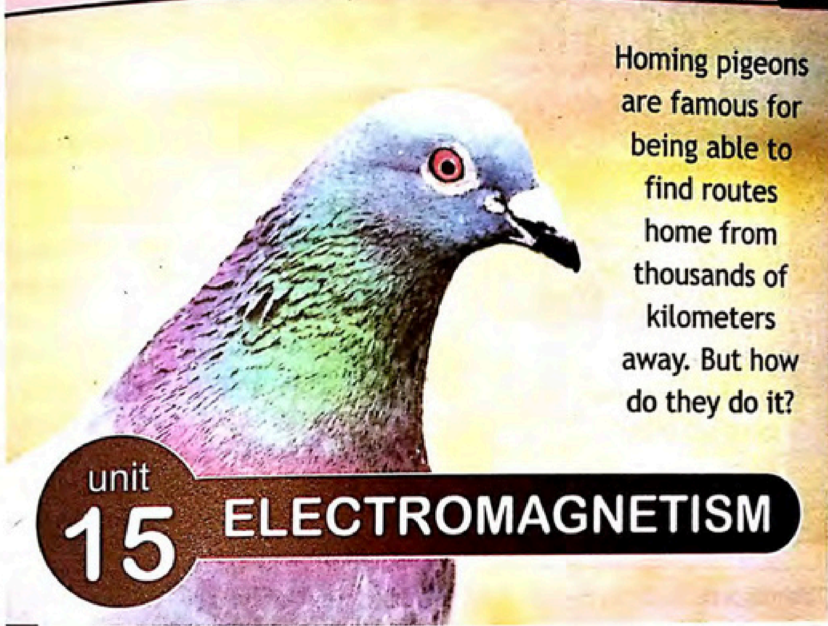
NUMERICAL QUESTIONS

1. A small electric heater has a resistance of 15 ohms when the current in it is 2 amperes. What voltage is required to produce this current?
2. If a potential difference of 10 V is maintained across a 1 m length of the Nichrome wire having resistance of 3.1 Ω, what is the current in the wire?
3. What resistor would have a 15 mA current if connected across the terminals of a 9.0 V battery?
4. Consider a circuit with three resistors $R_1 = 250.0\ \Omega$, $R_2 = 150.0\ \Omega$, $R_3 = 350.0\ \Omega$, connected in parallel with a 24.0-V battery. Find the total current supplied by the battery.
5. An electric hair dryer is rated at 1,875 watts when operating on 120 volts. What is the current flowing through it? If the hair dryer is used for 3 minutes, how much energy does it consume?
6. A battery with an emf of 12 V is connected to a 545 Ω resistor. How much energy is dissipated in the resistor in 65 s?
7. If the unit of electricity cost 8.11 Rs/kWh, what is cost of running two 160 W fans and four 100 W light bulbs for 6 hours in school?



unit 15 ELECTROMAGNETISM

STUDENT LEARNING OUTCOME

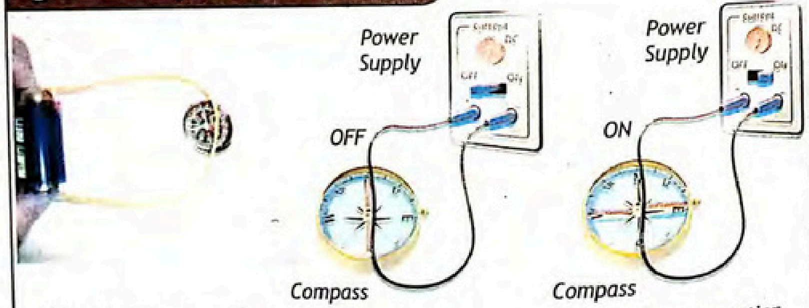
After studying this chapter you should be able to

- ✓ explain by describing an experiment that an electric current in a conductor produces a magnetic field around it.
- ✓ describe that a force acts on a current carrying conductor placed in a magnetic field as long as the conductor is not parallel to the magnetic field.
- ✓ state that a current carrying coil in a magnetic field experiences a torque.
- ✓ relate the turning effect on a coil to the action of a D.C. motor.
- ✓ describe an experiment to show that a changing magnetic field can induce e.m.f. in a circuit.
- ✓ list factors affecting the magnitude of an induced e.m.f.
- ✓ explain that the direction of an induced e.m.f opposes the change causing it and relate this phenomenon to conservation of energy.
- ✓ describe a simple form of A.C generator.
- ✓ describe mutual induction and state its units.
- ✓ describe the purpose of transformers in A.C. circuits.
- ✓ identify that a transformer works on the principle of mutual induction between two coils.

Just like electric field, the region or space around a magnet where magnetic effects can be observed is called the magnetic field and is represented by magnetic field vector or magnetic induction vector B and can be represented by magnetic field lines. When charges move (such as in a current carrying wire), they generate a magnetic field as well as an electric field. Thus, when charges move they also exhibit magnetic behavior, when they are at rest no such effect is seen. Magnetic effects created due to the presence of currents is the focus of study in this chapter.

This magnetic field can be detected, by bringing a compass needle close to the steady direct current carrying wire such as produced by the cell or Power Supply as shown in the figure 15.1.

Figure 15.1 - *Magnetic effect of current*



Using an apparatus similar to the one shown, we can demonstrate a connection between magnetism and electricity by applying current to the wire.

15.1 MAGNETIC EFFECT OF A STEADY CURRENT

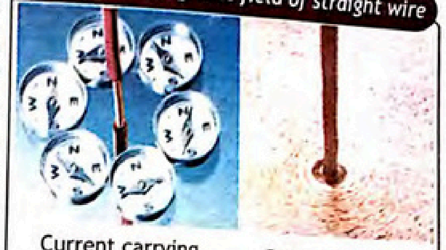
The magnetic field produced by steady current can be mapped by the following experiments.

15.1.1. Magnetic Field due to a straight steady current carrying wire:

When current is passed through a long wire with compass needles placed around it in a circle, the compass needles line up with the magnetic field in a circular pattern.

Similar observations can be made by using a cardboard on which iron filings have been placed. These iron fillings form concentric circles around the wire as shown in figure 15.2. These experiments show the orientation of a magnetic field around a current carrying wire is circular. Without any current in the wire all the compass needle will align with earth's magnetic field, pointing towards the north.

Figure 15.2 - *Magnetic field of straight wire*

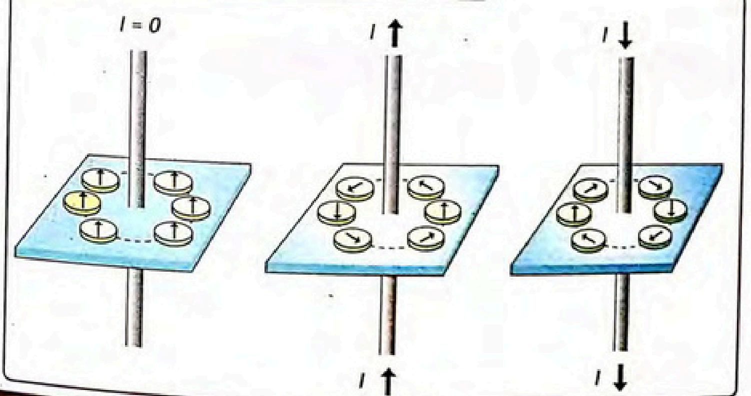


Current carrying wire, with compass needles lining up with the magnetic field in form of circular pattern.

Current carrying wire through a cardboard shows concentric circles of iron filings around the wire.

As soon as the current is passes through the wire, the compass needles will redistribute to align with magnetic field of the wire.

Figure 15.3 - *Magnetic field of straight wire*



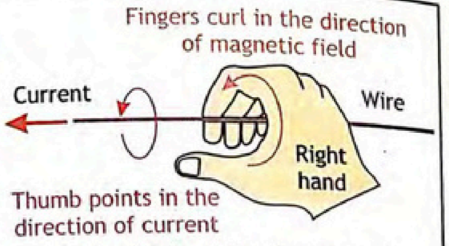
LAB WORK

Trace the magnetic field of a bar magnet.

The compass needle deflects in opposite direction when the current is reversed as shown in the figure 15.3, the direction of such field is determined by right hand rule I.

RIGHT-HAND RULE I

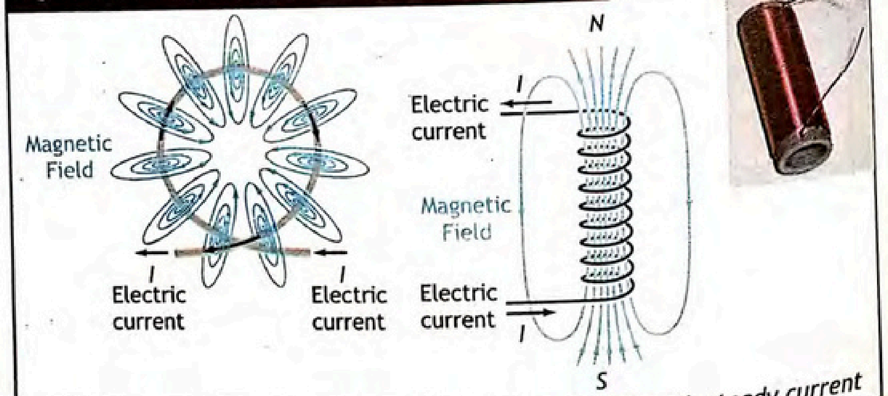
Right-hand rule for the magnetic field from a current carrying wire: Put your thumb in the direction of current and curl your fingers around the wire, the curled fingers will show the direction of magnetic field. This rule is for direction of conventional current or flow of positive charges. For electronic current flow the same rule is applied but with left hand.



Right-hand rule - I for the magnetic field from a current carrying wire.

15.1.2. Magnetic Field due to a coil or solenoid: When wire is shaped in to the loop or coil and steady current is applied through it. By applying the right hand rule around a loop of wire carrying current, we see that the magnetic field around a loop of wire carrying current is in same direction coming in and going out of coil, forming a north and south pole like bar magnet. Since the field lines cannot cross, the field lines are packed closer together inside therefore the field is stronger inside and weaker outside the coil.

Figure 15.4 - *Magnetic Field due to a Coil or Solenoid*

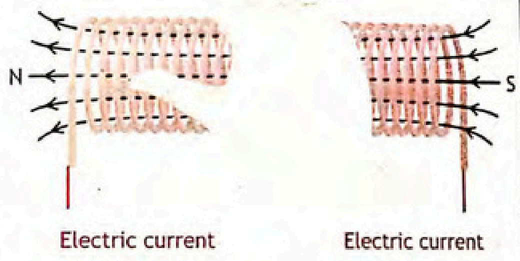


The magnetic field lines for a wire loop and solenoid with steady current

To make a field having resemblance with the field of a bar magnet, a coil is shaped as spiral (helix) called solenoid as shown in figure 15.4. When current is passed through a solenoid, a reasonably uniform magnetic field can be produced. This field is strong along the axis of solenoid and weaker outside. For a tightly wound solenoid, the field in the interior space is very uniform and strong. The field lines have resemblance to those of a bar magnet, meaning that the solenoid effectively has north and south poles. To determine the direction we use right hand rule II.

RIGHT-HAND RULE II

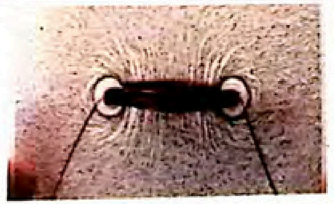
Right-hand rule II for a solenoid: Curl the fingers in the direction of current around the coil or solenoid and the extended thumb will point in the direction of north pole of a magnet. This rule is for direction of conventional current or flow of positive charges. For electronic current flow, the same rule is applied but with left hand.



The right-hand rule (II) for a solenoid

LAB WORK

To trace the magnetic field due to a current carrying circular coil.



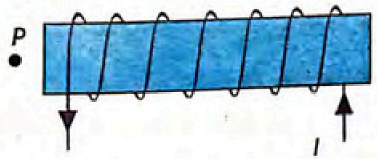
CHECK POINT

?

What is the direction of the magnetic field at point P in the figure? (P is on the axis of the coil.)

A. ? B. ?

C. ? D. ?



The compass needle deflects in opposite direction when the current is reversed as shown in the figure 15.3, the direction of such field is determined by right hand rule I.

RIGHT-HAND RULE I

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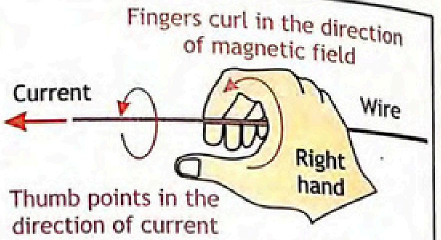

Right-hand rule - I for the magnetic field from a current carrying wire.

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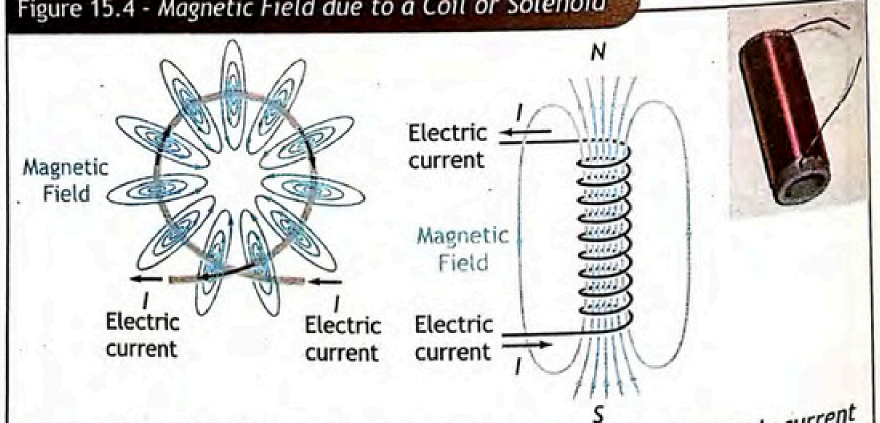
Figure 15.4 - *Magnetic Field due to a Coil or Solenoid*



The magnetic field lines for a wire loop and solenoid with steady current

To make a field having resemblance with the field of a bar magnet, a coil is shaped as spiral (helix) called solenoid as shown in figure 15.4. When current is passed through a solenoid, a reasonably uniform magnetic field can be produced. This field is strong along the axis of solenoid and weaker outside. For a tightly wound solenoid, the field in the interior space is very uniform and strong. The field lines have resemblance to those of a bar magnet, meaning that the solenoid effectively has north and south poles. To determine the direction we use right hand rule II.

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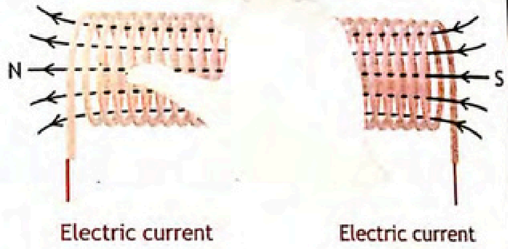
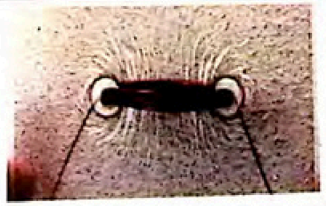


The right-hand rule (II) for a solenoid

LAB WORK

To trace the magnetic field due to a current carrying circular coil.

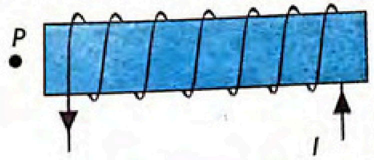


CHECK POINT

?

What is the direction of the magnetic field at point P in the figure? (P is on the axis of the coil.)

A. ?   B. ?
C. ?   D. ?



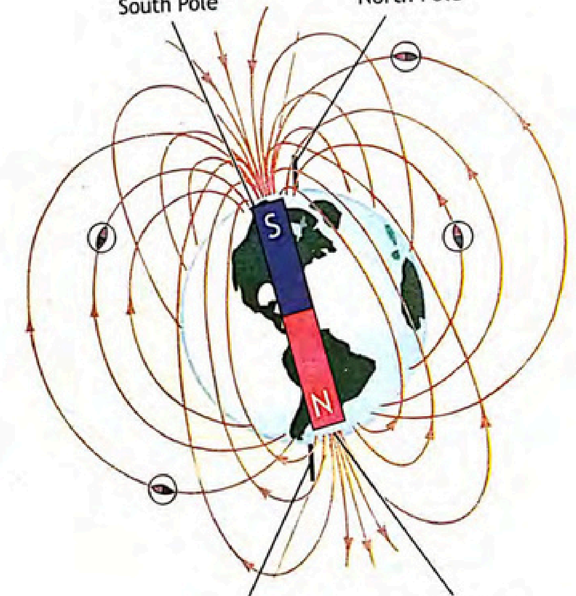
EARTH'S MAGNETIC FIELD

INFO

Origin of Earth's Magnetic Field: The magnetic field of the earth is probably caused by electric currents (electromagnetism) at its core. The Earth's core contains a liquid, which conducts electricity and the spin of the Earth about its axis causes the liquid to circulate much like the current in a conducting loop.

Jupiter rotates faster than the Earth and space probes indicate that Jupiter's magnetic field is stronger than ours. Venus, on the other hand, rotates more slowly than the Earth and its magnetic field is found to be weaker.

The north pole of a magnet is attracted toward the north geographic pole of the Earth. We conclude that the Earth's south magnetic pole is located near the north geographic pole and the Earth's north magnetic pole is located near the south geographic pole. In fact, the configuration of the Earth's magnetic field, pictured in figure, is very much like the a magnet.



POINT TO PONDER

Magnetoreception: Magnetoreception is a sense which allows an organism to detect a magnetic field to perceive direction, altitude or location. This sensory modality is used by a range of animals for orientation and navigation. Magnetoreception is present in bacteria, arthropods, molluscs and members of all major taxonomic groups of vertebrates. Humans are not thought to have magnetic sense, but there is a protein (a cryptochrome) in the eye which could serve this function.

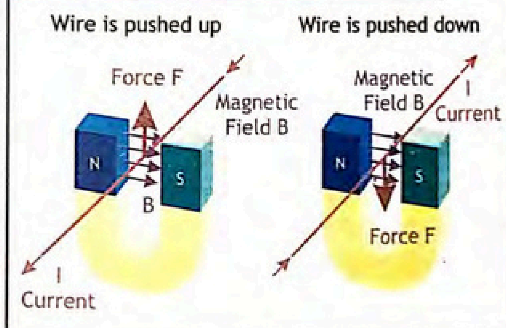
The pigeons also navigate by using Magnetoreception, evidence indicates that they sense this field at least partly by means of small magnetite crystals located in their beaks. When the area of the beak containing he crystals is anaesthetized or the nerves to it are cut, the birds lose their ability to sense the magnetic field. The pigeon shown in the opening photo has a small magnet attached to its beak; this also interferes with the bird's ability to sense the earth's magnetic fields.

15.2 FORCE ON A CURRENT CARRYING CONDUCTOR IN A MAGNETIC FIELD

When current carrying wire is placed in a magnetic field, charges flowing through the wire interact with the external magnetic field and thus the wire experiences a force.

Consider a wire connected to a battery and passing through a U-shaped magnet as shown in figure 15.5. It is observed that the wire experiences a force which is perpendicular to both the direction of current I and the direction of magnetic field B. If we reverse the direction of current, the direction of force is also reversed.

Figure 15.5 - *Force on a current carrying conductor in magnetic field*



We see that this force is maximum when the current carrying wire is placed perpendicular to the magnetic field and reduces in magnitude when the angle is changed and vanishes when the current carrying wire and magnetic field are parallel, showing a sine of angle θ variation.

With this experiment we can find that this force is directly proportional to the current flowing though the wire I, the magnetic field B, length L of the wire in the magnetic field and sine of angle θ between current and magnetic field. Thus, mathematically the force is

$$F_B \propto BIL\sin\theta$$

$$\text{or} \qquad F_B = kBIL\sin\theta$$

For SI units K = 1, therefore the equation that describes the force experienced by a current-carrying conductor in a uniform external magnetic field then becomes

$$F_B = BIL\sin\theta \qquad \text{—— 15.1}$$

Where F is the magnetic force in newtons (N), B is the magnetic field strength in tesla (T), I is the current in the conductor in amperes (A), L is the length of the conductor in the magnetic field in metres (m), and θ is the angle between the conductor and the magnetic field.

15.2.1 Maximum Magnetic Force: The force will be maximum when the angle between current direction and magnetic field is $\theta = 90°$.

$$F_B = BIL\sin 90^{o} \qquad \text{Since} \quad \sin 90^{o} = 1$$

$$\text{hence} \qquad F_B = BIL \qquad \text{—— 15.2}$$

$$\text{also} \qquad B = \frac{F_B}{IL}$$

15:2.2 Unit of magnetic field B: The SI unit for magnetic field strength is tesla (T). If one ampere of current in a one-metre-long wire produces a maximum force of one newton then the magnetic field is defined as one tesla (T), where

$$1T = \frac{1N}{1A \times 1m}$$

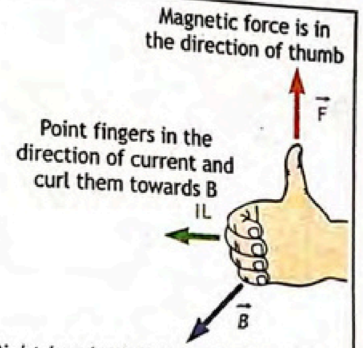
TABLE 15.1 : SOME APPROXIMATE MAGNETIC FIELDS

At surface of neutron star	10^{8} T
Near large electromagnet	1.5 T
Near small bar magnet	10^{-2} T
At earth's surface	10^{-4} T
Interstellar space	10^{-10} T
Magnetically sheilded room	10^{-14} T

15.2.3 Direction of force: Since force is a vector quantity it must be associated with proper direction. Fleming's Left hand rule or right hand rule III is used to determine the direction of force on a current carrying wire in magnetic field.

RIGHT-HAND RULE III

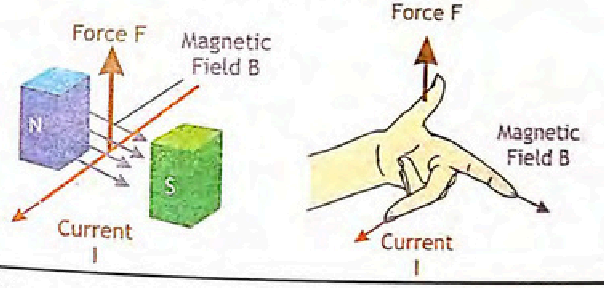
Right-hand rule for the force on a current carrying conductor: Outstretch the fingers of right hand in the direction of current then bend the fingers in the direction of magnetic field (through the shorter angle between them) then the extended thumb will give the direction of force on the current carrying wire. This rule is for direction of conventional current or flow of positive charges. For electronic current flow, the same rule is applied but with left hand.



Right-hand rule (III) for the force on a current carrying conductor

Fleming's Left hand rule

Fleming's left hand rule can also be used to represent the direction of force. The thumb and the first two fingers of the left hand are set at right angles to each other. With the first finger pointing in the direction of the field, the second finger pointing in the direction of current, the thumb will give the direction of force.

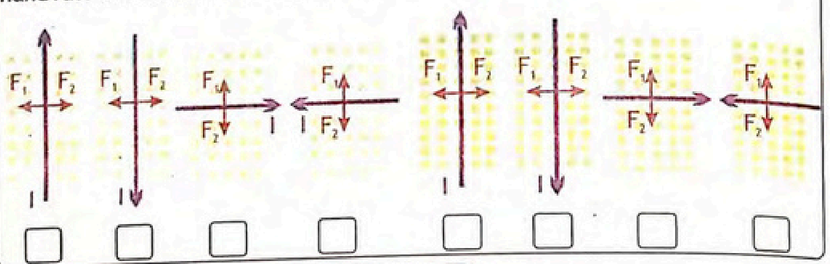


Since magnetism is inherently three-dimensional; we often need to draw vectors that are perpendicular to the page. The symbol • (or ⊙) represents a vector arrow pointing out of the page; think of the tip of an arrow coming toward you. The symbol × (or ⊗) represents a vector pointing into the page; it suggests the tail feathers of an arrow moving away from you.

- • out of the page
- × in to the page

ACTIVITY: IDENTIFY THE MAGNETIC FORCES

In each of the following different current I (blue) directions and magnetic field (green) into the page and out of the page are shown. Identify the direction of force (red) direction as either F_1 or F_2 using right hand rule III or Fleming's left hand rule and write in the box provided.



EXAMPLE 15.1: MAGNETIC LEVITATION

Can the magnetic force on a current-carrying wire be large enough to suspend the wire against gravity? Consider a wire having mass of 6.24×10^{-4} kg and length 3.5 cm placed perpendicular to a 2.4 T magnetic field. How large a current must the wire carry in order to be suspended against gravity?

GIVEN

Mass 'm' = 6.24×10^{-4} kg

Length 'L' = 3.5 cm = 0.035 m

Magnetic field 'B' = 2.4 T

Acceleration due to gravity 'g' = 9.8 m/s²

REQUIRED

Current 'I' = ?

SOLUTION: In order to suspend a wire against gravity, the magnetic force on a wire must balance its weight W, such that

$$F_B = W \qquad \text{Here} \quad F_B = ILB \quad \text{and} \quad W = mg$$

$$\text{Therefore} \quad ILB = mg \qquad \text{or} \quad I = \frac{mg}{LB}$$

$$\text{Putting values} \quad I = \frac{6.24 \times 10^{-4} kg \times 9.8 ms^{-2}}{0.035 m \times 2.4 T}$$

$$\text{or} \quad I = \frac{6.24 \times 10^{-4} \cancel{kg} \times 9.8 \cancel{m} \cancel{s^{-2}}}{0.035 \cancel{m} \times 2.4 \frac{\cancel{kg s^{-2}}}{A}}$$

$$\text{Hence} \quad I = 0.073 A = 73 mA \quad \text{Answer}$$

From Chapter 14, you know that 73 mA is a modest current for an ordinary copper wire of this size, so the suspension is easily accomplished.

EXTENSION EXERCISE 15.1

Where is this magnetic levitation is applied?

ASSIGNMENT 15.1: FORCE ON A WIRE

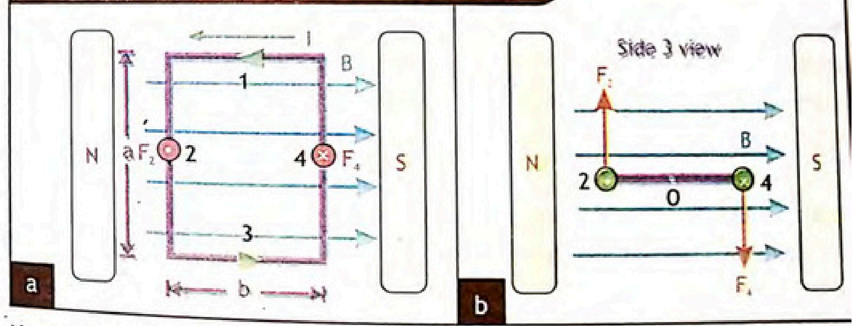
A wire carrying a steady (dc) 30 A current has a length of 0.12 m between the pole faces of a magnet. The wire is at an angle θ = 60° to the field. The magnetic field is approximately uniform at 0.90 T. Determine the magnitude of the force on the wire.

15.3 TURNING EFFECT ON A CURRENT CARRYING COIL IN A MAGNETIC FIELD

When a current carrying coil or loop is placed in uniform magnetic field it experiences a net force, this force can exert torque on the coil or loop of wire.

Consider a rectangular coil having four (1, 2, 3 and 4) sides of length a and b carrying a current I in the presence of a uniform magnetic field B directed parallel to the plane of the loop as shown in figure 15.6.

Figure 15.6 - *Torque on current carrying coil*



No magnetic forces act on sides 1 and 3 because these wires are parallel to the field θ = 0°; the length of sides 1 and 3 is b, therefore magnetic force F_1 and F_3 is

$$F_1 = F_3 = BIb\sin 0° \qquad \text{since} \ \sin 0° = 0$$

$$\text{Therefore} \quad F_1 = F_3 = 0 \quad (1)$$

However, maximum magnetic forces act on sides 2 and 4, because these sides are perpendicular to the field θ = 90°; the length of sides 2 and 4 is a, therefore magnetic force is

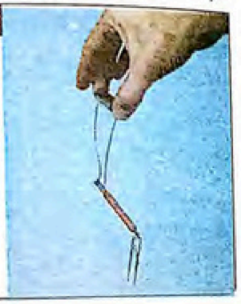
$$F_2 = F_4 = BIL\sin 90^o \qquad \text{since } \sin 90^o = 1$$

$$\text{Therefore } F_2 = F_4 = BIa \quad (2)$$

If we view the loop from side 3 and sight along sides 2 and 4, we see the view shown in figure 15.6 (b). The two magnetic forces F_2 and F_4 point in opposite directions such that they form a couple. If the loop is pivoted so that it can rotate about point O, these two forces produce a torque that rotates the loop (in this case clockwise).

ACTIVITY: BUILD AN ELECTROMAGNET

Wrap a copper wire around a nail and hold the ends of the wire with both terminals of the cell. This system will form an electromagnet and will be able to attract objects (paper pins) just like a magnet. The electromagnet that you'll construct in this experiment will become hot during use. Be prepared to drop the electromagnet if it becomes uncomfortably hot.



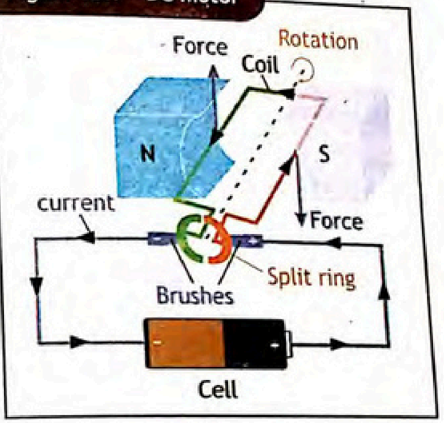
15.4 DC MOTOR

Electric motor is a device that converts electrical energy into mechanical energy. A DC Motor uses direct current (DC) for this purpose. It works on the principle that current carrying wire in a magnetic field experiences a torque. The electric motor is found in many devices, such as CD players, automobiles, washing machines and air conditioners.

Simplest and cheapest form of a DC motor is shown in the figure 15.7, it consists of a rectangular current carrying coil mounted on a spindle that can rotate between the poles of a permanent magnet. Practically, it is a coil of many turns wound on a soft iron cylinder (or core) which rotates with the coil to make it more powerful. The coil and core together are called the armature. Consider the motor to be initially in the position shown in fig. 15.7.(b). A clockwise torque acts on the coil causing it to turn. If the current in the coil were to continue to flow in the same direction when the green half of the coil rotates in front of the South pole, it would still experience an upward force causing the direction of the torque/couple to reverse. The coil would simply oscillate (wobble) back and forth.

To make the coil continue to rotate, the ends of the coil are attached to a split ring called the commutator. The power supply is connected to the commutator using a pair of brushes which allows the ring to rotate while maintaining electrical contact. Again consider the motor starting in the position in fig. 15.7. The coil rotates clockwise. When the coil becomes vertical (green conductor on the top, red on the bottom, coil perpendicular to the magnetic field), the gaps in the commutator align with the brushes

Figure 15.7 - DC Motor



and so the current stops flowing. The inertia of the coil carries it forward and now the green half is closer to the South pole. But the rotation of the commutator now means that the green half is connected to the positive terminal of the power supply instead of the negative. This causes the direction of current in the coil to reverse and so the force on the green half points down instead of up.

The torque/couple created is still clockwise and the coil continues to rotate.

Thus the commutator allows the direction of the current in the coil to reverse every half-cycle ensuring that the torque/coil continues to rotate in the same direction as long as DC power is supplied.

ACTIVITY: BUILD A SIMPLE DC MOTOR

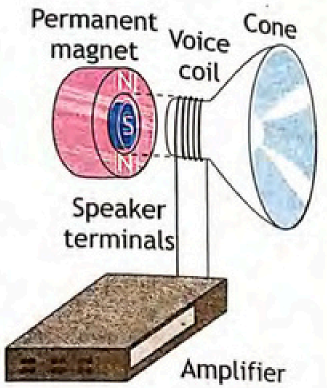
Attach the magnet on the side of the battery using a long piece of adhesive tape. Shape one end of each paper clip so as to make it longer and to make a small loop at the top. Fix these paper clips on the ends of the battery using adhesive tape. Make 10 to 15 coils of wire, scrap the insulation at the ends of the wire.

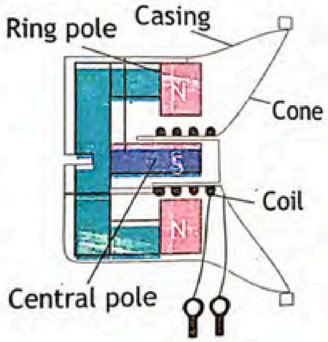
Using a permanent marker, color one side at each end in order to insulate that side. This will prevent current from flowing through the loops for half of every cycle. It has the same effect as that of a commutator. Finally, mount the coils onto the two paper clips and allow the motor to spin as shown.

MOVING-COIL LOUDSPEAKER

INFO

A common application of the magnetic forces on a current-carrying wire is found in loudspeakers. The radial magnetic field created by the permanent magnet exerts a force on the voice coil that is proportional to the current in the coil; the direction of the force is either to the left or to the right, depending on the direction of the current. The signal from the amplifier causes the current to oscillate in direction and magnitude. The coil and the speaker cone to which it is attached, responds by oscillating with an amplitude proportional to the amplitude of the current in the coil. Turning up the volume knob on the amplifier increases the current amplitude and hence the amplitudes of the cone's oscillation and of the sound wave produced by the moving cone.





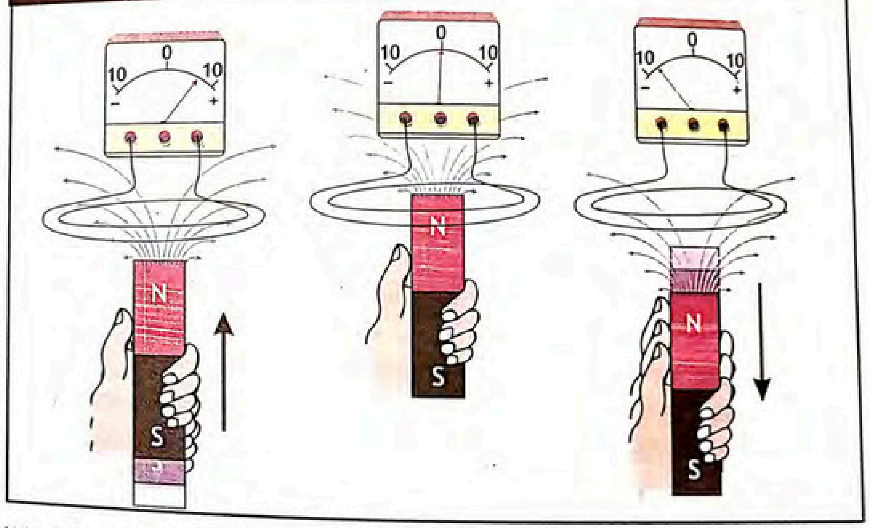
15.5 ELECTROMAGNETIC INDUCTION

When magnetic field through a wire is changed, current is found to flow in the loop, the phenomena is called Electromagnetic Induction. A changing magnetic field induces an emf. *The current in a circuit due to a changing magnetic field is called an* **induced current.** An induced current is not caused by a battery; it is a completely new way to generate a current. So there is a current in a coil of wire only if the magnetic field passing through the coil is **changing.**

Consider a coil of wire connected to a galvanometer as shown in figure 15.8. When the magnet is stationary (even inside the coil), the galvanometer shows no current. But when we move the magnet either toward or away from the coil, the galvanometer shows current in the circuit. If we keep the magnet stationary and move the coil, we again detect a current during the motion. We call this an induced current and the corresponding emf required to create this current is called an induced emf. Whenever we have a changing magnetic field, an emf is induced. If the circuit is completed, the induced emf will cause an induced current to flow. The emf is induced regardless of whether a current can flow or not.

It should be noted that when magnet and coil are moved towards each other, the galvanometer shows deflection in one direction.

Figure 15.8 - Electromagnetic induction



When the magnet and the coil are moved away from each other, the galvanometer shows deflection in the other direction. When both are fixed, no such deflection occurs.

Similar effects can be observed with two coils. When one coil is connected to a battery called primary coil (the steady current in the coil produces a steady magnetic field forming an electromagnet). While the other connected to a galvanometer is called as secondary coil.

When the primary coil is moved towards the secondary coil, the galvanometer shows a deflection. This indicates that electric current is induced in secondary coil. When the primary coil is moved away, the galvanometer shows a deflection again, but this time in the opposite direction. The deflection lasts as long as primary coil is in motion.

When the primary coil is held fixed and the secondary coil is moved, the same effects are observed. Again, it is the relative motion between the coils that induces the electric current.

If both coils are held fixed but the current in the primary coil is changed the magnetic field it produces changes and an emf is induced in the secondary coil. This is the basis of the working principle of a transformer.

15.5.1 Factors affecting magnitude of induced emf:

- When a double loop of wire is used, the deflection on the galvanometer is twice as large as before. A tripple loop induces three times the e.m.f. and so on. This shows that "the e.m.f. is proportional to the number of turns in a coil."
- The faster the wire is moved, the larger the deflection on the galvanometer. This indicates that the speed at which the conductor moves through the magnetic field also determines the magnitude of induced e.m.f.
- The longer the length of the conductor in the magnetic field, the greater is the induced e.m.f.
- The larger the magnetic field, the greater the e.m.f induced.

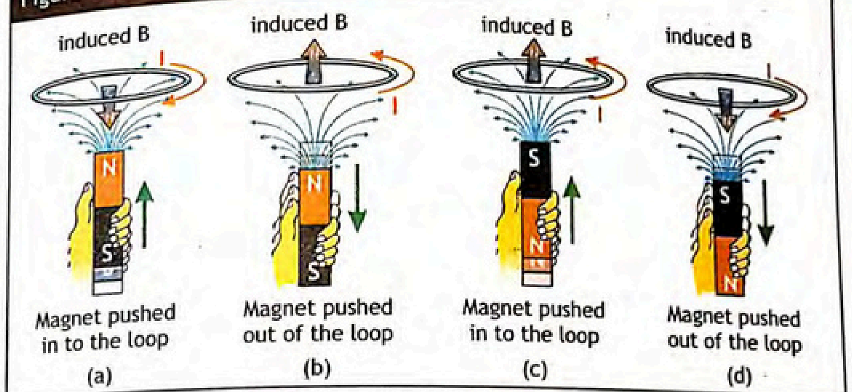
15.5.2 Direction of induced emf and conservation of energy:

Whenever there is a change of magnetic flux, there will be induced emf and current will flow in such a direction so as to oppose the cause producing it.

The induced current around a loop produces its own magnetic field. This field may be weak compared with the external magnetic field. It cannot prevent the magnetic flux through the loop from changing, but its direction is always such that it " tries " to prevent the flux from changing.

Consider pushing the bar magnet's North pole into the loop, it causes the magnetic field to increase in the upward direction. To oppose the change, the loop itself needs to generate the downward-pointing magnetic field (acting as a magnet with its North Pole at the bottom which repels the North pole of the bar magnet moving towards it) as shown in figure 15.9(a).

Figure 15.9 - Direction of induced current



The induced magnetic field at the center of the loop will point downward (using right hand rule II) only if the current is clockwise (cw) as seen from above. Now suppose the north pole of bar magnet is pulled away from the loop, as shown in figure 15.9(b). There is a upward magnetic field through the loop, but the magnetic field is decreasing as the magnet is moving away. Thus, the induced magnetic field of the loop opposes this decrease, therefore, the induced field needs to point in the upward direction, the induced current is counter clockwise (ccw) as seen from above.

Similar effects can also be observed with the south pole of a magnet pushed in and out of the loop figure 15.9(c,d). It is seen that the induced current sets up a magnetic field of its own. From the above discussion, it is clear that the motion of magnet is always opposed by the magnetic field generated from induced current. The mechanical energy spent in overcoming this opposition is converted into electrical energy.

If the induced current were in the opposite direction, the magnetic force would have accelerated it with no external energy source, even though electric energy would have been dissipated in the circuit. This would have been a clear violation of the law of conservation of energy, which doesn't happen in nature.

15.6 AC GENERATOR

Electricity generator is a device that converts mechanical energy into electrical energy. The principle of electromagnetic induction can be used to generate electricity for practical purposes.

In essence, electric generator is an electric motor operated in reverse. If the armature of DC motor is rotated we would get the DC output at the brushes which can be used. However, to produce AC (the current which changes polarity and reverses the flow of charge) some modifications needs to be made to the system.

The basic elements of an AC generator are shown in Figure 15.10. It consists of a coil mounted on a rotor shaft and placed between poles of a permanent magnet. The coil is mechanically rotated by some external means. The rotation of the coil causes the magnetic field to change through it, so an emf is induced in the coil. The ends of the coil are connected to an external circuit by means of circular rings called slip rings and brushes (usually graphite). As the coil rotates, the magnitude and direction of the induced emf changes. Therefore, this current is called alternating current and the generator is called alternating current generator.

Figure 15.10 - *AC Generator*

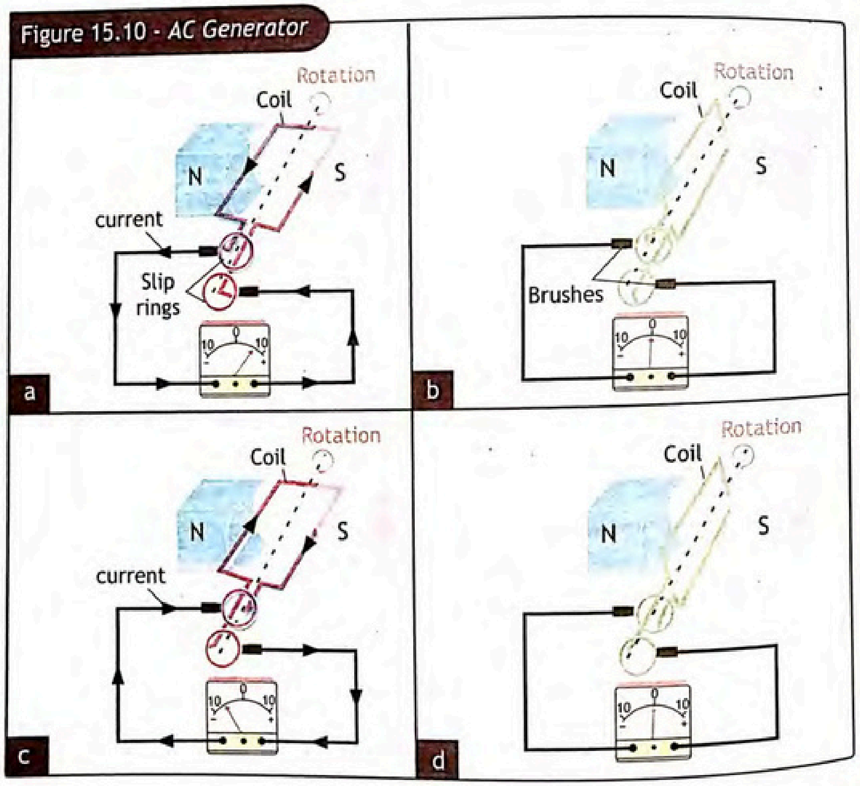
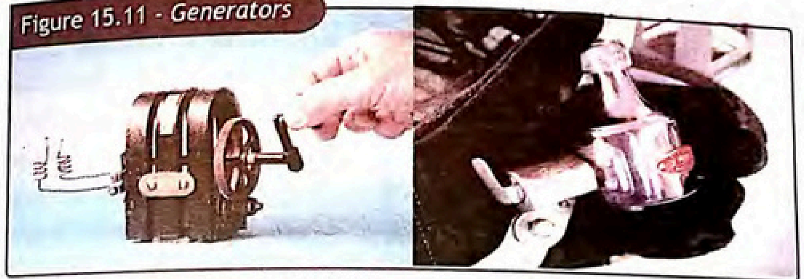


Figure 15.11 shows a coil rotated in a magnetic field of permanent magnet to light a bulb. A bicycle dynamo is also depicted. The AC generator and DC generator are the same, only the slip ring is replaced with commutator (split ring) for DC generator. The DC Generator produces current whose magnitude changes continuously but whose direction remains the same.

Figure 15.11 - *Generators*



(a) Coil rotation in magnetic field (b) Bicycle dynamo

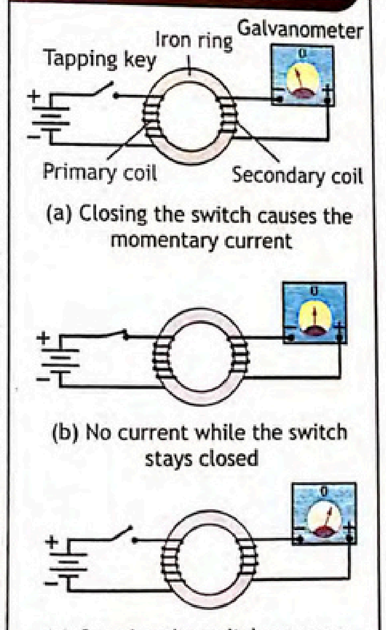
15.7 MUTUAL INDUCTION

The phenomena in which the emf induced in one circuit or coil due to the change in current in another circuit or coil is called mutual induction.

We have seen that an emf can be induced in a coil by keeping the coil stationary and moving a magnet nearby or by moving the coil near a stationary magnet. With another experiment, we can show that this relative motion is not an absolute requirement.

Consider two fixed coils placed side by side as shown in the figure 15.12, the coil that is connected to a battery is called primary coil, while the coil that has no source of emf is called secondary coil. Both are wound on an iron ring core well insulated from coils. The iron core is used only to increase the magnetic field produced.

Figure 15.12 - *Mutual Induction*



(a) Closing the switch causes the momentary current

(b) No current while the switch stays closed

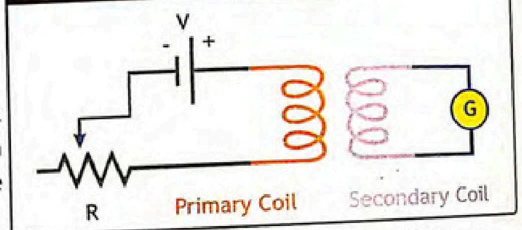
(c) Opening the switch causes a current in the opposite direction

The primary coil is connected to a battery through a tapping key, while the secondary coil is connected to galvanometer. It is observed that the galvanometer shows a momentary deflection when the tapping key 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 momentary deflection is observed again but in the opposite direction.

From this experiment, we can conclude that it is not the relative motion but the change in magnetic field that is responsible for electromagnetic induction. When the tapping key was pressed the magnetic field developed by primary coil was changed due to change in current per unit time which induced an emf in secondary coil.

Such that for a constantly changing current such as AC the time rate of change of current in the primary $\Delta I_P/\Delta t$ is proportional to the emf induced in the secondary ε_S. Mathematically,

Figure 15.13 - *Mutual Induction*



$$\varepsilon_S \propto -\frac{\Delta I_P}{\Delta t} \quad (1)$$

Where negative sign tells us that the induced current is always in opposite direction to the original current flow.

To change the sign of proportionality into equality, equation 1 can be written as

$$\varepsilon_S = -\text{Constant} \times \frac{\Delta I_P}{\Delta t} \quad \text{or} \quad \varepsilon_S = -M \times \frac{\Delta I_P}{\Delta t} \quad (2)$$

Where M is the constant of proportionality and is called as coefficient of Mutual induction. The Coefficient of mutual induction from equation 2 can therefore be written as

$$M = \frac{\varepsilon_S}{\Delta I_P / \Delta t} \quad \boxed{15.3}$$

The units of mutual induction is Henry (H). Mutual inductance of two coils will be one henry (H), if the current is changing at the rate of one ampere per second in the primary and causes an induced emf of one volt in the secondary.

$$1H = \frac{1V \times 1s}{1A} = \frac{Vs}{A}$$

EXAMPLE 15.2: INDUCED EMF

If the mutual inductance of two coils is 3.5 mH and the current through primary coil changes from 0 A to 10 A in 0.03 s, how much emf is induced in the secondary coil.

GIVEN

Mutual inductance 'M' = 3.5 mH = 3.5×10^{-3} H

Initial current 'I_i' = 0 A

Final current 'I_f' = 10 A

Time taken for change 'Δt' = 0.03 s

REQUIRED

Induced emf in secondary 'ε_s' = ?

SOLUTION: The emf induced in the secondary coil is given by the equation

$$\varepsilon_S = -M \times \frac{\Delta I_P}{\Delta t} \quad \text{or} \quad \varepsilon_S = -M \times \frac{I_f - I_i}{\Delta t}$$

Putting values $\varepsilon_S = -3.5 \times 10^{-3} H \times \dfrac{10A - 0A}{0.03s}$

or $\varepsilon_S = -3.5 \times 10^{-3} \dfrac{V\cancel{s}}{\cancel{A}} \times \dfrac{10\cancel{A}}{0.03\cancel{s}}$

Hence $\varepsilon_S = -1.17\,V$ — **Answer**

Thus the emf induced in the secondary coil is 1.17 V.

ASSIGNMENT 15.2: MUTUAL INDUCTANCE

If the current through the primary coil changes from 0 A to - 10 A in 0.02 s, such that the induced emf is 4.3 V. What is the mutual inductance?

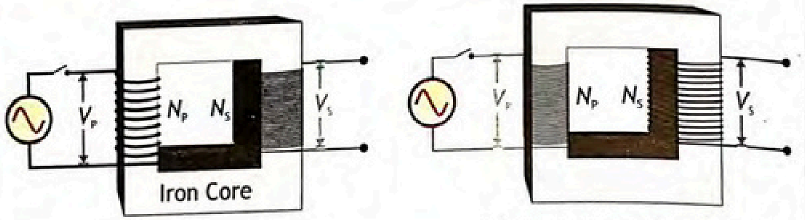
15.8 TRANSFORMER

A transformer is a device which is used to increase or decrease an AC voltage or current level. The principle of transformer is mutual induction. Changing current (alternating current) in one coil induces emf in another coil.

The key components of the transformer are two coils or windings, electrically insulated from each other but wound on the same core. The core is typically made of a material which supports magnetism, such as iron. This makes almost all of these field lines pass through to the other winding, maximizing the mutual inductance of the two windings.

The winding to which power is supplied is called the primary; the winding from which power is drawn is called the secondary.

Figure 15.14 - Step-up and step-down transformers



(a) Step-up transformer (b) Step-down transformer

Figure 15.14 shows a drawing of a transformer. The transformer consists of an iron core on which two coils are wounded: a primary coil with N_p turns and a secondary coil with N_s turns. If the voltage in the secondary is V_S and voltage in primary is V_p then

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} \qquad (15.4)$$

According to the equation 15.4, if N_S is greater than N_P ($N_S > N_P$), the secondary (output) voltage is greater than the primary (input) voltage ($V_S > V_P$). In this case we have a **step-up** transformer. On the other hand, if N_S is less than N_P ($N_S < N_P$), the secondary voltage is less than the primary voltage ($V_S < V_P$), and we have a **step-down** transformer. The ratio N_S / N_P is referred to as the **turns ratio** of the transformer.

EXAMPLE 15.3: X-RAY UNIT

A portable x-ray unit has a step-up transformer, the 220 V input of which is transformed to the 100 kV output needed by the x-ray tube. The primary has 50 loops, what is the number of loops in the secondary?

GIVEN

Primary voltage 'V_p' = 220 V

Secondary voltage 'V_s' = 100 kV = 10^5 V

Number of turns in the primary 'N_p' = 50

REQUIRED

Number of turns in the secondary 'N_s' = ?

SOLUTION: By transformer equation $\frac{V_S}{V_P} = \frac{N_S}{N_P}$ or $N_S = \frac{V_S}{V_P} \times N_P$

Putting values $N_S = \frac{10^5 V}{220 V} \times 50 turns$

Hence $N_S = 2.27 \times 10^4$ *turns* —— Answer

Therefore, a large number of loops in the secondary (compared with the primary) is required to produce such a large voltage.

EXTENSION EXERCISE 15.2

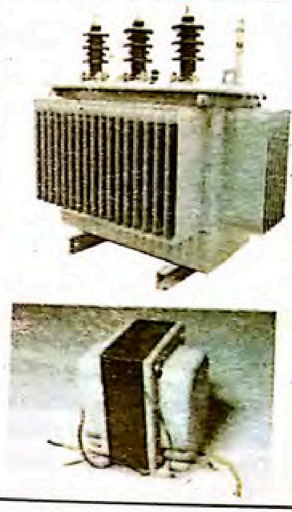
What is the turns ratio of transformer in X-ray tube?

ASSIGNMENT 15.3 : STEP UP TRANSFORMER

A step-up transformer has a primary coil consisting of 200 turns and a secondary coil consisting of 3000 turns. The primary coil is supplied with an effective AC voltage of 90.0 V. What is the voltage in the secondary circuit?

15.8.1 Purpose of Transformers: Transformers allow electricity to be efficiently transmitted over long distances. Whenever electricity is transmitted, there is always some loss of power in the transmission lines themselves due to resistive heating. To reduce the loss, power companies use transformers that step up the voltage to high levels while reducing the current. A smaller current means less power loss, since $P = I^2R$, where R is the resistance of the transmission wires. figure 15.16 shows one possible way of transmitting power.

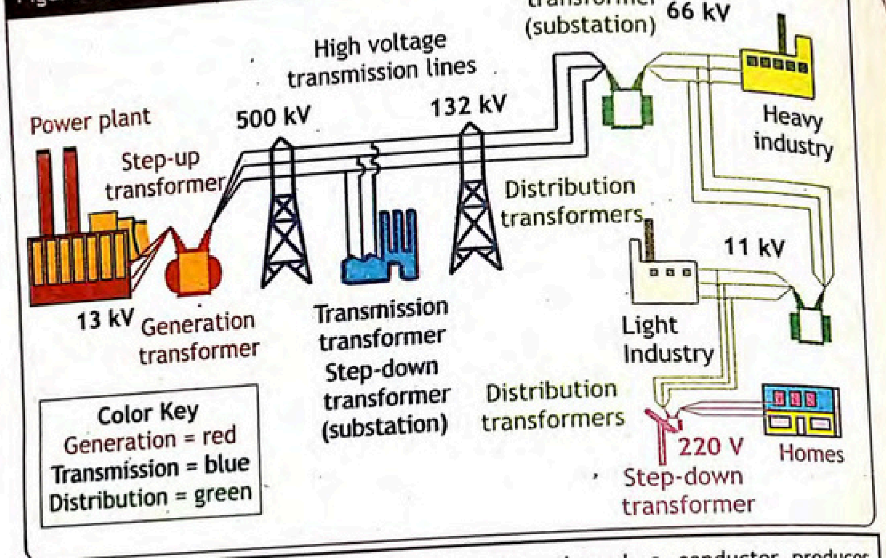
Figure 15.15 - Transformers



The power plant produces a voltage of 13,000 V. This voltage is then raised to 500,000 V by a 40: 1 step-up transformer. The high-voltage power is sent over the long-distance transmission line.

Upon arrival at the city, the voltage is reduced to about 11000 V at a substation using a step-down transformer. However, before any domestic use, the voltage is further reduced to 240 V by another step-down transformer that is often mounted on a utility pole.

Figure 15.16 - Transmission of Power



KEY POINTS

Magnetic effect of current: Electric current through a conductor produces magnetic field around it. In case of straight wire, it is in the form of concentric circles.

Force on a current carrying conductor in a magnetic field: When a current carrying conductor is placed in a magnetic field, the interaction between the moving charges in the current and the external magnetic field causes it to experience a force.

Torque on a current carrying coil in a magnetic field: When a current carrying coil is placed in a magnetic field, it experiences a couple due to which it begins to rotate.

DC Motor: Converts electrical energy into mechanical energy by principle of torque on a current carrying coil in a magnetic field.

Electromagnetic induction: *When a magnetic field through a loop of wire is changed, current is found to flow in the loop.* The direction of this induced e.m.f opposes the change causing it.

AC Generator: Simple form of AC generator consists of a coil which is made to rotate in external magnetic field and by principle of electro magnetic induction alternating voltage is induced.

Mutual induction: Emf induced in one circuit due to changing current in another circuit which is magnetically attached/coupled with it.

Transformer: A device which converts low voltage to high voltage vice versa.

PROJECTS

GROUP A 'ELECTROMAGNET': Build an electromagnet as an activity in this chapter. See how much the strength of electromagnet change by changing the current flow by using different batteries or increasing the number of turns in the coil or having other core materials (such as pencil, steel nail etc.) instead of iron nail. Summerize your findings in an article for school magazine.

GROUP B 'MAGNETIC EFFECT OF CURRENT': Research the application of the magnetic effect of an electric current in relay, door latch, loudspeaker, and circuit breaker from the internet and school library, and present your findings in classroom.

GROUP C 'MAGNETISM AND TECHNOLOGY': Identify different technologies related to magnetism such as electric motors and generators, medical equipment, loudspeakers, magnetic information storage devices. Write its historical over view relating when, how and where these devices were first formed. Write an essay for school magazine.

GROUP D 'ELECTRIC MOTOR AND GENERATOR': Read literature and search how different motors and generators can be easily made. Build a simple DC Motor or AC Generator for your school laboratory.

GROUP E 'TRANSFORMERS': Make a list of the use of transformers (step-up and step-down) for various purposes in your home. Make a chart and display it in your classroom.

EXERCISE

MULTIPLE CHOICE

1. A current carrying wire in which current flow in northward direction is deflected towards the east by a magnetic force. The direction of the magnetic field is
   A. straight up   B. straight down   C. south   D. west.
2. Which derived unit is equivalent to tesla T?
   A. Nm/A   B. NA/m   C. N/Am   D. Am/N
3. The unit of inductance, the henry, is equivalent to:
   A. Vs/A   B. VA/m   C. As/V   D. V/A
4. When the speed at which a magnet is moved through a coil is increased, the induced voltage
   A. increases   B. remain the same   C. decreases   D. goes to 0
5. Slip rings are part of
   A. DC motor   B. AC generator   C. transformer   D. magnet

QUESTIONS

6. A transformer is used for
A. both DC and AC B. AC voltages C. DC voltages D. farming

7. A step-up transformer increases
A. power B. energy C. voltage D. current

8. A certain transformer has a primary winding with 500 turns and a secondary winding with 250 turns. The turns ratio is
A. 0.5 B. 2 C. 250 D. 750

9. If the turns ratio is 5, the secondary voltage is greater than the primary voltage by a factor of
A. 0.2 B. 0.5 C. 2.5 D. 5

CONCEPTUAL QUESTIONS

Give a brief response to the following questions

1. Differentiate between electric and magnetic fields.
2. Can an electron at rest be set into motion with a magnetic field?
3. Which is more likely to show deflection in compass needle, AC current or DC current? Explain.
4. A constant magnetic field is applied to a current carrying conductor. What angle should the wire make with the field for the force to be (a) maximum, (b) minimum?
5. Why does a compass needle points North?
6. How can a magnetic field be used to generate electric current?
7. What would happen if we use a slip ring to drive a DC motor?
8. The primary coil of a transformer is connected to a DC battery. Is there an emf induced in the secondary coil? Why?

COMPREHENSIVE QUESTIONS

Give an extended response to the following questions

1. Describe an experiment to show that the steady current carrying wire produces a magnetic field around it. What is the direction of this magnetic field?
2. How the magnetic field of wire increases and resembles more like that from a permanent magnet, if the wire is formed in a circular coil? [Hint: Consider the magnetic field of a single coil and then a series of coils.]
3. Explain the force on a current carrying wire in a magnetic field.

4. Explain the torque on current carrying coil in a magnetic field.
5. Explain the working of DC motor.
6. Describe the phenomena of electromagnetic induction. List the factors effecting electromagnetic induction.
7. Explain the direction of induced emf and show its relation to conservation of energy.
8. Sketch and describe the construction and working of AC generator.
9. Describe the phenomena of mutual induction.
10. What are transformers? On what principle it works? Also describe the purpose of transformers in AC circuits.

NUMERICAL QUESTIONS

1. A 1.5 m long wire carries a current of 5 A, at right angle to a uniform magnetic field of 0.04 T. Determine the force exerted on the wire.
2. A wire carrying a direct current of 10.0 A is suspended 5.0 m east between a house and a garage perpendicular to the Earth's magnetic field of 5.0×10^{5} T. What is the magnitude of the force that acts on the conductor?
3. A 10 cm wire at 30° to uniform magnetic field of 0.06 T is exerted by a force of 0.024 N. What is the current flowing through the wire?
4. If the current through the primary coil changes from -5 A to +5 A in 0.05 s, such that the induced emf is 2.8 V. What is the mutual inductance?
5. A transformer connected to a 120-V AC line is to supply 9600 V for a neon sign. (a) What is the ratio of secondary to primary turns of the transformer? (b) If the transformer consisted of 275 primary windings, how many secondary windings would there be?
6. How many turns would you want in the secondary coil of a transformer having 400 turns in the primary, if it were to reduce the voltage from 220 V AC to 3.0 V AC?
7. A transformer steps down a main supply of 220 V AC to operate a 12 V AC lamp. Calculate the turns ratio of the windings.