PERIOD-3

P12CH3

TOPIC

# 3

# Magnetism and Electro-Magnetism

## 3.1 BAR MAGNET AND ITS PROPERTIES

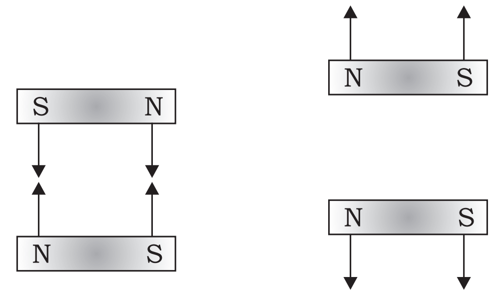
A piece of iron can be treated in such a way as to produce a magnet. The magnetic properties of a magnet can also be destroyed in several ways, one of which is by heating it. Ordinarily, the ends of the magnet are the centres of this attraction. The two centres of attraction in any magnet are called its **poles.** After a magnet is suspended so that it is free to rotate about a vertical axis and it has lined up along a meridian, the pole in the northern end of the magnet is called a north pole and the pole in the southern end is called a south pole. Forces are exerted between the poles of two adjacent magnets such that unlike poles attract each other while like poles repel each other.

*The region around a magnet in which it exerts forces on other magnets and on objects made of iron is called a* ***magnetic field.***

The main **properties** of a bar magnet can be summed up as follows :

**1. Directive property.** When a magnet is suspended freely, it aligns itself with one end pointing towards north of earth and other towards south of earth.

**2. Force between poles.** Unlike poles attract and like poles repel (Fig. 3.1). The force of attraction or repulsion acts along the line joining the two poles and is directly proportional to the product of the pole strengths and inversely proportional to the square of the distance between them.



(a) Unlike poles attract (b) Like poles repel

Fig. 3.1

**3. Attractive property.** A magnet attracts magnetic materials such as iron, steel, cobalt, nickel etc. This attraction is maximum at the poles. *It may be noted that the poles are situated near the ends of the magnet and not exactly at the ends.*

**4. Isolated magnetic pole does not exist *i.e.*, magnetic poles always exist in pairs.** The similarity in the behaviour of electric charges and poles seems to suggest the possibility of 'magnetic charges'—N-type and S-type. But, so far, every attempt at finding single magnetic charges or to isolate the poles of a magnet from one another have failed. If we break a long bar magnet into two (or even more) pieces, then we shall observe that each piece is complete magnet in itself (Fig. 3.2).

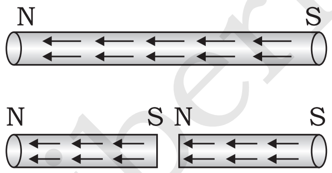


**Fig. 3.2.** Breaking of a magnet.

**5. A magnet can induce magnetism in substances like soft iron, cobalt, nickel and various ferrous alloys.** When an iron, nickel or cobalt rod is placed near a bar magnet, the bar magnet induces magnetism in the rod.

## 3.2 REPULSION—SUREST TEST OF MAGNETISATION

An iron rod is attracted towards a magnet. The opposite poles also attract each other. So, attraction is not a sure test of magnetisation. On the other hand, if there is repulsion between a magnet and a given rod, we can be sure that the given rod is magnetised.

## 3.3 ATOMIC THEORY OF MAGNETISM

Both the orbital and spin motions of electrons give rise to tiny circular currents. These tiny current loops behave like small magnets. These small magnets are called elementary or atomic magnets. When the material is not magnetised, these magnets form closed chains thereby annulling each other's effect (Fig. 3.3).

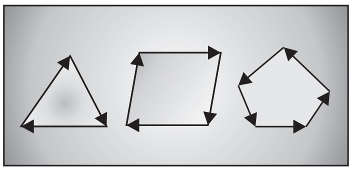


**Fig. 3.3.** Closed chains of elementary magnets.

When the material is magnetised, the elementary magnets are aligned nearly in the same direction (Fig. 3.4).

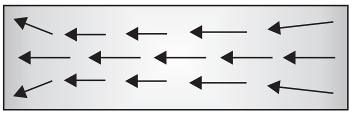


**Fig. 3.4.** Alignment of elementary magnets.

The atomic theory of magnetism explains the following facts :

**(i)** Single poles cannot exist. Poles always exist in pairs.

**(ii)** The magnetic poles are of equal strength.

**(iii)** When a magnet is heated, the thermal energy of the elementary magnets increases. These again form closed chains and magnetism is lost.

## 3.4 THE MAGNETIC FIELD LINES

We begin our study by examining iron filings sprinkled on a sheet of glass placed over a short bar magnet. The arrangement of iron filings is shown in Fig. 3.5.

The pattern of iron filings suggests that the magnet has two poles similar to the positive and negative charges of an electric dipole. One pole is designated the north pole and the other, the south pole. When suspended freely, these poles point approximately towards the geographic north and south poles, respectively. A similar pattern of iron filings is observed around a current-carrying solenoid.

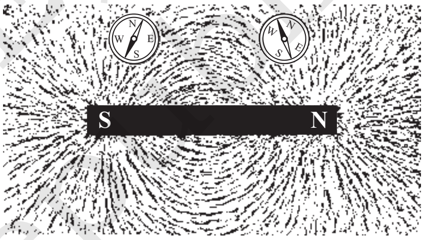


**Fig. 3.5.** The arrangement of iron filings surrounding a bar magnet. The pattern mimics magnetic field lines. They suggest that the bar magnet is a magnetic dipole.

The pattern of iron filings permits us to plot the magnetic field lines. This is shown both for the bar magnet and the current-carrying solenoid in Fig. 3.6. The magnetic field lines are a visual and intuitive realisation of the ‘unseen’ magnetic field.

Some **important properties** of magnetic field lines are as under :

***(i)*** Outside the body of the magnet, the magnetic field lines are **directed from north pole to south pole.**

***(ii)*** Magnetic field lines have a **tendency to contract** longitudinally. This explains attraction between unlike magnetic poles.

***(iii)*** Magnetic field lines have a tendency to exert **lateral pressure.** This explains repulsion between like magnetic poles.

***(iv)*** The magnetic field lines of a magnet (or a solenoid) **form continuous closed loops.**

**(v)** The **tangent to the field line** at a given point represents the direction of the net magnetic field $\vec{B}$ at that point.

**(vi)** The **larger the number of field lines** crossing per unit normal area, the larger is the magnitude of the magnetic field $\vec{B}$. In Fig. 3.6(*a*), $\vec{B}$ is larger around region II than in region I.

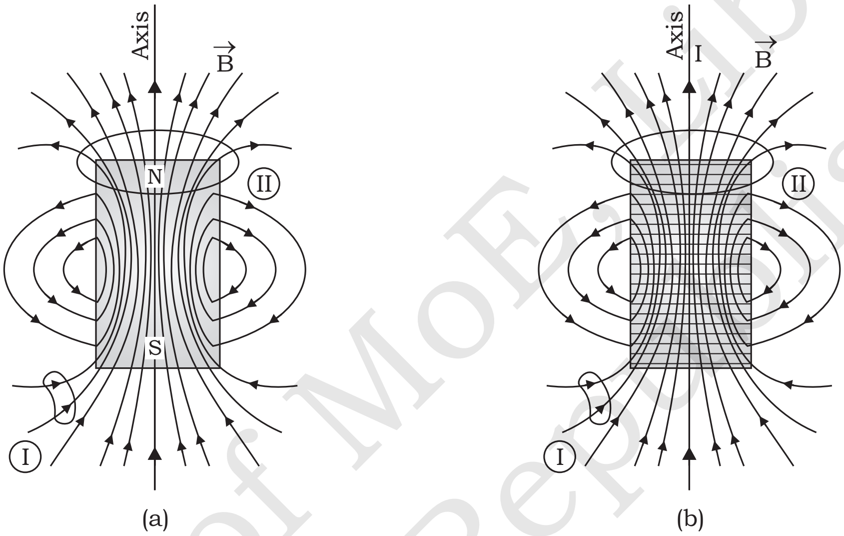


**Fig. 3.6.** The field lines of (*a*) a bar magnet, (*b*) a current-carrying finite solenoid. At large distances, the field lines are very similar.

**(vii)** The magnetic field lines **do not intersect.** This is so since the direction of the magnetic field would not be unique at the point of intersection.

One can plot the magnetic field lines in a variety of ways. One way is to place a small magnetic compass needle at various positions and note its orientation. This gives us an idea of the magnetic field direction at various points in space.

## 3.5 REPRESENTATION OF UNIFORM MAGNETIC FIELD

*A **magnetic field** is said to be uniform over a region if its magnetic field induction $\vec{B}$ has the same magnitude and direction at all points in the region.*

**Example.** Earth's magnetic field may be regarded as uniform over a small region.

If $\vec{B}$ varies in magnitude or in direction or both, then the magnetic field is non-uniform.

A uniform magnetic field in the plane of paper is represented by a set of equal, equidistant and parallel lines pointing in the same direction as shown in Fig. 3.7 (*a*).

A uniform magnetic field perpendicular to the plane of paper and directed outwards is represented by a group of equidistant tiny dots as shown in Fig. 3.7 (*b*).

A uniform magnetic field perpendicular to the plane of paper and directed inwards is represented by a group of equidistant crosses as shown in Fig. 3.7 (*c*).

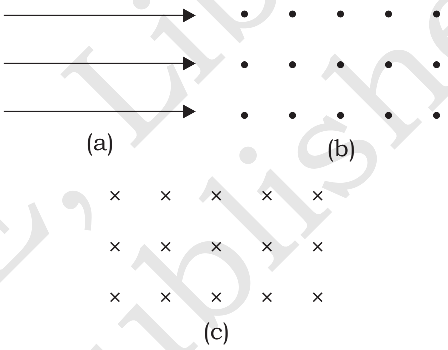


**Fig. 3.7.** Representation of uniform magnetic field.

## 3.6 MAGNETIC DIPOLE AND MAGNETIC DIPOLE MOMENT

A pair of magnetic poles of equal and opposite strengths separated by a finite distance is called a **magnetic dipole.**

**Examples.** Bar magnet, compass needle and current loop.

*Magnetic length of a dipole is the distance between the two poles. It is a vector directed from S-pole to the N-pole.* It is represented by $\overrightarrow{2l}$.

*The magnetic dipole moment* $\vec{m}$ *(also denoted by* $\vec{p}_m$ *) is a vector directed from south pole to the north pole along the axis of the dipole. The magnitude of the dipole moment is the product of the pole strength* $q_m$ *and the separation 2l between the poles.*

$\boxed{m = q_m \times 2l}$ In vector notation, $\vec{m} = q_m(\overrightarrow{2l})$

The SI unit of $m$ is A $m^2$ or J $T^{-1}$.

## 3.7 MAGNETISATION AND DEMAGNETISATION

A popular theory of magnetism considers the molecular alignment of the material. This is known as Weber's theory. This theory assumes that all magnetic substances are composed of tiny molecular magnets.

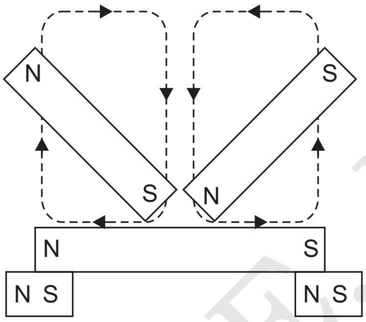


Fig. 3.8. Current loop as a magnetic dipole.

Any unmagnetized material has the magnetic forces of its molecular magnets neutralized by adjacent molecular magnets, thereby eliminating any magnetic effect. A magnetized material will have most of its molecular magnets lined up so that the north pole of each molecule points in one direction, and the south pole faces the opposite direction. A material with its molecules thus aligned will then have one effective north pole, and one effective south pole.

An illustration of Weber's Theory is shown in Fig. 3.8, where a steel bar is magnetized by stroking. When a steel bar is stroked several times in the same direction by a magnet, the magnetic force from the north pole of the magnet causes the molecules to align themselves.

**Ways of making magnets**

1. **'Stroke' method:** A piece of magnetic material can be truned into a magnet if it is stroked by a magnet. As the magnet moves along the magnetic material, it causes the magnetic dipoles in the magnetic material to become aligned in one direction and give rise to a magnetic field.
2. **Electrical method using a direct current:** When a large direct current is passed through the solenoid, the unmagnetised steel bar will become magnetized after a while. This is because when an electric current flows through the solenoid, it produces a strong magnetic field which magnetizes the steel bar.

The poles of the magnet can be determined by a simple method known as Right-hand grip rule.

**Ways of damagnetizing magnets**

1. **Heating:** Heating a piece of magnetized metal in a flame will cause demagnetization by destroying the long-range order of molecules within the magnet. By heating a magnet, each molecule is infused with energy. This forces it to move, pushing each molcule out of order within the magnet and leaving the piece of metal with very little or no magnetization.
2. **Hammering:** When a magnet is hammered or dropped, the vibrations caused by the impact on the magnet randomize the magnetic molecules within the magnet, forcing them out of order and destroying the long-range order of the unit magnet.
3. **Alternating Current (AC) field:** Using an AC current produces a magnetic field which can be moved and reduced to demagnetize materials. The field created by the AC current drags the magnetic molecules of the magnet in different directions. When the AC current is altered or reduced, the molecules within the magnet do not all return to previous positions, causing randomization of the molecules and reducing the force of the magnet.

## 3.8 ELECTROMAGNETIC INDUCTION

The phenomenon of generation of an emf in a coil due to change in magnetic flux linked with it is known as *electromagnetic induction*. The emf so produced is called induced emf. If the coil is closed, a current flows in the coil. This current is called induced current.

## 3.9 MAGNETIC FLUX

**(*i*)** *The magnetic flux linked with a surface held in a magnetic field is defined as the total number of magnetic field lines crossing the surface normally.*

Magnetic flux is a scalar quantity and is denoted by $\phi_B$.

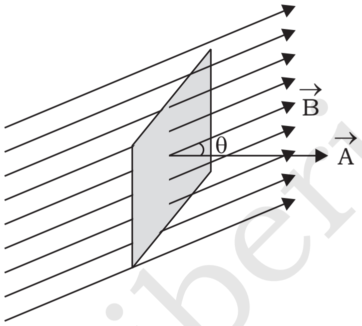


**Fig. 3.9.** A plane of surface area $\vec{A}$ placed in a uniform magnetic field $\vec{B}$.

Magnetic flux through a plane of area A placed in a uniform magnetic field $\vec{B}$ is the dot product of magnetic field vector $\vec{B}$ and area vector $\vec{A}$.

$$\therefore \quad \phi_B = \vec{B}\cdot\vec{A} = BA\cos\theta \qquad \ldots(1)$$

where θ is the angle between $\vec{B}$ and $\vec{A}$.

Magnetic flux is measured as the product of the component of the magnetic field normal to the surface and the surface area.

The magnetic flux linked with a surface area ΔA held inside a magnetic field B is given by :

$$\Delta\phi_B = B_n\,\Delta A$$

Here, $B_n$ is the component of magnetic field B along the normal to the surface area ΔA.

$$B_n = B\cos\theta$$

where θ is the angle which the normal to the surface area makes with the direction of the magnetic field.

$$\therefore \qquad \Delta\phi_B = B\,\Delta A\cos\theta \qquad \text{or} \qquad \Delta\phi_B = \vec{B}\cdot\Delta\vec{A}$$

If $\hat{n}$ is a unit vector along the normal to the plane surface area, then

$$\Delta\phi_B = \vec{B}\cdot(\hat{n}\,\Delta A)$$

Here, $\vec{B}\cdot\hat{n}$ (= $B_n$) represents the component of the magnetic field along the normal to the surface area.

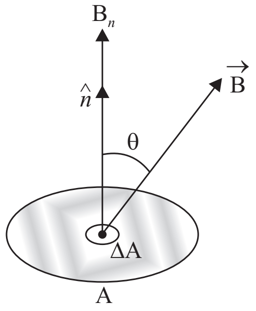


**Fig. 3.10**

***(ii)*** If the magnetic field B under consideration is uniform over surface area A, then

$$\phi_B = B_nA \qquad \text{and} \qquad \phi_B = \vec{B}\cdot\vec{A}$$

***(iii)*** If the magnetic field $\vec{B}$ is not uniform, then the surface is divided into a large number of area elements. Each area element should be small enough so that magnetic field through that element is taken as uniform. The total magnetic flux $\phi_B$ linked with complete area A is given by the algebraic sum of the magnetic fluxes linked with all elementary areas of the surface.

**(*iv*) Positive magnetic flux**

If the normal is drawn in the direction of the magnetic field, then the flux is taken as positive. In this case, $\theta$ is 0°. Even if $\theta$ is an acute angle, the flux is taken as positive.

**(*v*) Negative magnetic flux**

If the normal is drawn opposite to the direction of the field, then $\theta = 180°$. In this case, the magnetic flux is taken as negative. In fact, an obtuse value of angle $\theta$ makes $\cos\theta$ negative and hence the magnetic flux is negative.

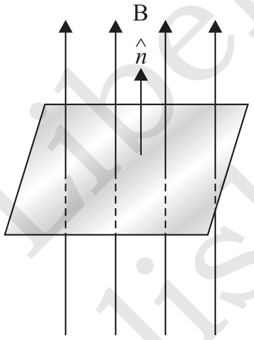


**Fig. 3.11.** Maximum magnetic flux

**(*vi*) Maximum magnetic flux**

When the uniform magnetic field is normal to the plane of the surface, then $\theta = 0°$.

$$\therefore \qquad \phi_B = BA\cos 0°$$

$$\text{or} \qquad \phi_B = BA \qquad \text{(maximum value)}$$

So, when the magnetic field is normal to the surface, the magnetic flux through the surface will be maximum *i.e.,* maximum number of lines will pass normally through the given surface.

**(*vii*) Minimum (zero) magnetic flux**

When the magnetic field is parallel to the plane of the surface, then $\theta = 90°$.

$$\therefore \qquad \phi_B = BA\cos 90° = 0$$

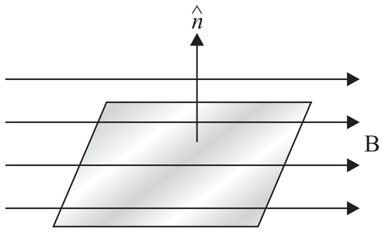


**Fig. 3.12.** Minimum magnetic flux

**(*viii*) Units of magnetic flux**

(*i*) The SI unit of magnetic flux is weber (Wb).

$$1\ \text{Wb} = 1\ \text{T} \times 1\ \text{m}^2$$

*One weber is the magnetic flux linked with a surface area of 1 m$^2$ when held normally inside a uniform magnetic field of 1 tesla.*

(*ii*) The *cgs* unit of magnetic flux is maxwell (Mx.)

$$1 \text{ Mx} = 1 \text{ G} \times 1 \text{ cm}^2$$

*One maxwell is the magnetic flux linked with a surface area of 1 cm$^2$ when held normally inside a uniform magnetic field of 1 gauss.*

A single magnetic line of force is known as a maxwell of flux.

**(*ix*) Relation between units of magnetic flux**

$$1 \text{ Wb} = 1 \text{ T} \times 1 \text{ m}^2 = 10^4 \text{ G} \times 10^4 \text{ cm}^2 = 10^8 \text{ Mx}$$

**(*x*) Dimensional formula of magnetic flux**

$$\phi_B = BA\cos\theta$$

Now, $$F_m = Bqv \quad \text{or} \quad B = \frac{F_m}{qv}$$

$$\therefore \qquad \phi_B = \frac{F_m}{qv} A\cos\theta$$

$$[\phi_B] = \frac{[MLT^{-2}][L^2]}{[AT][LT^{-1}]} = \frac{[ML^2T^{-2}]}{[A]} = [ML^2T^{-2}A^{-1}]$$

**Electromagnetic induction: *It is the relative motion between the magnet and the coil that is responsible for generation (induction) of electric current in the coil.***

*When magnetic flux changes through a coil, a current is induced in the coil.* Quicker the relative motion between the magnet and the coil, greater is the rate of change of magnetic flux through the coil and larger is the current induced in it. This is the **elementary idea of electromagnetic induction.**

***Electromagnetic induction*** *is the process in which an emf is induced in a circuit placed in a magnetic field when the magnetic flux linked with the circuit changes.*

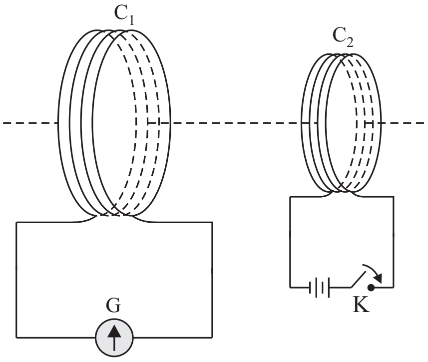


**Fig. 3.13.** Experimental set-up for Experiment No. 3.

It is observed that the galvanometer shows a momentary deflection when the tapping key K is pressed. The pointer in the galvanometer returns to zero immediately. If the key is held pressed continuously, there is no deflection in the galvanometer. When the key is released, a momentory deflection is observed again, but in the opposite direction. It is also observed that the deflection increases dramatically when an iron rod is inserted into the coil along their axis.

## 3.10 FARADAY'S LAWS OF ELECTROMAGNETIC INDUCTION

On the basis of the above experiments, Faraday formulated two laws of electromagnetic induction stated as follows :

**First law.** ***Whenever there is a change in the magnetic flux linked with a circuit, an emf and consequently a current is induced in the circuit. However, it lasts only so long as the magnetic flux is changing.***

**Second law.** ***The magnitude of the induced emf is directly proportional to the rate of change of magnetic flux linked with the circuit.***

It may be noted that Faraday's laws of electromagnetic induction tell us nothing about the direction of the induced emf and current. This direction is given by Lenz's law.

## 3.11 LENZ'S LAW

In 1834, German physicist Heinrich Friedrich Lenz [1804–1865] deduced a law, now known as Lenz's law. This law describes the polarity of the induced emf very clearly. The statement of Lenz's law is :

***The direction of the induced emf or induced current is such that it opposes the change that is producing it.***

This law may also be stated as under :

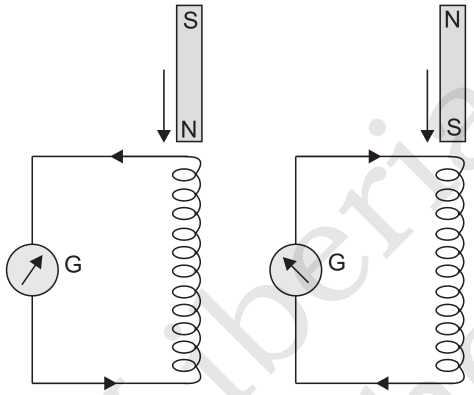
*The polarity of the induced emf is such that it tends to produce a current which opposes the change that produces it.*

When the north pole of the magnet is moved towards the coil (Fig. 3.15 (*a*)), the direction of the induced current in the coil will be such that the upper face of the coil acquires north polarity. So, the coil repels the magnet. In other words, the coil opposes the motion of the magnet towards itself which is really the cause of the induced current in the coil. Similarly, if the south pole of a magnet is moved towards the coil (Fig. 3.15 (*b*)), the upper face of the coil will acquire south polarity thereby opposing the motion of the magnet.

### Lenz's Law and Law of Conservation of Energy

According to Lenz's law, the induced emf opposes the change that produces it. It is this opposition against which we perform mechanical work in causing the change in magnetic flux. So, it is the mechanical energy which is converted into electrical energy. Thus, *Lenz's law is in accordance with the law of conservation of energy.*

If, however, the reverse would happen, then a little change of flux would produce an induced electric current which would help the change of flux further thereby producing more electric current. The increased emf would then cause further change of flux and it would further increase the current and so on. This would create energy out of nothing. It would then violate the law of conservation of energy.



(a) N pole approaching the coil

(b) S pole approaching the coil

**Fig. 3.14**

## 3.12 MOTIONAL ELECTROMOTIVE FORCE

(*Induced emf by changing A*)

*Induced emf produced by changing the area of a closed circuit by the movement of the circuit or a part of it through a steady magnetic field is known as motional emf.*

Consider a straight conductor moving in a uniform and time-independent magnetic field. Fig. 3.15 shows a rectangular conductor PQRS in which the conductor PQ is free to move. The rod PQ is moved towards the left with a constant velocity $v$ as shown in the figure. Assume that there is no loss of energy due to friction. PQRS forms a closed circuit enclosing an area that changes as PQ moves. It is placed in a uniform magnetic field $\vec{B}$ which is perpendicular to the plane of this system. If the length RQ = $x$ and RS = $l$, the magnetic flux $\Phi_B$ enclosed by the loop PQRS will be

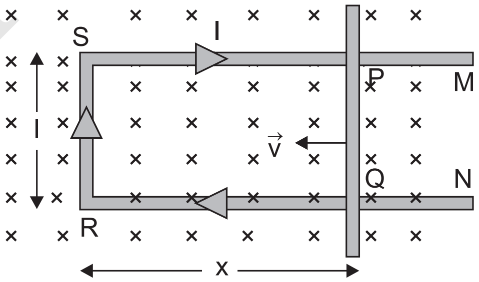


**Fig. 3.15.** The arm PQ is moved to the left side, thus decreasing the area of the rectangular loop. This movement induces a current I as shown.

$$\Phi_B = Blx$$

Since $x$ is changing with time therefore the time rate of change of magnetic flux $\Phi_B$ will induce an emf given by :

$$\varepsilon = \frac{-d\Phi_B}{dt} = -\frac{d}{dt}(Blx) = -Bl\frac{dx}{dt} = Blv$$

Here we have used $\frac{dx}{dt} = -v$ which is the speed of the conductor PQ.

The induced emf $Blv$ is due to the motion of the conductor. So, it is termed as **'motional emf '.** It disappears as soon as the motion of the conductor stops.

The direction of the motional emf is given by Lenz's law. However, it is more convenient to apply **Fleming's right hand rule** stated as follows :

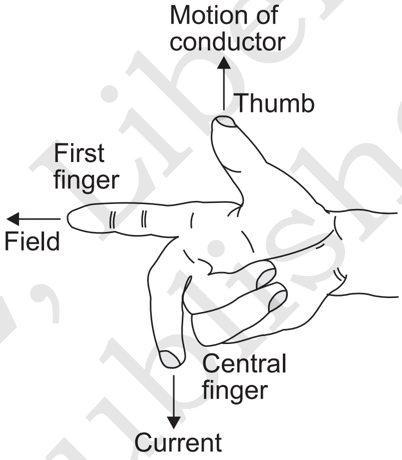


**Fig. 3.16.** Fleming's right hand rule.

***Stretch the thumb and the first two fingers of your right hand in mutually perpendicular directions. If the first finger points in the direction of the magnetic field, the thumb in the direction of motion of the conductor, then the central finger points in the direction of the induced emf or induced current in the conductor [Fig. 3.16].***

Applying this rule, we find that the induced current flows from P to Q.

Fleming's right hand rule is also known as **Generator rule.**

**Four Important Points**

- When a straight conductor of length $l$ moves with constant velocity $v$ in a magnetic field B, the induced emf, $\varepsilon = Blv$ **when $B$, $l$ and $v$ are mutually perpendicular**.
- When $l$ or $v$ is parallel to B, then $\varepsilon = 0$.
- Fleming's right hand rule is used to determine the direction of induced current/induced emf.
- Fleming's left hand rule is used to determine the direction of force on a current-carrying conductor.

## 3.13 EXPLANATION OF MOTIONAL EMF IN TERMS OF LORENTZ MAGNETIC FORCE

It is possible to explain the motional emf in terms of the Lorentz force acting on the free charge carriers of conductor PQ (Fig. 3.16). Consider any arbitrary charge $q$ in the conductor PQ. When the rod moves with speed $v$, the charge will also be moving with speed $v$ in the magnetic field $\vec{B}$. The Lorentz force on this charge is $qvB$ in magnitude, and its direction is towards Q. All charges experience the same force, in magnitude and direction, irrespective of their position in the rod PQ. The work done in moving the charge from P to Q is,

$$W = qvBl$$

Since emf is the work done per unit charge,

$$\therefore \qquad \varepsilon = \frac{W}{q} = Blv$$

This equation gives emf induced across the rod PQ.

**Stationary Conductor in a Changing Magnetic Field**

Let us now study how an emf is induced when a conductor is stationary and the magnetic field is changing – a fact which Faraday verified by numerous experiments. In the case of a stationary conductor, the force on its charges is given by

$$\vec{F} = q\,(\vec{E} + \vec{v} \times \vec{B}) = q\vec{E} \qquad [\because \ \vec{v} = 0]$$

Thus, any force on the charge must arise from the electric field term $\vec{E}$ alone. Therefore, to explain the existence of induced emf or induced current, we must assume that a time-varying magnetic field generates an electric field. However, it may be noted that the electric fields produced by static electric charges have properties different from those produced by time-varying magnetic fields.

## 3.14 GALVANOMETER

A galvanometer is a device that is used to detect small electric current or measure its magnitude. The current and its intensity is usually indicated by a magnetic needle's movement or that of a coil in a magnetic field that is an important part of a galvanometer.

## Moving Coil Galvanometer

A moving coil galvanometer is an instrument which is used to measure electric currents. It is a sensitive electromagnetic device which can measure how currents even of the order of a few microamperes.

Moving-coil galvanometers are mainly divided into two types:

- Suspended coil galvanometer
- Pivoted-coil or Weston galvanometer

## Moving Coil Galvanometer Principle

A current-carrying coil when placed in an external magnetic field experiences magnetic torque. The angle through which the coil is deflected due to the effect of the magnetic torque is proportional to the magnitude of current in the coil.

## Construction and Diagram

The moving coil galvanometer is made up of a rectangular coil that has many turns and it is usually made of thinly insulated or fine copper wire that is wounded on a metallic frame. The coil is free to rotate about a fixed axis. A phosphor-bronze strip that is connected to a movable torsion head is used to suspend the coil in a uniform radial magnetic field.

Essential properties of the material used for suspension of the coil are conductivity and a low value of the torsional constant. A cylindrical soft iron core is symmetrically positioned inside the coil to improve the strength of the magnetic field and to make the field radial. The lower part of the coill is attached to a phosphor-bronze spring having a small number of turns. The other end of the spring is connected to binding screws.

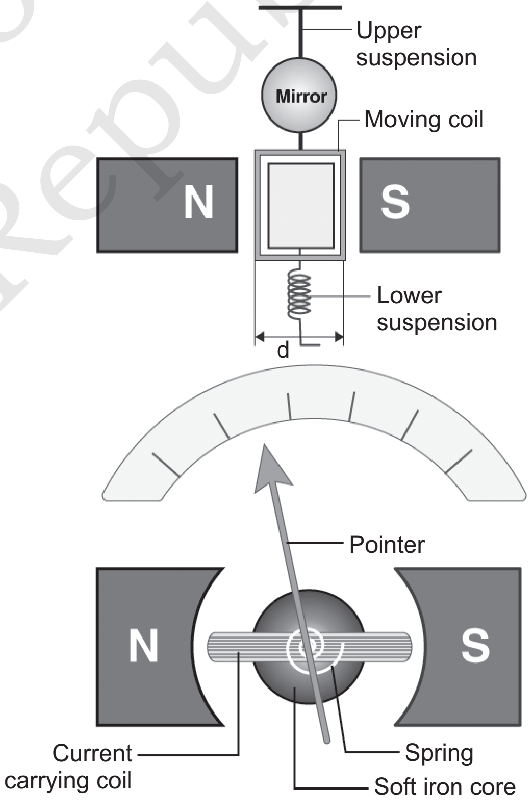


**Fig. 3.17.** Moving coil galvanometer

The spring is used to produce a counter torque which balances the magnetic torque and hence helps in producing a steady angular deflection. A plane mirror which is attached to the suspension wire, along with a lamp and scale arrangement, is used to measure the deflection of the coil. Zero-point of the scale is at the centre.

## Working of Moving Coil Galvanometer

Suppose a current I flows through the rectangular coil of a number of turns and a cross-sectional area A. When this coil is placed in a uniform radial magnetic field B, the coil experiences a torque T.

Let us first consider a simple turn ABCD of the rectangular coil having a length $l$ and breadth $b$. This is suspended in a magnetic field of strength B such that the plane of the coil is parallel to the magnetic field. Since the sides AB and DC are parallel to the direction of the magnetic field, they do not experience any effective force due to the magnetic field. The sides AD and BC being perpendicular to the direction of field experience an effective force F given by F = BI$l$.

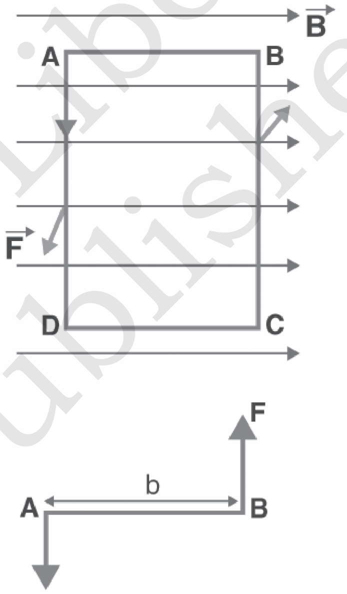


Fig. 3.18

Using Fleming's left-hand rule we can determine that the forces on AD and BC are in opposite directions to each other. When equal and opposite forces F called couple acts on the coil, it produces a torque. This troque causes the coil to deflect.

We know that torque τ = force × perpendicular distance between the forces

$$\tau = F \times b$$

Substituting the value of F we already know,

Torque τ acting on single-loop ABCD of the coil = BI$l$ × $b$

Where $l \times b$ is the area A of the coil,

Hence, the torque acting on $n$ turns of the coil is given by

$$\tau = nlAB$$

The magnetic torque thus produced causes the coil to rotate, and the phosphor bronze strip twists. In turn, the spring S attached to the coil prodcues a counter torque or restoring torque $k\theta$ which results in a steady angular deflection.

Under equilibrium condition:

$$k\theta = nl\mathrm{AB}$$

Here $k$ is called the torsional constant of the spring (restoring couple per unit twist). The deflection or twist θ is measured as the value indicated on a scale by a pointer which is connected to the suspension wire.

$$\theta = (n\mathrm{AB}/k)l$$

Therefore, $\theta \propto l$

The quantity $n\mathrm{AB}/k$ is a constant for a given galvanometer. Hence it is understood that the deflection that occurs the galvanometer is directly proportional to the current that flows through it.

The deflection θ per unit voltage is known as voltage sensitivity θ/V. Dividing both sides by V in the equation $\theta = (n\mathrm{AB}/k)l$:

$$\theta/\mathrm{V} = (n\mathrm{AB}/\mathrm{V}k)l = (n\mathrm{AB}/k)(l/\mathrm{V}) = (n\mathrm{AB}/k)(1/\mathrm{R})$$

R stands for the effective resistance in the circuit.

It is worth nothing that voltage sensitivity = Current sensitivity/ Resistance of the coil. Therefore, under the condition that R remains constant, voltage sensitivity ∝ Current sensitivity.

### Applications of Galvanometer

The moving coil galvanometer is a highly sensitive instrument due to which it can be used to defect the presence of current in any given circuit.

The galvanometer can be used to measure:

(a) the value of current in the circuit by connecting it in parallel to low resistance.

(b) the voltage by connecting it in series with high resistance.

## 3.15 ELECTRIC MOTOR (D.C. MOTOR)

D.C. motor works on the principle which states that ***when a rectangular coil is placed in a magnetic field and current is passed through the coil then a force (torque) acts on the coil and due to this torque, the coil rotates continuously. Direction of rotation of the coil is given by Fleming's Left Hand Rule.***

It is a device which converts electrical energy into mechanical energy of rotation.

Main parts of a D.C. motor are shown in Fig. 3.19.

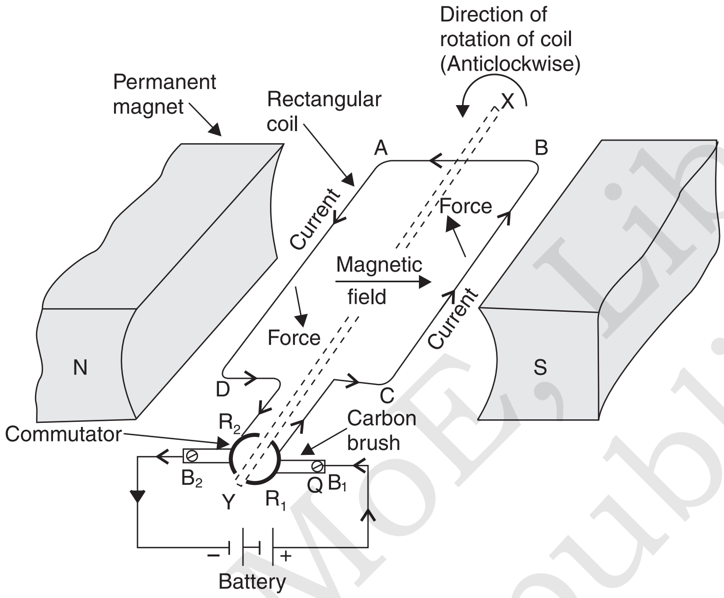


**Fig. 3.19.** D.C. motor.

DC motor has following **four** main parts:

1. A **permanent magnet** having concave magnetic poles N-S, which provides a strong magnetic field.
2. An **armature,** which is moving part of the motor. It has two parts :
    - (*i*) Laminated shaft X-Y and
    - (*ii*) Copper coil ABCD wrapped on end X of the shaft inside the field.
3. A **pair of metallic split rings** $R_1$ and $R_2$ (commutator).
4. A **pair of metallic or carbon brushes** $B_1$ and $B_2$.

## Working

A direct current (D.C.) source is connected between metallic brushes $B_1$ and $B_2$. When current passes through the coil, it flows in arms DB and AC in a direction perpendicular to the magnetic field. Equal and opposite forces act on these arms (in a direction according to Fleming's Left Hand Rule) and they form a couple. Torque which acts on the coil is given by, $\tau$ = NAIB. The coil rotates in anticlockwise direction. After half rotation, split parts of ring change brushes. Current becomes reverse in the arms but couple acts in same direction as before. The coil continues to rotate the shaft on which it is wrapped. Thus, rotatory motion (motor action) becomes available.

## 3.16 DIRECT CURRENT GENERATOR (DYNAMO)

Electric generator works on the principle that *when a straight conductor is moved in a magnetic field then current, is induced in the conductor.*

It is a device which converts mechanical kinetic energy of rotation into electrical energy.

Main parts of the dynamo and their arrangement is shown in Fig. 3.20.

From Fig. 3.20 we see that it has **four** main parts

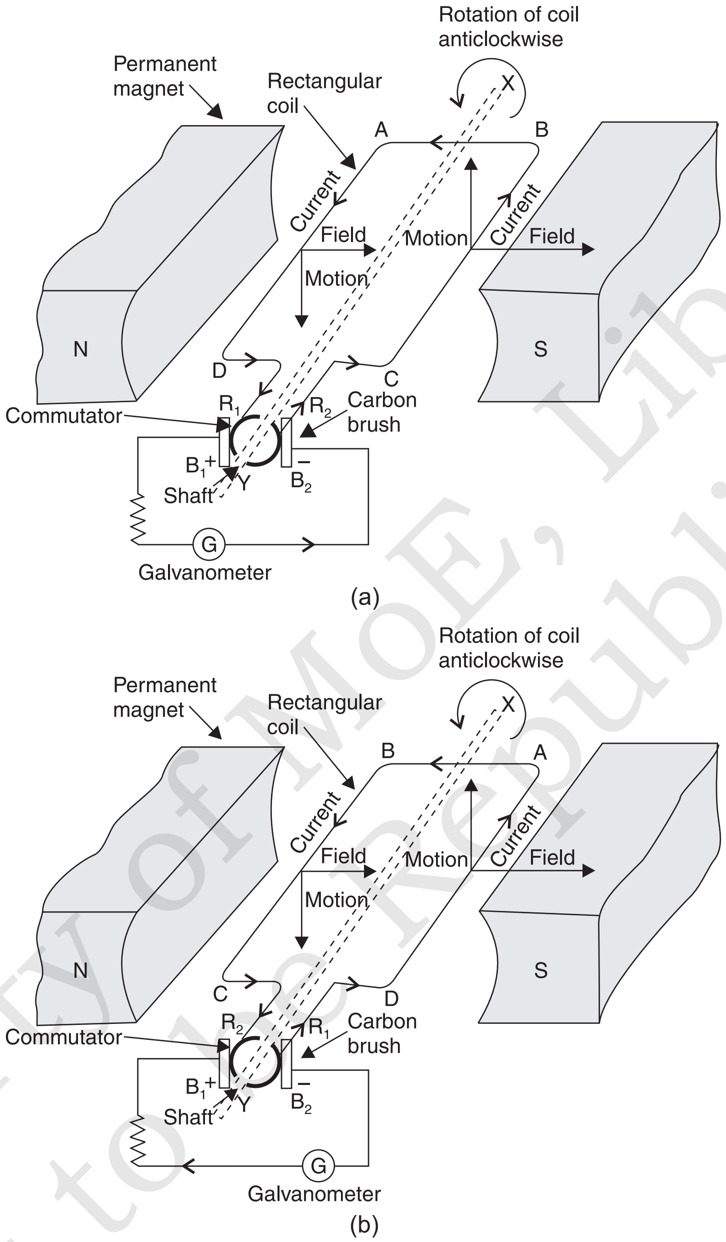
1. A **field magnet** having concave magnetic poles N-S, which provides a strong magnetic field.
2. An **armature** which is the moving part of the dynamo. It has two parts.
    (*i*) Laminated shaft XY.
    (*ii*) Copper coil ABCD wrapped on end X of the shaft inside the field.
3. A **pair of metallic split rings** $R_1$ and $R_2$ (commutator).
4. A **pair of metallic or carbon brushes** $B_1$ and $B_2$.

### Working

The shaft is rotated by some mechanical means (strong water current or steam). As the shaft rotates, magnetic flux through the coil changes. This changing magnetic flux produces induced e.m.f. in the coil, whose magnitude changes from zero to maximum and then from maximum to zero, through half the rotation of the coil [Fig. 3.20(a)].

Current flows out from coil into external circuit (load), through $B_2$, returning through $B_1$.

During next half rotation, the current would like to change direction. But by then split ring parts exchange brushes. Then $B_1$ touches $R_2$ and $B_2$ touches $R_1$ [Fig. 3.20(b)].



(a)

(b)

**Fig. 3.20.** D.C. generator.

Hence, direction of current does not change in external circuit, only its magnitude changes. Current flow in the circuit is **unidirectional** and not steady [Fig. 3.20].

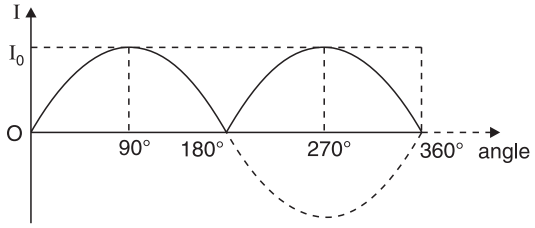


**Fig. 3.21.** Unidirectional current with single phase D.C. dynamo.

## 3.17 DIRECT AND ALTERNATING CURRENT

**Direct Current (D.C.).** A current which has a constant magnitude and same direction, is called a direct current.

Current due to a cell or a battery is a direct current.

**Alternating Current (A.C.).** A current which changes in magnitude and direction at regular intervals of time is called an alternating current.

Current produced by an A.C. dynamo (A.C. generator) is alternating current. Such a dynamo has separate **slip rings** in place of a **split ring.** Current changes direction after each rotation of the coil.

**Frequency.** Frequency of A.C. is the number of cycles per second completed by the current. One cycle is completed when the A.C. rises from zero to maximum positive then back to zero and then the maximum negative and zero again.

**Remember:** These days, most power stations produce AC. In India AC changes directions after every $\frac{1}{100}$ second i.e., frequency of AC produced in India is 50 Hz.

## 3.18 OPERATION OF AN ALTERNATING CURRENT GENERATOR

The working principle of an alternator or AC generator is similar to the basic working principle of a DC generator.

The following figure will help you understand how an alternator or AC generator works. According to the Faraday's law of electromagnetic induction, whenever a conductor moves in a magnetic field EMF gets induced across the conductor. If the close path is provided to the conductor, induced emf causes current to flow in the circuit.

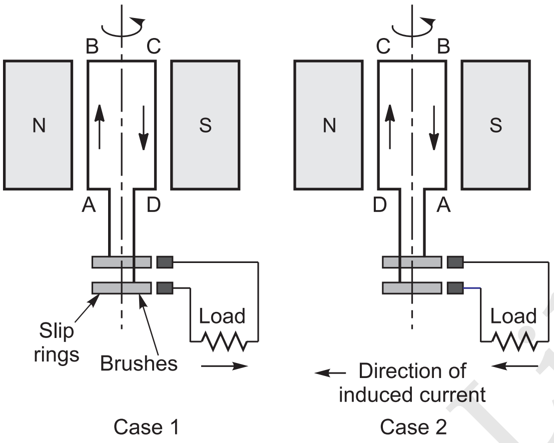


**Fig. 3.22.** AC Generator

Now, see the above figure. Let the conductor coil ABCD is placed in a magnetic field. The direction of magnetic flux will be from N pole to S pole. The coil is connected to slip rings, and the load is connected through brushes resting on the slip rings.

Now, consider the case 1 from above figure. The coil is rotating clockwise, in this case the direction of induced current can be given by Fleming's right hand rule, and it will be along A-B-C-D.

As the coil is rotating clockwise, after half of the time period, the position of the coil will be as in second case of above figure. In this case, the direction of the induced current according to Fleming's right hand rule will be along D-C-B-A. It shows that, the direction of the current changes after half of the time period, that means we get an alternating current.

## 3.19 TRANSFORMERS

For many purposes, it is necessary to change (or transform) an alternating voltage from one to another of greater or smaller value. This is done with a device called *transformer* using the principle of mutual induction.

A transformer consists of two sets of coils, insulated from each other. They are wound on a soft-iron core, either one on top of the other as in Fig. 3.23(*a*) or on separate limbs of the core as in Fig. 3.23(*b*). One of the coils called the *primary coil* has $N_p$ turns. The other coil is called the *secondary coil*; it has $N_s$ turns. Often the primary coil is the input coil and the secondary coil is the output coil of the transformer.

When an alternating voltage is applied to the primary, the resulting current produces an alternating magnetic flux which links the secondary and induces an emf in it. The value of this emf depends on the number of turns in the secondary. We consider an ideal transformer in which the primary has negligible resistance and all the flux in the core links both primary and secondary windings. Let $\phi$ be the flux in each turn in the core at time $t$ due to current in the primary when a voltage $v_p$ is applied to it.

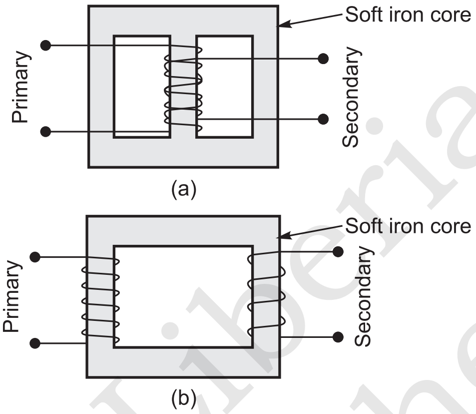


**Fig. 3.23.** Two arrangements for winding of primary and secondary coil in a transformer: (*a*) two coils on top of each other, (*b*) two coils on separate limbs of the core.

Then the induced emf or voltage $\varepsilon_s$, in the secondary with $N_s$ turns is

$$\varepsilon_s = -\mathrm{N}_s \frac{d\phi}{dt} \qquad [1]$$

The alternating flux $\phi$ also induces an emf, called back emf in the primary. This is

$$\varepsilon_p = -\mathrm{N}_p \frac{d\phi}{dt} \qquad [2]$$

But $\varepsilon_p = v_p$. If this were not so, the primary current would be infinite since the primary has zero resistance (as assumed). If the secondary is an open circuit or the current taken from it is small, then to a good approximation

$$\varepsilon_s = v_s$$

Where $v_s$ is the voltage across the secondary. Therefore, Eqs. [1] and [2] can be written as

$$v_s = -\mathrm{N}_s \frac{d\phi}{dt} \qquad [1\ (a)]$$

$$v_p = -\mathrm{N}_s \frac{d\phi}{dt} \qquad [2\ (a)]$$

From Eqs. [1 (*a*)] and [2 (*a*)], we have

$$\frac{v_s}{v_p} = \frac{N_s}{N_p} \qquad [3]$$

Note that the above relation has been obtained using three assumptions: (*i*) the primary resistance and current are small; (*ii*) the same flux links both the primary and the secondary as very little flux escapes from the core, and (*iii*) the secondary current is small.

If the transformer is assumed to be 100% efficient (no energy losses), P = IV,

$$I_p V_p = I_s V_s \qquad [4]$$

Although some energy is always lost, this is a good approximation, since a well designed transformer may have an efficiency of more than 95%. Combining Eqs. [3] and [4], we have

$$\frac{I_p}{I_s} = \frac{V_s}{V_p} = \frac{N_s}{N_p} \qquad [5]$$

Since I and V both oscillate with the same frequency as the ac source, Eq. [5] also gives the ratio of the amplitudes or rms values of corresponding quantities.

Now, we can see how a transformer affects the voltage and current we have.

$$V_s = \left(\frac{N_s}{N_p}\right) V_p \quad \text{and} \quad I_s = \left(\frac{N_p}{N_s}\right) I_p \qquad [6]$$

That is, if the secondary coil has a greater number of turns than the primary ($N_s > N_p$), the voltage is stepped up ($V_s > V_p$). This type of arrangement is called a *step-up transformer*.

If the secondary coil has less turns than the primary ($N_s < N_p$), we have a *step-down transformer*. In this case, $V_s < V_p$ and $I_s > I_p$. That is, the voltage is stepped down, or reduced, and the current is increased.

# REVIEW EXERCISE

## A. MULTIPLE CHOICE QUESTIONS (MCQs)

**1.** The fact that magnetic field is produced around a wire carrying a current, was discovered by

(*a*) Faraday (*b*) Oersted

(*c*) Maxwell (*d*) Joule

**2.** When current is straight, the associated magnetic field is

(*a*) straight (*b*) elliptical

(*c*) circular (*d*) parabolic

**3.** When current is circular, the associated magnetic field is

(*a*) straight (*b*) elliptical

(*c*) circular (*d*) parabolic

**4.** When current flows clockwise in a loop, the polarity of its face is

(*a*) east (*b*) south

(*c*) west (*d*) north

**5.** When current flows anticlockwise in a loop the magnetic polarity of the face is

(*a*) east (*b*) south

(*c*) west (*d*) north

**6.** For a solenoid carrying a current $I$ and having $n$ turns per unit length, wrapped on a core of permeability $\mu$, the correct expression for magnetic field intensity ($B$) is

(*a*) $B = \frac{\mu_0}{\mu} nI$

(*b*) $B = \frac{\mu_0 \mu I}{n}$

(*c*) $B = \mu_0 \mu n I$

(*d*) $B = \frac{\mu_0 \mu n}{I}$

**7.** Magnets having temporary magnetism are called

(*a*) electromagnets

(*b*) bar magnets

(*c*) circular magnets

(*d*) horse-shoe magnets.

**8.** Direction of force acting on a current carrying conductor kept in a magnetic field is given by

(*a*) Fleming's right hand rule
(*b*) Fleming's left hand rule
(*c*) Lenz's rule
(*d*) Faraday's rule.

**9.** The electric device which works on the phenomenon of force on a current carrying conductor in a magnetic field is

(*a*) generator
(*b*) accelerator
(*c*) motor
(*d*) transformer.

**10.** The moving part of an electric motor is called

(*a*) armature
(*b*) shaft
(*c*) slip ring
(*d*) split ring.

**11.** Electromagnetic induction was discovered by

(*a*) Oersted
(*b*) Maxwell.
(*c*) Thomson
(*d*) Faraday.

**12.** Direction of induced current produced by motion of a conductor in a magnetic field is given by

(*a*) Fleming's right hand rule
(*b*) Fleming's left hand rule
(*c*) Lenz's rule
(*d*) Faraday's rule.

**13.** In domestic electric circuits, fuse must be placed in series with

(*a*) earth wire
(*b*) neutral wire
(*c*) live wire
(*d*) any of the three wires.

**14.** Meter and main switch is contained in a main board fitted usually

(*a*) at street electric pole

(*b*) at main gate of building

(*c*) in varandah or poarch

(*d*) in bed or study room.

**15.** High powered electrical appliances are earthed to

(*a*) avoid shock

(*b*) avoid wastage

(*c*) make the appliance look beautiful

(*d*) reduce the bill.

## B. FILL IN THE BLANKS

**1.** The phenomenon of production of magnetic field round a current carrying conductor is called ______ effect of current.

**2.** The rule which relates direction of deflection of magnetic needle with direction of field is called ______ rule.

**3.** When a wire is wrapped into many close turns over a cylindrical core, it forms a ______ .

**4.** To have north polarity at a face, the current in loop must flow in ______ direction.

**5.** To have south polarity at a face, the current in loop must flow in ______ direction.

**6.** In electromagnets, magnetism is ______ .

**7.** In an electric motor ______ energy is converted into mechanical energy.

**8.** In electromagnetic induction, motion of a ______ in a fixed coil produces electric current.

**9.** In an electric generator, ______ energy is converted into an electrical energy.

**10.** An electric current having a constant magnitude and direction, is called a ______ current.

## C. VERY SHORT ANSWER TYPE QUESTIONS

**1.** What does the divergence of magnetic field lines near the ends of a current-carrying straight solenoid indicate?

2. Name three appliances wherein an electric motor, a rotating device that converts electrical energy to mechanical energy, is used as an important component. In what respect motors are different from generators?
3. A magnetic compass shows a deflection when placed near a current-carrying wire. How will the deflection of the compass get affected if the current in the wire is increased? Support your answer with a reason.
4. It is established that an electric current through a metallic conductor produces a magnetic field around it. Is there a similar magnetic field produced around a thin beam of moving (*i*) alpha particles, (*ii*) neutrons? Justify your answer.
5. What is the ratio of SI to CGS units of magnetic induction?
6. Why is soft-iron not used for making a permanent magnet?
7. Name the rule to find the direction of force on a current-carrying conductor placed in direction perpendicular to the direction of magnetic field.
8. What is the relation between a tesla, an ampere and a meter.
9. What is the force acting on charge ($q$) moving in a direction perpendicular to a magnetic field ($B$) with velocity v?
10. What does the direction of thumb indicate in the right-hand thumb rule? In what way this rule is different from Fleming's left-hand rule?

## D. SHORT ANSWER TYPE QUESTIONS

1. A student performs an experiment to study the magnetic effect of current around a current carrying straight conductor. He reports that
   (i) the direction of deflection of the north pole of a compass needle kept at a given point near the conductor remains unaffected even when the terminals of the battery sending current in the wire are interchanged.
   (*ii*) for a given battery, the degree of deflection of a N-pole decreases when the compass is kept at a point farther away from the conductor. Which of the above observations of the student is incorrect and why?
2. A current carrying conductor is placed perpendicular to the magnetic field of horse-shoe magnet. The conductor is displaced upward. What will happen to the displacement of the conductor if (*i*) current in the conductor is increased, (*ii*) a horse-shoe magnet is replaced by another stronger horse-shoe magnet and (*iii*) the length of the conductor is increased.
3. What is frequency of a direct current?

4. Can a 12 volt battery be used to operate a step-up transformer?
5. Can alternating current be used to perform electrolysis?

## E. LONG ANSWER TYPE QUESTIONS

1. What does the direction of thumb indicate in the right-hand thumb rule? In what way this rule is different from Fleming's left-hand rule?
2. Meena draws magnetic field lines of field close to the axis of a current-carrying circular loop. As she moves away from the centre of the circular loop, she observes that the lines keep on diverging. How will you explain her observation?
3. What does the divergence of magnetic field lines near the ends of a current-carrying straight solenoid indicate?
4. Name four appliances wherein an electric motor, a rotating device that converts electrical energy to mechanical energy, is used as an important component. In what respect motors are different from generators?
5. What is the role of the two conducting stationary brushes in a simple electric motor?