor depends upon the oscillation of the rotating magnetic field of the stator.

Let us study the production of rotating field for the one applied A.C. cycle by considering the working of two phase A.C. motor. Such two phase motor consists of two pole stator having two identical windings S_1 and S_2 separated by 90^o phase difference between them as shown in Fig.14.16(a). The flux due to the applied alternating current flowing in each phase winding is sinusoidal. Let ϕ_1 and ϕ_2 be magnetic fluxes setup by two winding S_1 and S_2 respectively and let ϕ be the resultant flux of ϕ_1 and ϕ_2. i.e., $\phi = \phi_1 + \phi_2$.

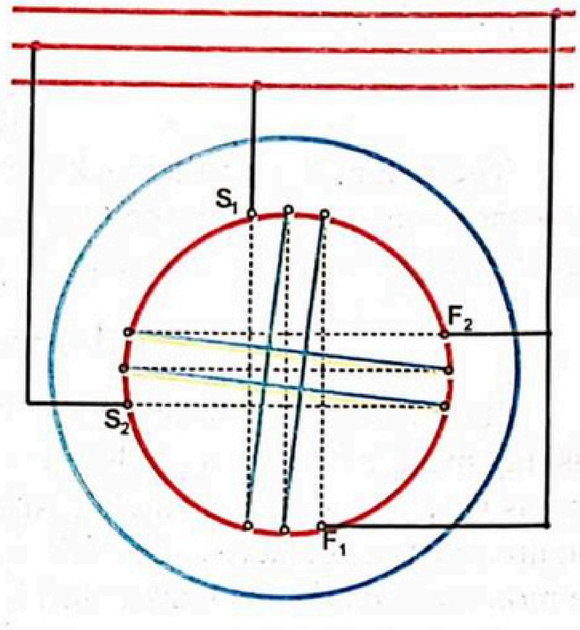


Fig.14.16(a) Circuit diagram of two phase A.C. motor contains two stator windings S_1 and S_2 at 90° apart.

Now we observe the condition of two flux ϕ_1 and ϕ_2 at different angles for one applied cycle of alternating current.

I If $\theta = 0$ then $\phi_1 = 0$ and ϕ_2 is maximum.

II If $\theta = \frac{\pi}{2}$ then ϕ_1 is maximum and $\phi_2 = 0$.

III If $\theta = \pi$ then $\phi_1 = 0$ and ϕ_2 is maximum.

IV If $\theta = \frac{3\pi}{2}$ then ϕ_1 is maximum and $\phi_2 = 0$.

V If $\theta = 2\pi$ then $\phi_1 = 0$ and ϕ_2 is maximum.

Graphically, the values of flux ϕ_1 and ϕ_2 in S_1 and S_2 at different angles of the applied A.C. voltage are shown in Fig.14.16(b). The two resultant sinusoidal waves of ϕ_1 and ϕ_2 show that when the flux in one winding is minimum then at the same time the flux in other winding is maximum and vice versa but the magnitude of the resultant flux remains constant.

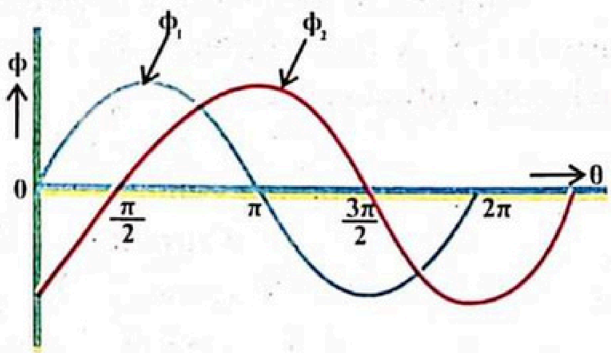


Fig.14.16(b) Wave shape of the two rotating induced magnetic fluxes.

14.10 BACK E.M.F. IN A MOTOR

When the potential difference V from a source is applied across an A.C. motor, the rotor starts rotation in the stator magnetic field and there is changing magnetic flux through the rotor. This changing magnetic flux causes of an induced e.m.f. According to Lenz's law, the induced e.m.f. opposes the applied potential difference. Due to this reason, the induced e.m.f. is called back e.m.f. of the motor. As the applied voltage (V) and induced e.m.f. (ε) act in opposite direction, the resultant e.m.f. in the circuit is $V-\varepsilon$. Similarly, if R be the resistance of the rotor then the current drawn by the motor is given by

$$I = \frac{V-\varepsilon}{R} \quad ......(14.30)$$

The magnitude of the back e.m.f. depends on the speed of the rotor. i.e., the faster the rotor, the greater the back e.m.f.. In the beginning, when the motor is just started, the back e.m.f. is zero and the current is maximum. i.e.,

$$I = \frac{V}{R} \quad ......(14.31)$$

It is our daily observations that when we start a motor of refrigerator or washing machine, the room lights near the load are affected and become dim. Because there is no ε in the starting and the motor draws a large current. At the same time the potential difference across the bulb is reduced, causing a momentary brownout. As the motor speeds up, the back e.m.f. is induced and as a result the potential difference across the motion reduces, the current drawn in it is much smaller, so the brownout ends. Now if the motor is overloaded, it turns slow. According to Eq.14.30, the back e.m.f. reduces and there is a large current drawn in the motor. If this large current maintains for a long time, the motor may burn out.

Example 14.7

An electric motor is connected across the potential difference of 220V. If the current of 50A flows through the resistance of 2Ω of the motor, then calculate the back e.m.f. produced in the motor.

Solution:

Applied voltage = V = 220V

Current = I = 50A

Resistance = R = 2Ω

Back e.m.f. = ε = ?

Using the relation

$$I = \frac{V-\varepsilon}{R}$$

$$\varepsilon = V - IR$$

$$\varepsilon = 220V - (50A)(2\Omega)$$

$$\varepsilon = 220 - 100$$

$$\varepsilon = 120V$$

14.11 EDDY CURRENT

As we have observed that when an armature or any other conductor rotates in a magnetic field, it changes the magnetic flux through it. According to law of electromagnetic induction, the changing magnetic flux induces an e.m.f. in the armature. Hence this induced e.m.f. sets up a current which circulate throughout the volume of the armature. Such current is known as eddy current. It is explained by an example:

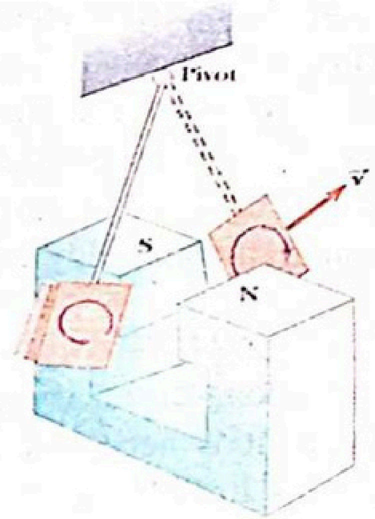
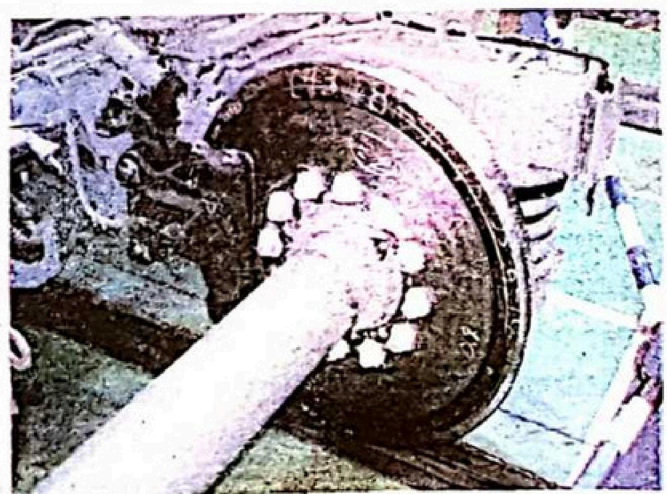


Fig.14.17 Formation of eddy currents in a conducting plate moving through a magnetic field. As the plate enters or leaves the field, the changing magnetic flux induces in e.m.f., which causes eddy currents in the plate.

Consider a copper plate attached at the end of a rigid rod to swing back and forth through a magnetic field as shown in Fig.14.17. As the plate enters the field, it cuts the magnetic flux which causes the changing magnetic flux. This changing magnetic flux induces an e.m.f. in the plate, as a result, a swirling eddy current is induced in the plate. Now according to Lenz's law, the direction of such eddy current is opposite to the direction of motion of the pivoted plate. It is therefore, the eddy current creates an opposite magnetic pole on the plate which is repelled by the poles of the magnetic field. So, there is a repulsion force that opposes the motion of the plate. In this case law of conservation of energy does not hold. On the other hand, there is power loss due to the flow of this eddy current in the body.

In order to reduce the power loss and the consequent heating, conducting parts of the rotating body are often laminated. That is, they are built-up in thin layers separated by a non-conducting material such as lacquer or a metal oxide. This layered structure prevents large current loops and effectively confines the currents to small loops in individual layers. Such a laminated structure is used in transformer cores and motors to minimize eddy currents and increase the efficiency of these devices.

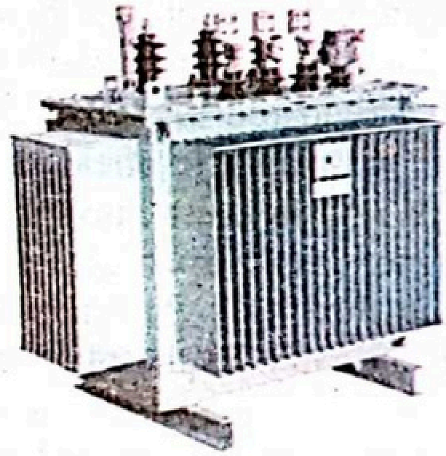


Braking system of eddy current

Conversely, eddy current in some cases are very useful, for example, the braking systems in many trains and cars make use of electromagnetic induction and eddy current. An electromagnet attached to the train is positioned near the steel rails. The braking action occurs when a large current is passed through the electromagnet. The relative motion of the magnet and rails induces eddy currents in the rails, and the direction of these currents produces a drag force at the moment acting on train. These eddy currents decrease steadily in magnitude as the train slows down, the braking effect is quite smooth. Eddy current heating is used in the unduction furnance

14.12 TRANSFORMER

For a long-distance electrical power transmission, it is necessary to use a high voltage and a low current to minimize the power (I^2R) loss in the transmission lines. Consequently, 132kV lines are used in our country (Pakistan). But in practice, the voltage should be decreased to approximately 66kV at distributing station, then to 11kV for delivery to residential areas and finally to 220V at the customer's household wires. The necessary voltage conversion is done by a device named as transformer which is defined as:



External structure of a transformer

A transformer is an electrical device that is used to change the applied alternating voltage into high or low alternating voltages. The working principle of transformer is based on mutual induction between two coils. A simple transformer consists of two coils of copper wire wound around a common soft iron core as shown in Fig.14.18.

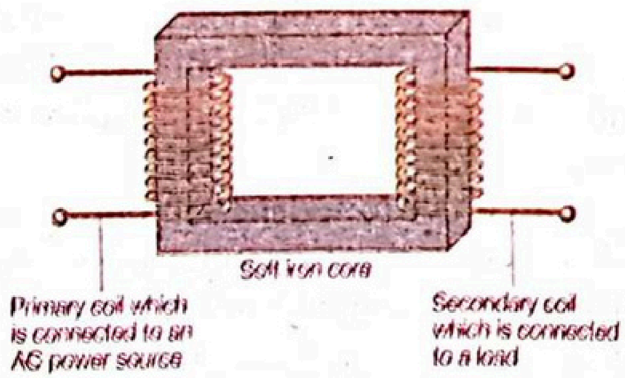


Fig.14.18. A schematic diagram for a simple transformer which consists of two coils primary and secondary

These two coils are electrically separated but are magnetically linked. The coil which is connected to the input A.C. source is called the primary coil, and has N_p number of turns. The coil which is connected to the load resistor and has N_s number of turns is called the secondary coil. Here, the function of the common iron core is to enhance the magnetic flux and to provide a medium such that all the flux through one coil passes through the other.

When the input A.C. voltage V_P is applied to the primary coil, then according to Faraday's law of electromagnetic induction, the magnitude of e.m.f. induced in the primary coil is given by

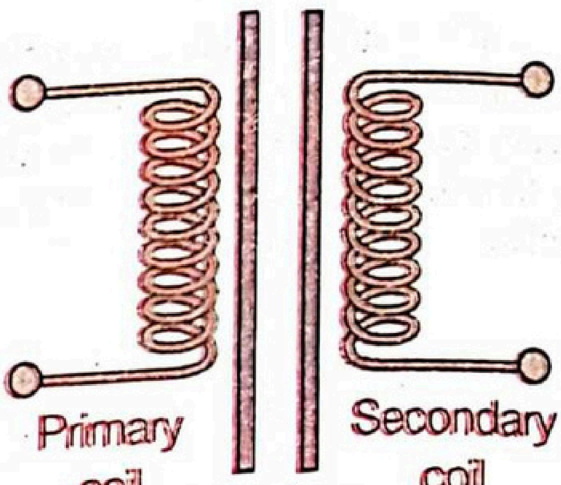
$$V_P = -N_P \frac{\Delta\phi}{\Delta t} \quad ...(14.32)$$

If there is no leakage of flux from the iron core, then the flux through each turn of the primary coil is equal to the flux through each turn of the secondary coil. Thus, voltage V_s induced in the secondary coil is given as;

$$V_S = -N_S \frac{\Delta\phi}{\Delta t} \quad ...(14.33)$$

Dividing Eq.14.33 by Eq.14.32 we get

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} \quad ......(14.34)$$



A symbol of a transformer

POINT TO PONDER

If the primary coil of the transformer is connected to a D.C. source, is there an e.m.f. induced in the secondary coil?

Now let us consider an ideal transformer which has no losses. i.e., both coils are pure inductive and have no resistance. Similarly, there is no magnetic flux leakage in the core of an ideal transformer and hence it has no power losses. Thus, its input power equals to its output power. i.e.,

$$\text{Power in} = \text{Power out}$$

$$V_P I_P = V_S I_S$$

$$\frac{V_P}{V_S} = \frac{I_S}{I_P} \quad ......(14.35)$$

FOR YOUR INFORMATION

In power transmission line, there are very high voltage 132kV or more and very small current are being used in order to decrease the power (I^2R) losses in the transmission line conductor

This relation shows that the voltage across primary or secondary coil is inversely proportional to current through the coil. This principle is being followed for long distance electrical power transmission. i.e., when high voltage from a step-up transformer is used for transmission, the current through the transmission line is decreased. Thus, the power loss I^2R due to the resistance of the transmission line is minimized.

Power losses of a transformer

The power losses of an ideal transformer is always zero. The actual transformer has some power losses. The power losses are due to the following factors.

Eddy Current (Iron Loss)

When an A.C. voltage is applied, the magnetic flux is generated in the coil. This flux also passes through the core and it induces a current in the iron core known as eddy current. This eddy current causes power dissipation and heating the core of the transformer. The eddy current can be minimized by using core having thin insulated laminations.

Hysteresis loss

The power loss that occurs during magnetization and demagnetization of the iron core in each cycle of the A.C. is known as hysteresis loss.

Resistance of the Coil

The wire that is used for winding of the coils has some finite resistance. The resistance of the coils causes power loss (I^2R) which is quite significant for large values of current. This loss can be minimized by using thick wire for winding of the coil.

Flux Leakage (magnetic loss)

The observations show that the rate of change of magnetic flux linked with the secondary coil is always less than that of primary coil. It means there is some flux leakage. It can be reduced by winding the two coils one over one another.

All these result shows that output power of a transformer is always less than its input power. Thus, the percentage efficiency (η) of a transformer can be calculated as:

$$\eta = \frac{\text{Output}}{\text{Input}} \times 100\% \quad \ldots\ldots(14.36)$$

Types of Transformers

There are two types of transformers:

1. **Step Up Transformer:** If the number of turns of secondary coil 'N_S' is greater than the number of turns of primary coil 'N_P' and output voltage 'V_S' is more than input voltage 'V_P' then the transformer is said to step up transformer as shown in Fig.14.19(a).

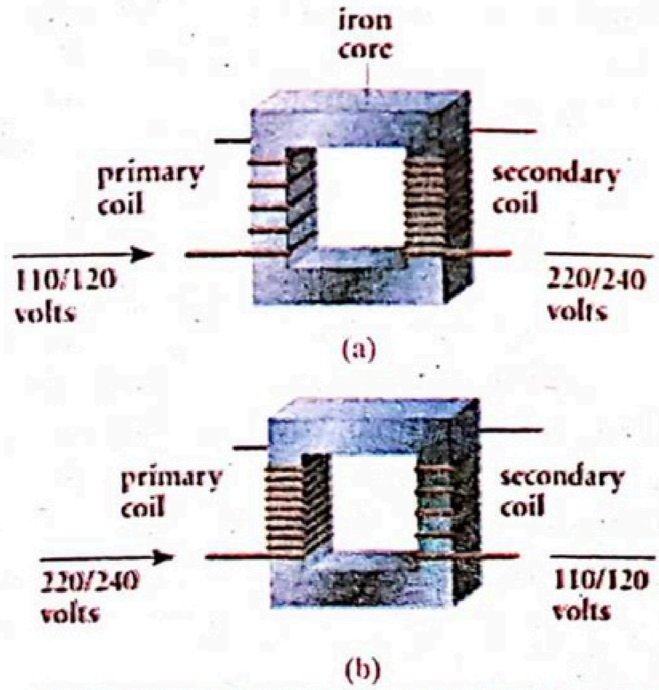


Fig.14.19(a) Step up transformer, where $N_S > N_P$ and $V_S > V_P$ (b) step down transformer, where $N_P > N_S$ and $V_P > V_S$.

2. **Step Down Transformer:** If the number of turns of secondary coil 'N_S' is less than the number of turns of the primary coil 'N_P' and the output voltage 'V_S' is smaller than input voltage 'V_P' then the transformer is said to be step down transformer as shown in Fig.14.19(b).

Example 14.8

A transformer used on a 220V line delivers 1.5A at 1800V. What current is drawn from the line (assume 100% efficiency).

Solution:

Input voltage = V_P = 220V
Output voltage = V_S = 1800V
Input current = I_P = ?
Output current = I_S = 1.5A

As the efficiency of the transformer is 100% so its input power equals to its output power

Input power = output power

$$V_P I_P = V_S I_S$$

$$I_P = \frac{I_S V_S}{V_P}$$

$$I_P = \frac{(1.5)(1800)}{220} = 12.3\text{A}$$

Example 14.9

A step-up transformer is used on a 220V line to furnish 3600V. The primary coil has 200turns. How many turns are on the secondary coil?

Solution:

Input voltage = V_P = 220V
Output voltage = V_S = 3600V
Number of turns of primary = N_P = 200
Number of turns of secondary = N_S = ?

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

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

$$N_S = \frac{3600\text{V}}{220\text{V}} \times 200 = 3273\text{turns}$$

SUMMARY

- **Induced e.m.f.:** The current that induces in a conductor due to changing magnetic flux linked with the conductor is called induced current and its corresponding e.m.f. is called induced e.m.f..
- **Faraday's Law:** This law states that the induced e.m.f. in a coil, having N-number of turns, is directly proportional to the rate of change of magnetic flux linked with the coil. Mathematically it is expressed as

$$\varepsilon = -N\frac{\Delta\phi}{\Delta t}$$

- **Lenz's Law:** This law states that the direction of induced current is always opposite to that action which causes of induced e.m.f..
- **Motional e.m.f.:** The e.m.f. that induces due to the motion of conductor across a magnetic field is called motional e.m.f..

$$\text{Motional e.m.f. } (\varepsilon) = vB\ell \sin\theta$$

- **Mutual induction:** The phenomenon in which the rate of change of current in one coil induces an e.m.f. in another nearby coil is called mutual induction.
- **Self-Induction:** The phenomenon in which a changing current in a coil induces an e.m.f. in the same coil is called self-induction.
- **Henry:** Henry is the unit of inductance and it is defined as: if the changing of current at the rate of one ampere per second induces an e.m.f. of one volt then this inductance is called one henry.
- **A.C. generator:** An A.C. generator is a device which converts mechanical energy into electrical energy.
- **A.C. motor:** An A.C. motor is a device which converts electrical energy into mechanical energy.
- **Back e.m.f.:** The e.m.f. that induces due to the rotation of motor and it opposes the applied e.m.f. is called back e.m.f..
- **Transformer:** A transformer is an electrical device which steps-up or steps-down the input voltage at the output.

EXERCISE

○ Multiple choice questions.

1. The source of induced e.m.f. is
   (a) Cell (b) Battery
   (c) Interaction between stationery magnet and coil
   (d) Relative motion between magnet and coil
2. When the coil and a bar magnet are placed very closed to each other then the value of their induced e.m.f. will be

(a) Maximum (b) Positive (c) Negative (d) Zero

3. The unit of induced e.m.f. is
(a) Ampere (b) Volt (c) Watt (d) Weber

4. The law of electromagnetic induction was introduced by
(a) Maxwell (b) Faraday (c) Lenz (d) Fleming

5. According to Faraday's Law of electromagnetic induction, the induced e.m.f. depends upon
(a) Minimum magnetic flux (b) Maximum magnetic flux
(c) Change in magnetic flux (d) Rate of change of magnetic flux

6. Lenz's law of electromagnetic induction explains:
(a) The production of induced e.m.f. (b) Magnitude of induced e.m.f.
(c) Direction of induced e.m.f. (d) Both magnitude and direction of induced e.m.

7. Lenz's law is related to the law of conservation of
(a) Momentum (b) Energy (c) Mass (d) Charges

8. The mutual inductance of two coil is maximum when the coils are
(a) Parallel to each other (b) Perpendicular to each other
(c) Facing each other (d) Touching each other

9. When a current change in a coil from 4A to 6A in 0.05s and it induces an e.m.f. of 8V. The co-efficient of self-inductance is
(a) 0.1H (b) 0.2H (c) 0.4H (d) 0.8H

10. The unit of inductance is
(a) Weber (b) Tesla (c) Henry (d) Watt

11. A conducting rod of length 0.5m moves in a magnetic field of magnitude 2T with velocity 5 m s^{-1}, the e.m.f. induced in the moving rod is
(a) 5V (b) 10V (c) 20V (d) 50V

12. Which one of the following device stores magnetic potential energy in its magnetic field?
(a) Resistor (b) Capacitor (c) Inductor (d) Thermistor

13. At constant inductance of 'L' henry, the energy stored in a magnetic field is
(a) $\frac{1}{2}CQ^2$ (b) $\frac{1}{2}mv^2$ (c) $\frac{1}{2}kx^2$ (d) $\frac{1}{2}LI^2$

14. The working principle of an A.C. motor is
(a) Self-induction (b) Mutual induction
(c) Motional e.m.f. (d) None of those

15. The stator and the rotor of an A.C. motor are connected by a
(a) Copper Wire (b) Silver wire
(c) Aluminum wire (d) No physical connection between them

16. Two phase A.C. contains
(a) One wire two stators (b) Two wires two stators

(c) Three wires two stators (d) Three wires three stators

17. A transformer works when we apply
(a) A.C. voltage (b) D.C voltage
(c) A.C. as well as D.C (d) Neither A.C. nor D.C

18. The quantity that remains constant in a transformer is
(a) Voltage (b) Current (c) Power (d) Frequency

19. The soft iron core is used in a transformer in order to
(a) Enhance the magnetic flux (b) Increase the weight
(c) Increase the copper losses (d) Decrease the copper losses

20. Which relation is true for an ideal transformer?
(a) Input power > output power (b) Input power < output power
(c) Input power = output power (d) Output power = 0

21. When a step up transformer delivers high voltage then the current will be
(a) Remain same (b) Decreased (c) Increased (d) Maximum

22. For long distance electrical power transmission, we use
(a) Smaller current and lower voltage (b) Larger current and higher voltage
(c) Larger current and lower voltage (d) Smaller current and higher voltage

23. Lamination is used in a transformer in order to
(a) Reduce flux leakage (b) Minimize hysteresis loss
(c) Decrease coil resistance (d) Minimize eddy current

SHORT QUESTIONS

1. What is the meaning of induced current and induced e.m.f.?
2. What factor causes of induced e.m.f.?
3. Does e.m.f. induce in a coil, when a magnet is placed near to it?
4. The law of electromagnetic induction is expressed as: $\varepsilon = -N\frac{\Delta\phi}{\Delta t}$. What is the meaning of negative sign?
5. What is the difference between Faraday's law and Lenz's law of induction?
6. What is the difference between induced e.m.f. and back e.m.f.?
7. What is the advantage and disadvantage of eddy current?
8. Distinguish between self-inductance and mutual inductance.
9. Define Henry and express its dimension.
10. How magnetic energy is stored in an inductor?
11. Explain the motional e.m.f. due to the motion of rod of length 'ℓ' with velocity 'v' which is perpendicular to the magnetic field B.
12. What is the working principle of an A.C. generator?
13. What is the role of carbon brushes in an A.C. generator?

14. Why does the bulb light become dim for a moment when we start the refrigerator or some other heavy electrical appliance at home?
15. What is the working principle of a transformer?
16. What is the difference between step up and step down transformer?
17. Why does not transformer work on D.C.?
18. What is the meaning of an ideal transformer?
19. Describe the power losses of a transformer?
20. How can you minimize the power loses of a transformer?

COMPREHENSIVE QUESTIONS

1. What is induced e.m.f.? Explain induced e.m.f. with experimental examples.
2. State and explain Faraday law of electromagnetic induction with examples.
3. What do you know about the Lenz's law of electromagnetic induction? How can you determine the direction and conservation of energy by using Lenz's law?
4. Explain motional e.m.f. and derive its mathematical relation.
5. State and explain mutual induction, co-efficient of mutual induction and its unit.
6. Define and explain self-induction.
7. How does magnetic potential energy store in an inductor? Also derive its mathematical relation.
8. What is A.C. generator? Explain its construction and working principle.
9. What is A.C. motor? Explain its construction and working principle.
10. State and explain back e.m.f. in an A.C motor.
11. Define and explain eddy current.
12. What do you know about a transformer? Describe the function, working and kinds of transformer.

NUMERICAL PROBLEMS

1. A coil 200 turns linked by a flux of 40mwb. If this flux is reversed in a time of 4ms then determine the average induced e.m.f. in the coil. **(2000V)**
2. At what rate would it be necessary for a single conductor loop to cut the flux in order that the current of 1.2mA flows through it when 10Ω resistor is connected across its ends? **($1.2 \times 10^{-2}Wbs^{-1}$)**
3. A 60m long conductor is moving in a uniform magnetic field 0.9T at a speed of $7\,ms^{-1}$. If the motion of the conductor is at right angle to the field then calculate the e.m.f. induced in the conductor. **(378V)**
4. When the current in a coil A is increased uniformly from zero to 18A in 0.3s, an e.m.f. of 6V is induced in a nearby coil B. What is the value of the mutual inductance between the coils A and B? **(0.1H)**

5. The current in a coil changes at the rate of 3A in 60ms. An e.m.f. of 10V is induced in the coil. What is the self-inductance of the coil? **(0.2H)**

6. An inductor of inductance 0.5H carries a current of 6A. Calculate the energy stored in the magnetic field of the inductor? **(9J)**

7. The frequency of the coil of an A.C. generator is 60Hz has 150 turns. If its area is $150 cm^2$ and it induces maximum e.m.f. of 250V during its rotation in a uniform magnetic field, then calculate the magnitude of such magnetic field? **(0.3mT)**

8. An A.C. motor is rotated by applying the potential difference of 220V. If the motor has a resistance of 4Ω and a back e.m.f. of 50V is induced in it during its rotation, then calculate (a) the current when the motor just start up (b) current when the motor is running at normal speed. **(55A, 42.5A)**

9. A step-down ideal transformer operates on a 2.5kV line and supplies a load with 80A. The ratio of the primary winding to the secondary winding is 20:1. Determine (a) the secondary voltage (b) the primary current (c) the output power. **(0.13kV, 4A, 10kW)**

10. A step-down transformer is used on 1kV line to deliver 220V. How many turns are on the primary winding if the secondary has 50 turns? **(227turns)**