Electromagnetism is the study of magnetic effects of current. The use of electromagnetism in different fields of science and technology is very wide. Motors and electric meters are based on the effect of magnetism produced by the electric current in wires. Generators produce electric current due to the movement of wires near very large magnets.

**Interesting information**

Electric charges can be separated into a single type. For example, you can have a single negative charge or a single positive charge. Magnetic poles cannot be separated. It is not possible to have a magnetic north pole without a magnetic south pole. This is a fundamental difference between magnetism and electricity.

## 15.1 MAGNETIC EFFECTS OF A STEADY CURRENT

Ampere discovered that when a current passes through a conductor, it produces magnetic field around it. To demonstrate this, we take a straight conductor wire and pass it vertically through a cardboard (Fig.15.1-a). Now connect the two ends of the conductor wire with the terminals of the battery so that current flows through the circuit in the clockwise direction. The lines of force of the magnetic field produced around the wire would be in the form of concentric circles. If we place a compass needle at different points in the region of magnetic field, it will align along the direction of magnetic field. Also if we sprinkle some iron filings on the cardboard around the wire, they will align themselves in concentric circles in the clockwise direction.

**For your information**

Weak ionic current in our body that travels along the nerve can produce the magnetic effect. This forms the basis of obtaining images of different parts of body. This is done using the technique called Magnetic Resonance Imaging (MRI). Heart and brain are two main organs where significant magnetic fields can be produced. Using MRI doctors can diagnose the disorders of brain and heart etc.

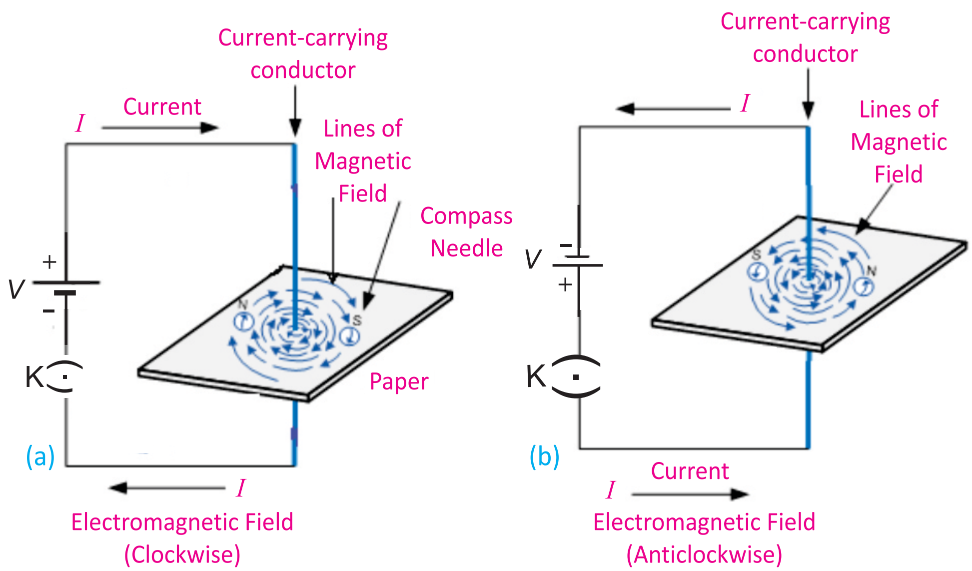



Fig. 15.1

If we reverse the direction of the current by reversing the terminals of the battery, the compass needle also reverses its direction. Now the magnetic field lines will align in the anticlockwise direction (Fig.15.1-b). The magnetic field produced is stronger near the current-carrying conductor and weaker farther away from it.

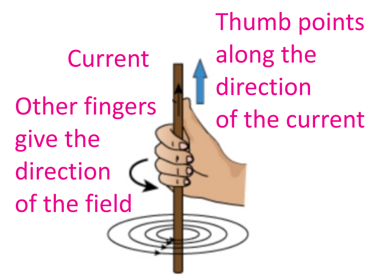



**Fig.15.2:** Right hand grip rule

## Direction of magnetic field

The direction of the magnetic field is governed by the direction of the current flowing through the conductor. A simple method of finding the direction of magnetic field around the conductor is the Right Hand Grip Rule.

*Grasp a wire with your right hand such that your thumb is pointed in the direction of current. Then curling fingers of your hand will point in the direction of the magnetic field.*

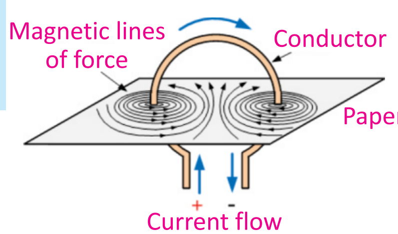



**Fig.15.3**

**Activity 15.1:** Take a straight piece of wire and bend it in the form of a single loop. Now pass it through a cardboard having two holes. Connect the ends of loop to a battery so that a current starts flowing through it (Fig.15.3). Now sprinkle some iron filings on the cardboard. Note the pattern of the iron filings formed on the cardboard. Do the magnetic field lines between the two parts of the loop resemble to that of the bar magnet?

## Magnetic field of a solenoid

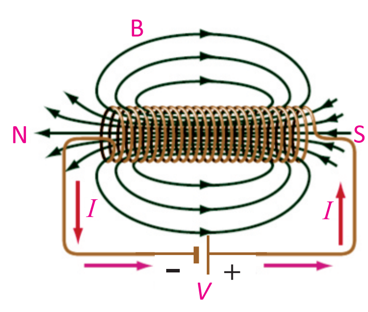



**Fig. 15.4:** Magnetic field due to a solenoid

A coil of wire consisting of many loops is called a solenoid (Fig.15.4). The field from each loop in a solenoid adds to the fields of the other loops and creates greater total field strength. Electric current in the solenoid of wire produces magnetic field which is similar to the magnetic field of a permanent bar magnet. When this current-carrying solenoid is brought close to a suspended bar magnet, one end of the solenoid repels the north pole of the bar magnet. Thus, the current-carrying solenoid has a north and a south pole and behaves like a magnet.

*The type of temporary magnet, which is created when current flows through a coil, is called an electromagnet.*

The direction of the field produced by a coil due to the flow of conventional current can be found with the help of right hand grip rule (Fig.15.5) stated as

*If we grip the coil with our right hand by curling our fingers in the direction of the conventional current, our thumb will indicate the north pole of the coil.*

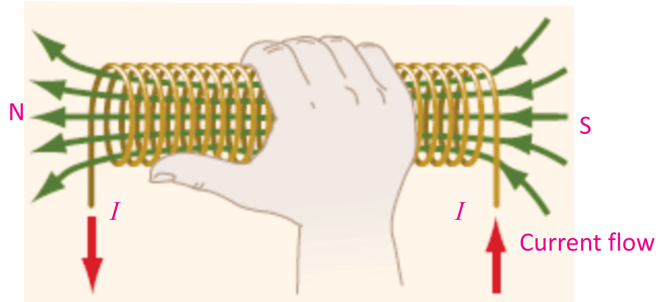
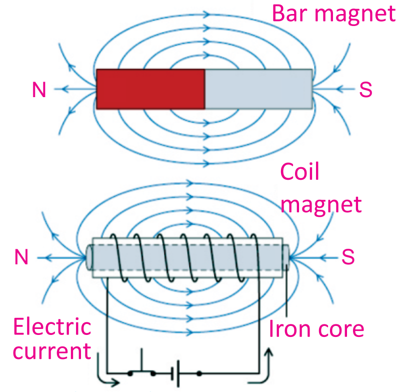



**Fig. 15.5:** Right hand grip rule for a coil

**For your information**




Similarity between magnetic fields of a bar magnet and that of a coil.

## 15.2 FORCE ON A CURRENT-CARRYING CONDUCTOR PLACED IN A MAGNETIC FIELD

We know that electric current produces a magnetic field similar to that of a permanent magnet. Since a magnetic field exerts force on a permanent magnet, it implies that current-carrying wire should also experience a force when placed in a magnetic field.

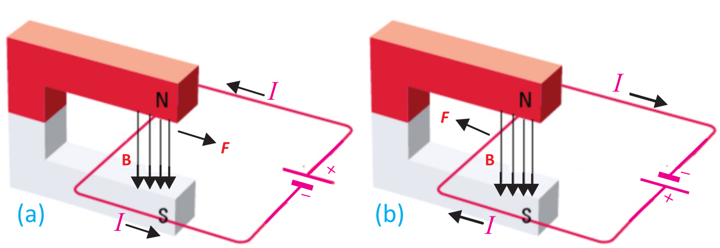
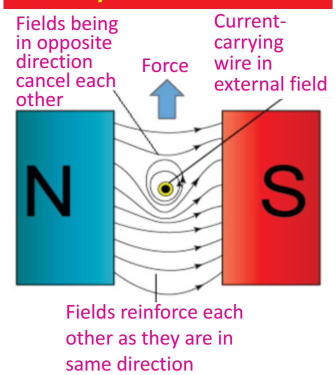



**Fig. 15.6:** Force on a current-carrying wire in magnetic field

The force on a wire in a magnetic field can be demonstrated using the arrangement shown in Fig. 15.6. A battery produces current in a wire placed inside the magnetic field of a permanent magnet. Current-carrying wire produces its own magnetic field which interacts with the field of the magnet. As a result, a force is exerted on the wire. Depending on the direction of the current, the force on the wire either pushes or pulls it towards right (Fig. 15.6-a) or towards left (Fig.15.6-b).

**For your information**



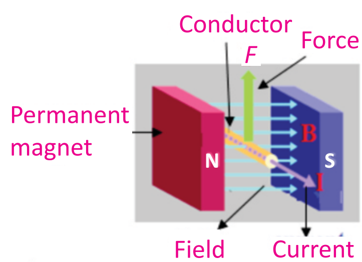

Michael Faraday discovered that the force on the wire is at right angles to both the direction of the magnetic field and the direction of the current. The force is increased if

- The current in the wire is increased
- Strength of magnetic field is increased
- The length of the wire inside the magnetic field is increased

## Determining the direction of force

Faraday's description of the force on a current-carrying wire does not completely specify the direction of force because the force can be towards left or towards right. The direction of the force on a current-carrying wire in a magnetic field can be found by using Fleming's left hand rule stated as:

*Stretch the thumb, forefinger and the middle finger of the left hand mutually perpendicular to each other. If the forefinger points in the direction of the magnetic field, the middle finger in the direction of the current, then the thumb would indicate the direction of the force acting on the conductor.*



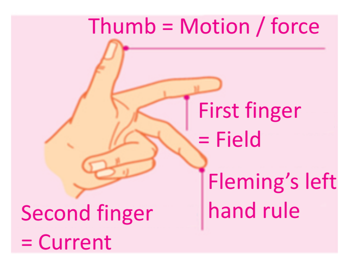




**Fig. 15.7:** Direction of force on a current-carrying conductor placed in a magnetic field

As shown in Fig. 15.7, the force acting on the conductor is at right angles to both the directions of current and magnetic field according to Fleming's left hand rule.

## 15.3 TURNING EFFECT ON A CURRENT-CARRYING COIL IN A MAGNETIC FILED

If instead of a straight conductor, we place a current-carrying loop inside the magnetic field, the loop will rotate due to the torque acting on the coil. This is also the working principle of electric motors. Consider a rectangular coil of wire with sides PQ and RS, lying perpendicular to the field, placed between the two poles of a permanent magnet (Fig. 15.8). Now if the ends of the coil are connected with the positive and negative terminals of a battery, a current would start flowing through the coil. The current passing through the loop enters from one end of the loop and leaves from the other end.

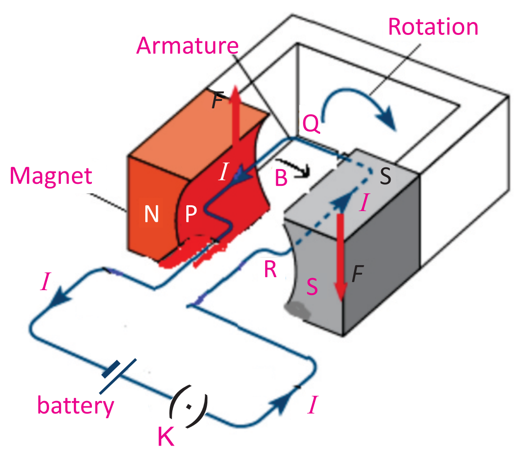



**Fig. 15.8:** A current-carrying coil in a magnetic field

Now apply Fleming's left hand rule to each side of the coil (Fig. 15.8). We can see that on PQ side of the loop force acts upward, while on the RS side of the loop force acts downward. It is because the direction of the current through the two sides of the loop facing the two poles is at right angles to the field but opposite to each other. The two forces which are equal in magnitude but opposite in direction form a couple. The resulting torque due to this couple rotates the loop, and the magnitude of the torque acting on the loop is proportional to the magnitude of the current passing through the loop. If we increase the number of loops, the turning effect is also increased. This is the working principle of electric motors.

**Activity**

Suppose direction of current passing through two straight wires is same. Draw the pattern of magnetic field of current due to each wire. Would the wires attract or repel each other?

## 15.4 D. C. MOTOR

We can see from Fig. 15.9 that the simple coil placed in a magnet cannot rotate more than 90°. The forces push the PQ side of the coil up and the RS side of the loop down until the loop reaches the vertical position. In this situation, plane of the loop is perpendicular to the magnetic field and the net force on the coil is zero. So the loop will not continue to turn because the forces are still up and down and hence balanced.

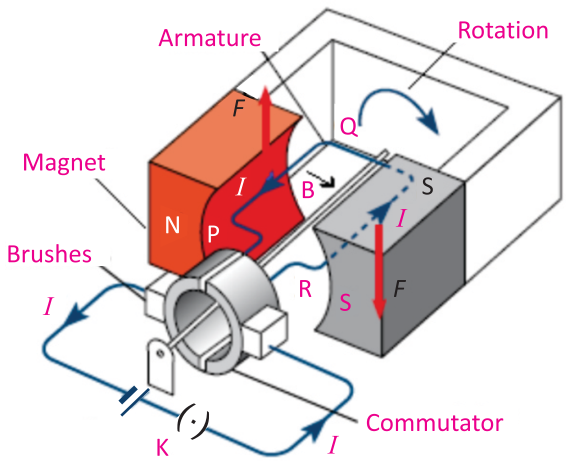



**Fig. 15.9:** Working principle of D.C motor

**Do you know?**

Bank credit cards have a magnet strips engraved on them. On this strip account information of the user are stored which are read by the ATM machine.

How can we make this coil to rotate continuously? It can be done by reversing the direction of the current just as the coil reaches its vertical position. This reversal of current will allow the coil to rotate continuously**.** To reverse direction of current, the connection to coil is made through an arrangement of brushes and a ring that is split into two halves, called a split ring commutator (Fig. 15.9). Brushes, which are usually pieces of graphite, make contact with the commutator and allow current to flow into the loop. As the loop rotates, so does the commutator. The split ring is arranged so that each half of the commutator changes brushes just as the coil reaches the vertical position. Changing brushes reverse the current in the loop.

As a result, the direction of the force on each side of the coil is reversed and it continues to rotate. This process repeats at each half-turn, causing coil to rotate in the magnetic field continuously. The result is an **electric**

**motor,** which is a device that converts electric energy into rotational kinetic energy.

In a practical electric motor, the coil, called the **armature,** is made of many loops mounted on a shaft or axle. The magnetic field is produced either by permanent magnets or by an electromagnet, called a field coil. The torque on the armature, and, as a result, the speed of the motor, is controlled by varying the current through the motor.
The total force acting on the armature can be increased by

- Increasing the number of turns of the coil
- Increasing the current in the coil
- Increasing the strength of the magnetic field
- Increasing the area of the coil

**CONNECTION:**
Magnetic field lines help us to visualize the magnitude and direction of the magnetic field vectors, just as electric field lines do for the magnitude and direction of **E.**

## 15.5 ELECTROMAGNETIC INDUCTION

Hans Christian Oersted and Ampere discovered that an electric current through a conductor produces a magnetic field around it. Michael Faraday thought that the reverse must also be true; that a magnetic field must produce an electric current. Faraday found that he could induce electric current by moving a wire through a magnetic field. In the same year, Joseph Henry also showed that a changing magnetic field could produce electric current. Now we shall discuss Faraday's experiments for the production of e.m.f. in magnetic field.
The strength of magnetic field is defined as the number of magnetic lines of force passing through any surface. The number of lines of force is maximum when the surface is held perpendicular to the magnetic lines of force (Fig.15.10). It will be minimum when surface is held parallel to the magnetic lines of force (Fig.15.11). If we place a coil in the magnetic field of a bar magnet, some of the magnetic lines of force will pass through it. If the coil is far away from the magnet, only a few lines of force will pass through the coil (Fig.15.12-a). However, if the coil is close to the magnet, a large number of lines of force will pass through it (Fig.15.12-b).

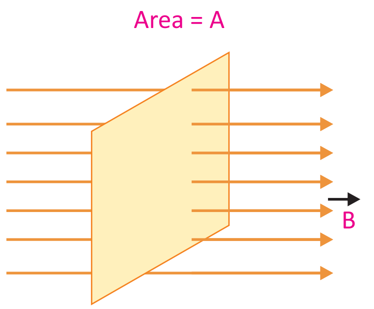



**Fig.15.10:** Maximum strength of magnetic field

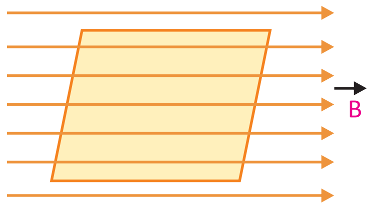



**Fig 15.11:** Minimum strength of magnetic field

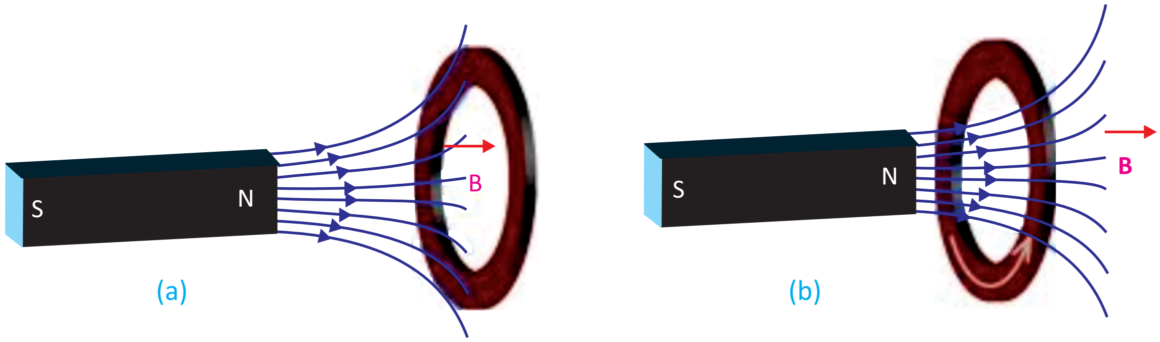



Fig. 15.12: Variation of magnetic field lines of force through a coil placed at different distances from the magnet

This means, we can change the number of magnetic lines of force through a coil by moving it in the magnetic field. This change in the number of magnetic field lines will induce an e.m.f. in the coil. This is the basic principle of the production of electricity.

**Physics fact**

It is said; Joseph Henry (1797–1878) had observed an induced current before Faraday, but Faraday published his results first and investigated the subject in more detail.

**Activity 15.2:** Take a rectangular loop of wire and connect its two ends with a galvanometer. Now hold the wire stationary or move it parallel to the magnetic field of a strong U-shaped magnet. Galvanometer shows no deflection and hence there is no current. Now move the wire downward through the field, current is induced in one direction as shown by the deflection of the galvanometer (Fig. 15.13-a). Now move the wire upward through the field, current is induced in the opposite direction (Fig. 15.13-b).

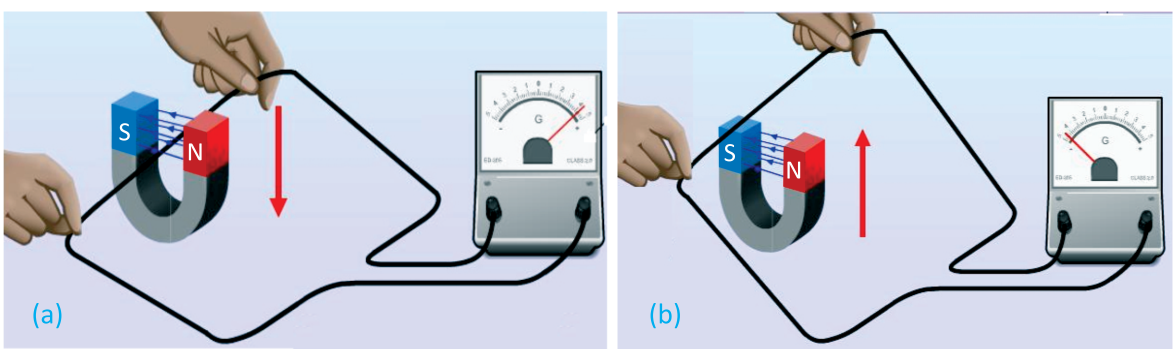



Fig. 15.13: Demonstration of electromagnetic induction by the movement of a wire loop in the magnet field

It implies that an electric current is generated in a wire only when the wire cuts magnetic field lines. This induced current is generated by the induced e.m.f. in the circuit. Faraday found that to generate current, either the conductor must move through a magnetic field or a magnetic field must change across the conductor. Thus,

***The process of generating an induced current in a circuit by changing the number of magnetic lines of force passing through it is called electromagnetic induction.***

**Activity 15.3:** Fig. 15.14 shows one of Faraday's experiments in which current is induced by moving a magnet into the solenoid or out of the solenoid. When the magnet is stationary, no current is induced. When the magnet is moved towards the solenoid, the needle of galvanometer deflects towards right, indicating that a current is being induced in the solenoid (Fig.15.14-a). When the magnet is pulled away from the solenoid, the galvanometer deflects towards left, indicating that the induced current in the solenoid is in the opposite direction (Fig.15.14-b).

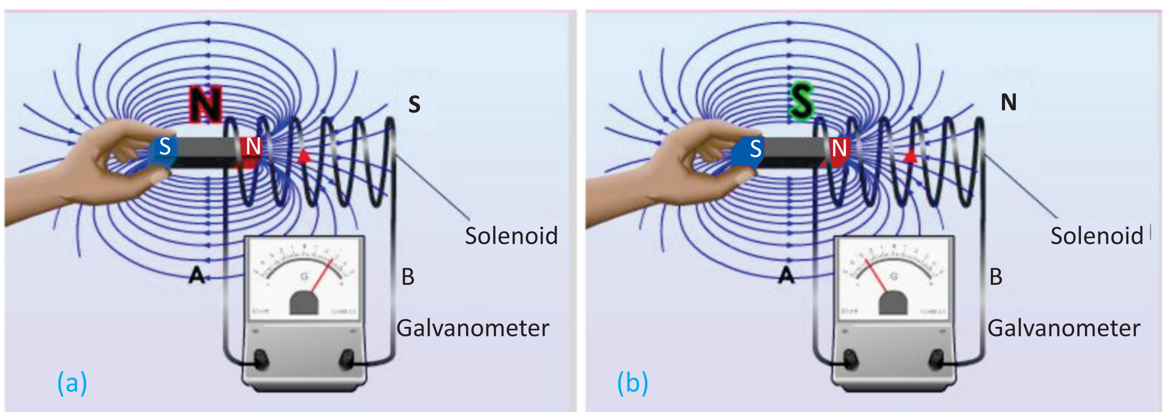



**Fig. 15.14:** Phenomenon of electromagnetic induction by the movement of a magnet through solenoid. (a) Magnet moves towards the stationary solenoid (b) Magnet moves away from the stationary solenoid

From the above experiments, we conclude that an e.m.f. is induced in the coil when there is a relative motion between the coil and the magnet. This phenomenon in which an e.m.f. is induced due to the relative motion between the coil and the magnet is called electromagnetic induction.

*The value of induced e.m.f. in a circuit is directly proportional to the rate of change of number of magnetic lines of force through it.*

This is called Faraday's law of electromagnetic induction.

**Factors Affecting Induced e.m.f**

The magnitude of induced e.m.f. in a circuit depends on the following factors:

1. Speed of relative motion of the coil and the magnet
2. Number of turns of the coil

## 15.6 Direction of induced e.m.f. – Lenz's Law

Lenz devised a rule to find out the direction of a current induced in a circuit. It is explained from the following activity:

**Activity 15.4:** If we bring a north pole of a bar magnet near a solenoid, an e.m.f. will be induced in the solenoid by electromagnetic induction (Fig. 15.15-a). The direction of the induced current in the solenoid by the induced e.m.f. will be such that it will repel the north pole of the magnet. This is only possible if the right end of the solenoid becomes a north pole. Hence, according to right hand grip rule, the direction of the induced current in the solenoid will be clockwise. Similarly, when we move the north pole of the magnet away from the solenoid, the direction of the induced current will be anticlockwise (Fig.15.15-b). In this case, left end of solenoid becomes south pole.

**Direction of induced current**

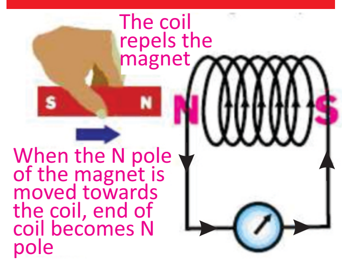



**Fig.15.15 (a)** Direction of induced current when magnet is moved towards the coil

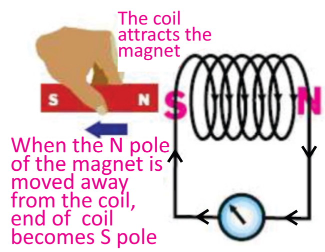



**Fig.15.15 (b)** Direction of induced current when magnet is moved away from the coil

*The direction of an induced current in a circuit is always such that it opposes the cause that produces it.*

If we apply the law of conservation of energy to electromagnetic induction, we realize that the electrical energy induced in a conductor comes from the kinetic energy of the moving magnet. We do some work on the magnet to bring it close to the solenoid. This work consequently appears as electrical energy in the conductor. Thus, mechanical energy of our hand used to push the magnet towards or away from the coil results into electrical energy. Hence, Lenz's law is a manifestation of the law of conservation of energy.

## 15.7 A.C. GENERATOR

If a coil is rotated in a magnetic field, a current will be induced in the coil. The strength of this induced current depends upon the number of magnetic lines of force passing through the coil. The number of lines of magnetic force passing through the coil will be maximum when the plane of the coil is perpendicular to the lines of magnetic force. The number of lines of magnetic force will be zero when plane of the coil is parallel to the lines of force. Thus, when a coil rotates in a magnetic field, the induced current in it continuously changes from maximum to minimum value and from minimum to maximum value and so on. This is the basic principle on which an A.C generator works (Fig. 15.16).

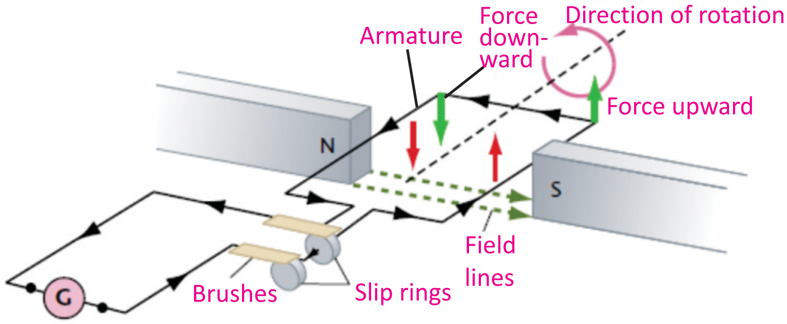



**Fig. 15.16:** A.C Generator

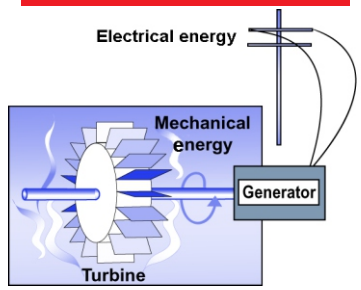
The armature is arranged so that it can rotate freely in the magnetic field. As the armature turns, the wire loops cut through the magnetic field lines and induced e.m.f. will be produced. The e.m.f. developed by the generator depends on the length of the wire rotating in the field. Increasing the number of loops in the armature, increases the wire length, thereby increasing the induced e.m.f

### Current from a generator

When a generator is connected in a closed circuit, the induced *e.m.f.* generates an electric current. As the loop rotates, the strength and the direction of the current changes as shown in Fig. 15.17.

When the plane of will is perpendicular to field, the number of lines of magnetic force passing the trough it is maximum. Butt the change in the number of line through the coil is minimum. So e.m.f. induced is minimum.

**Do you know?**




A generator inside a hydroelectric dam uses electromagnetic induction to convert mechanical energy of a spinning turbine into electrical energy.

**Michael Faraday (1791-1867)**

Michael Faraday was a British chemist and physicist. At the early stage of his age, he had to work as a book binder to meet his financial needs. There he learnt a lot from the books that helped him to become an expert. Although Faraday received little formal education. He was one of the most influential scientists in history, and was one of the best experimentalist in the history of science. He discovered the principle of electromagnetic induction and the laws of electrolysis etc.

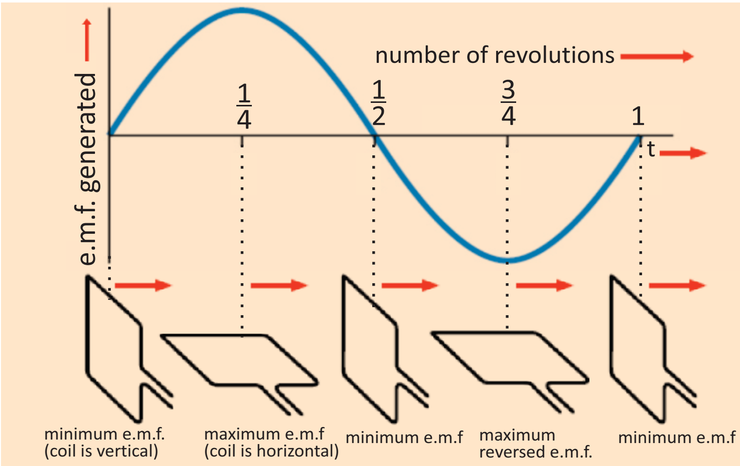



**Fig. 15.17:** e.m.f. Vs time for AC generator

The current is minimum when the plane of the loop is perpendicular to the magnetic field; that is, when the loop is in the vertical position. As the loop rotates from the vertical to the horizontal position, it cuts through larger magnetic field lines per unit of time, thus the e.m.f and the current increase. When the loop is in the horizontal position, the plane of the loop becomes parallel to the field, so the e.m.f and the current reaches its maximum value. As the loop continues to turn, the segment that was moving up begins to move down and reverses the direction of the e.m.f and the current in the loop. This change in direction takes place each time the loop turns through 180°. Thus, the e.m.f and the current change smoothly from zero to some maximum values and back to zero during each half-turn of the loop.

**Connection:**

A generator is a d.c motor with its input and output reversed.

**For your information**

Walk-through metal detectors are installed at airports and other places for security purpose. These detectors detect metal weapons etc. using the principle of electromagnetic induction.

## 15.8 MUTUAL INDUCTION

*The phenomenon of production of induced current in one coil due to change of current in a neighboring coil is called mutual induction.*

Suppose a system of two coils A and B placed close to each other (Fig.15.18). The coil A is connected to a battery and a switch, while a sensitive galvanometer is connected to the coil B. We observe that as soon as the switch of the coil A is closed, the galvanometer shows a momentary deflection.

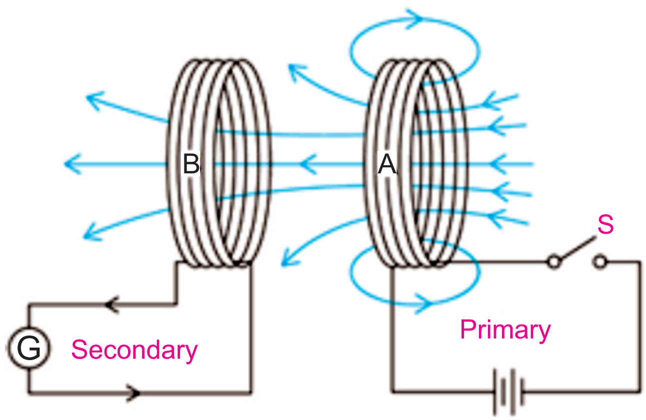
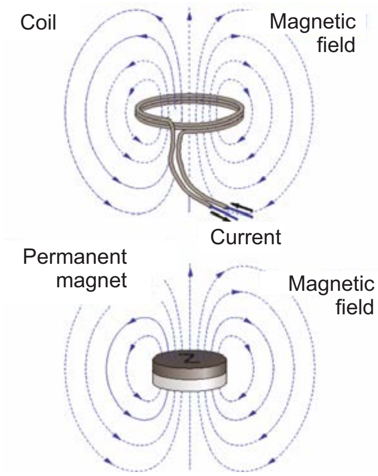



**Fig.15.18:** Mutual induction

Similarly, when the switch is opened, the galvanometer again shows a deflection but this time its direction is opposite to that of the previous case.

We can explain these observations using Faraday's law of electromagnetic induction. When the switch of coil A is closed, a current begins to flow in the coil due to which magnetic field is developed across the coil. Some of the magnetic lines of force of this field start passing through the coil B. Since current is changing in the coil A, hence number of magnetic lines of force across the coil B also changes due to which a current is induced in the coil B in accordance with Faraday's law. When current in the coil A becomes steady, number of magnetic lines of force across the coil A also becomes constant. Therefore, there is no more change in number of magnetic lines of force through the coil B due to which induced current in coil B reduces to zero.
Similarly, when the switch of the coil A is opened, the flow of current through it stops and its magnetic field reaches to zero. The number of magnetic lines of force through the coil B decreases to zero due to which current is again induced in it but in opposite direction to that in the previous case.

**Do you know?**




The magnetic field of a coil is identical to the field of a disk shaped permanent magnet.

## 15.9 TRANSFORMER

The transformer is a practical application of mutual induction. Transformers are used to increase or decrease AC voltages. Usage of transformers is common because they change voltages with relatively little loss of energy. In fact, many of the devices in our homes, such as game systems, printers, and stereos use transformers for their working.

### Working of a transformer

A transformer has two coils, electrically insulated from each other, but wound around the same iron core. One coil is called the primary coil. The other coil is called the secondary coil. Number of turns on the primary and the secondary coils are represented by $N_P$ and $N_S$ respectively.

When the primary coil is connected to a source of AC voltage, the changing current creates a changing magnetic field, which is carried through the core to the secondary coil. In the secondary coil, the changing field induces an alternating e.m.f.

The e.m.f. induced in the secondary coil, called the secondary voltage $V_S$, is proportional to the primary voltage $V_P$. The secondary voltage also depends on the ratio of the number of turns on the secondary coil to the number of turns on the primary coil, as shown by the following expression:

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

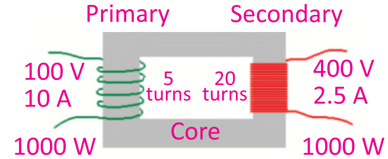



**Fig. 15.19 (a)** Step-up transformer

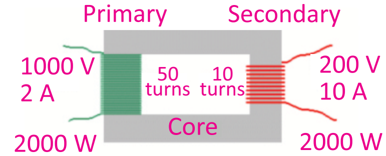



**Fig. 15.19 (b)** Step-down transformer

If the secondary voltage is larger than the primary voltage, the transformer is called a step-up transformer (Fig.15. 19-a). If the secondary voltage is smaller than the primary voltage, the transformer is called a step-down transformer (Fig.15. 19-b).

In an ideal transformer, the electric power delivered to the secondary circuit is equal to the power supplied to the primary circuit. An ideal transformer dissipates no power itself, and for such a transformer, we can write:

$$P_p = P_s$$
$$V_p I_p = V_s I_s$$

**Example 15.1:** If a transformer is used to supply voltage to a 12 V model train which draws a current of 0.8 A. Calculate the current in the primary if the voltage of the a.c. source is 240 V.

**Solution:** Given that, $V_p$ = 240 V

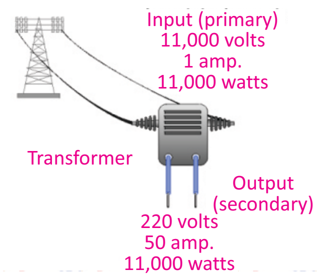
$V_s = 12$ V
$I_s = 0.8$ A
$I_p = ?$

By law of conservation of energy,
Input power of the primary = Output power of the secondary

i.e., $I_p V_p = I_s V_s$

Therefore, $I_p = \frac{I_s V_s}{V_p}$ or $I_p = \frac{(12\text{ V})(0.8\text{ A})}{240\text{ V}} = 0.04$ A

**Do you know?**




A high power transformer can reduce the voltage keeping the power constant.

## 15.10 HIGH VOLTAGE TRANSMISSION

Electric power is usually generated at places which are far from the places where it is consumed. The power is transmitted over long distances at high voltage to minimize the loss of energy in the form of heat during transmission. As heat dissipated in the transmission cable of resistance $R$ is $I^2Rt$. Hence, by reducing the current through the cable, power loss in the form of heat dissipation can also be reduced. So the alternating voltage is stepped up at the generating station.

It is then transmitted to the main sub-station. This voltage is stepped down and is transmitted to the switching transformer station or the city sub-station. At the city sub-station, it is further stepped down to 220 V and supplied to the consumers. A schematic diagram of high voltage transmission is shown in Fig. 15.20.

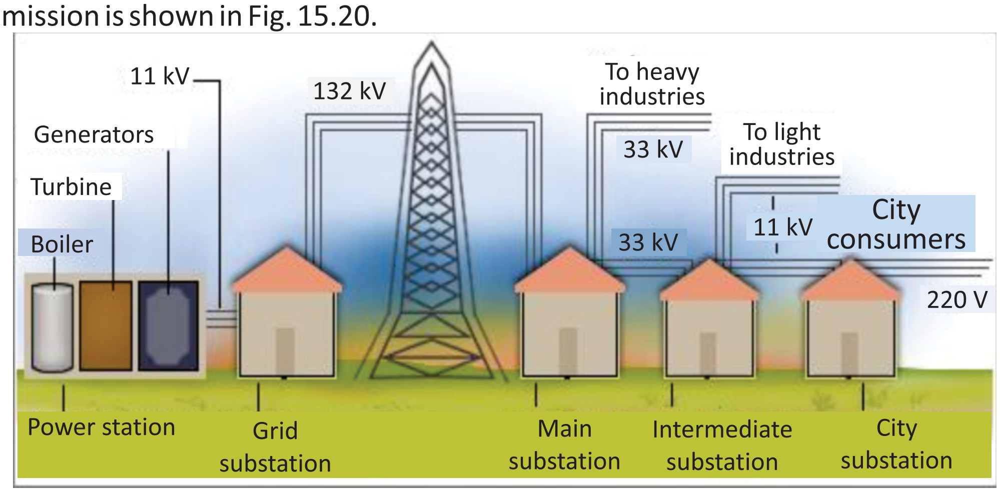



**Fig.15.20:** High voltage transmission

Transformers play an essential part in power distribution. Transformers work only with A.C. This is one reason why mains power is supplied as an alternating current.

## Applications of Electromagnet

Magnetic effect of current is called electromagnet. This effect is used in many devises like relay, electric bell, etc. Soft iron can easily be magnitized and demagnitized

## RELAY

The relay is used to control a large current with the help of a small current. A relay is an electrical switch that opens and closes under the control of another electrical circuit (Fig. 15.21). The 1st circuit (input circuit) supplies current to the electromagnet. The electromagnet is magnetized and attracts one end of the iron armature. The armature then closes the contacts (2nd switch) and allows current to flow in the second circuit. When the 1st switch is opened again, the current to the electromagnet stops. Now electromagnet loses its magnetism and the 2nd switch is opened. Thus, the flow of current stops in the 2nd circuit. Some other examples of the magnetic effect of an electric current are loudspeaker, circuit breaker and door latches.

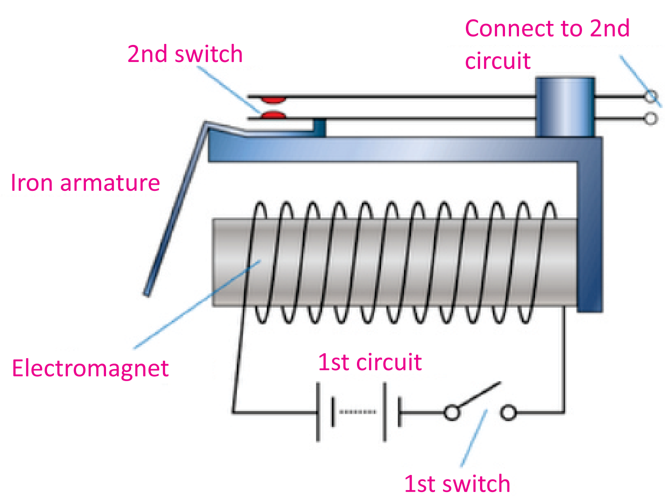



**Fig. 15.21:** Relay circuit