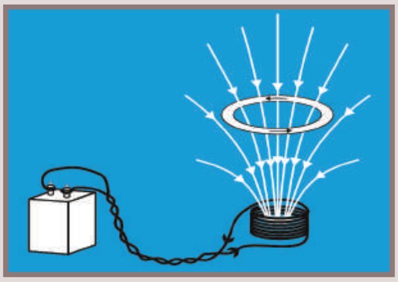
Chapter 10



Electromagnetism

In the previous chapter on 'Electricity' you have learnt about the heating effects of electric current. We use many electric appliances in our daily life such as electric motor, electric generators, electric calling bells, electric cranes etc.,

- How do they work?
- How do electromagnets work?
- Is there any relation between electricity and magnetism?
- Can we produce magnetism from electricity?

In this chapter we will study electromagnetic effects. We also study electric motors which involve magnetic effects of electric current and electric generator which involves electric effects of moving magnets.

Hans Christian Oersted (1777 - 1851) was one of the leading scientists of the 19th century, played a crucial role in understanding *electromagnetism*. He gave lectures which were quite popular among the public and also learnt a lot during the tours. During one such lecture in April 1820, Oersted carried out an experiment that was never performed before. He placed a compass needle underneath a wire and then turned on electric current. The needle of compass showed deflection.

Oersted recognized the significance of what he had just done. Earlier, it was believed that electricity and magnetism were two different unconnected sciences. Oersted had demonstrated that they were interconnected. Through this observation he showed that electricity and magnetism were related phenomena. Some scientists, influenced by this experiment, continued to work in the modern field of "electromagnetism". Their research resulted in several new scientific theories and various vital inventions like the dynamo and the electric motor, with this a new technology prospered, leading to inventions such as radio, television and fiber optics.

The unit of magnetic field strength is named Oersted in his honour.

Oersted was made a foreign member of the Royal Swedish Academy of Sciences in 1822.

Activity 1

Oersted experiment

Take a thermocole sheet and fix two thin wooden sticks of height 1cm which have small slit at the top of their ends. Arrange a copper wire of 24 gauge so that it passes through these slits and make a circuit. The circuit consists of a 3 (or 9) volt battery, key and copper wire which are connected in series as shown in figure 1. Now, keep a magnetic compass below the wire. Bring a bar magnet close to the compass.

- Does the needle get deflected by the bar magnet?

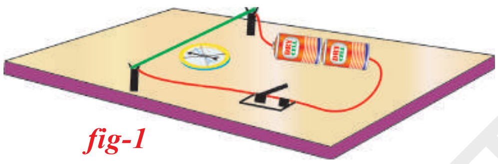


fig-1

- Why does the needle get deflected by the magnet?

Take the bar magnet far away from the circuit and switch on the circuit. Look for changes in the position of the needle.

- What do you notice?
- Is there any change in the position of the compass needle?
- Which force is responsible for the deflection of the compass needle?
- Does the current-carrying wire apply a force on the needle?
- What do we call this force? (Recall the idea of field forces in class 8, chapter "Force").

In order to understand the reasons for the deflection of the compass needle with no bar magnet near it we need to understand the idea of 'magnetic field' and the influence of electric field on magnetic field.

Let us learn about it.

Magnetic Field

We use the term field when a force gets applied on an object by another object without there being any physical contact between them. You have observed this already in activity 1. Let us call this field which is responsible for deflection of the compass needle as 'magnetic field'.

- How was this field produced?
- Can we observe the field of a bar magnet?

Let us try.

Activity 2

Take a sheet of white paper and place it on the horizontal table. Place a bar magnet in the middle of the sheet. Place a magnetic compass near the magnet. It settles to a certain direction. Use a pencil and put dots on the sheet on either side of the needle. Remove the compass. Draw a small line segment connecting the two dots. Draw an arrow on it from South Pole of the needle to North Pole of the needle. Repeat the same by placing the compass needle at various positions on the paper. The compass needle settles in different directions at different positions.

- Why does this happen?

Remove the bar magnet and place the magnetic compass on the paper. It comes to rest along the north-south direction. Now place the bar magnet in its previous place.

- Is there any change in the direction of the needle of the magnetic compass? Why?

The needle of the magnetic compass is affected by the bar magnet without any physical contact. A force causes the needle to deflect and makes it to come to rest in a certain direction.

- What is the nature of force that acts on the needle?

The force which acts on the needle from a distance is due to the magnetic field of the bar magnet.

In activity 2, you have already seen that the orientation of needle is different at different places on paper. This gives us an idea that the magnetic field has direction and it varies from one point to another.

When you changes the place of the compass near the bar magnet you can observe that its orientation changes from point to point. Now take the needle to places far away on the sheet and observe the orientation of the compass needle in each case.

- What do you observe?

The compass needle shows almost the same direction along north and south at places far from the magnet.

- What does it mean?

From these observations we conclude that the strength of the field varies with distance from the bar magnet. Now hold the compass a little above the table and at the top of the bar magnet. You can observe that field exists in all directions around the bar magnet. Hence we can say that the magnetic field is three dimensional i.e., magnetic field surrounds its source such as bar magnet. From the above discussion we can generalize that:

A magnetic field exists in the region surrounding a bar magnet and is characterized by strength and direction.

Lines of magnetic field

- How can we find the strength of the field and direction of the field?

You know that the direction of the field can be determined by using a compass. Let us find out how to determine the strength of the field.

Activity 3

Place a white sheet of paper on a horizontal table. Place a compass in the middle of it. Put two dots on either side of the compass needle. Take it out. Draw a line connecting the dots which shows the North and South of the earth. Now place the bar magnet on the line drawn in such a way that its north pole points towards geographic north. Now place the compass at the north pole of the bar magnet. Put a dot at the north pole of the compass needle. Now remove the compass and place it at the dot. It will point in other direction. Again put a dot at the north pole of the compass needle. Repeat the process till you reach the south pole of the bar magnet. Connect the dots from 'N' of the bar magnet to 'S' of the bar magnet. You will get a curved line. Now select another point from the north pole of the bar magnet. Repeat the process for many points taken near the north pole. You will get different curves as shown in fig.-2.

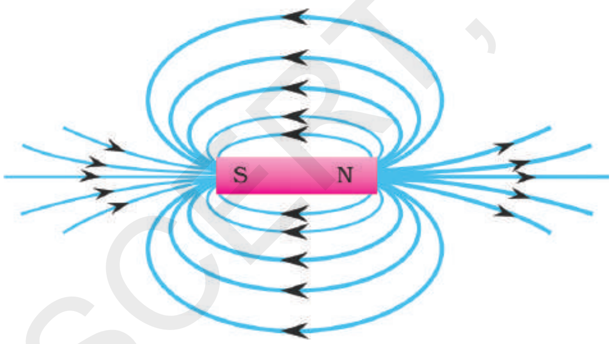


fig-2: Magnetic field lines

- What are these curves?

Technically these curves are called "magnetic field lines". Field lines are imaginary lines. These lines help us to understand the nature of the field. So these curved lines represent the field lines. If you place a compass at any point on the line, the needle comes to rest along the tangent to the line. So we conclude that the tangent drawn to the field line at a point gives the direction of the field.

- Are these field lines closed or open loops?

The field lines appear to be closed loops, but you can't conclude that lines are closed or open loops by looking at the picture of field lines because we do not know about the alignment of lines that are passing through the bar magnet. We will come to know about this point later in this chapter.

Observe the spacing between lines. In some places the field lines are crowded (near the poles of a bar magnet) and in some places the field lines are spread apart (at long distances from the bar magnet). From this picture we can conclude that the field is strong when lines are crowded and field is weak when lines are spaced apart.

Thus, the field drawn is non uniform because the strength and direction both change from point to point.

We may define the nature of the field with its characteristics such as its strength and direction. The field is said to be non uniform when any one of the characterstics of field i.e., strength or direction changes from point to point. Similarly the field is said to be uniform if both strength and direction are constant throughout the field. Let us define the strength of a uniform magnetic field.

- Can we give certain values to magnitude of the field at every point in the magnetic field?

Magnetic flux - Magnetic flux density

Consider a uniform magnetic field in space. Imagine a plane of certain area 'A' placed perpendicular to the field at a certain point in the magnetic field as shown in figure 3(a). You notice that a few field lines pass through this plane. This number gives an estimation of strength of the field at that point.

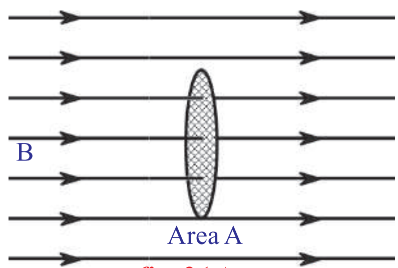


fig-3(a)

The number of lines passing through the plane of area 'A' perpendicular to the field is called magnetic flux. It is denoted by 'Φ'.

Magnetic flux represents the number of lines passing through the imagined plane in the field. Of course, flux depends on the orientation of the plane in the field. But here we are concerned only with the perpendicular case. The S.I unit of magnetic flux is Weber. Now strength of the field is easily defined using the idea of flux. If the imagined plane is perpendicular to the field and has unit area, then the flux through this plane of unit area gives the strength of the field. This strength of the field is technically called magnetic flux density (**B**). So, magnetic flux density is defined as the magnetic flux passing through unit area taken perpendicular to the field. **B** is also known as magnetic field induction.

Let the flux through the area 'A' be Φ.

- What is the flux through unit area perpendicular to the field?

It is equal to $\frac{\Phi}{A}$. The ratio of magnetic flux passing through a plane perpendicular to the field and the area of the plane is called the magnetic flux density.

So magnetic flux density = magnetic flux/ area.

$$B = \frac{\Phi}{A}. \Rightarrow \quad \Phi = BA$$

Units of magnetic flux density is Weber/(meter)^2. It is also called Tesla.

Generalize the formula of flux for any orientation of the plane taken in the field.

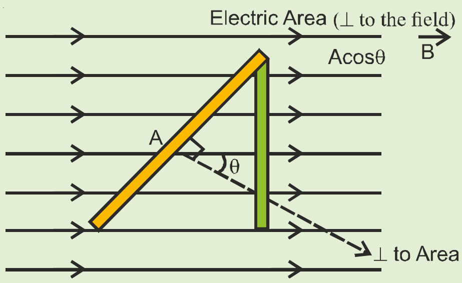


fig-3(b)

Let 'θ' be the angle between magnetic field (B) and normal to the plane with area (A) as shown in figure 3(b). The effective area of the plane perpendicular to the field is A cosθ. Then magnetic flux density is given by,

$$B = \frac{\text{magnetic flux}}{\text{effective area}}$$

(this formula is used when plane makes an angle with the field).

$$\text{Then } B = \frac{\Phi}{A \cos\theta}$$

The flux through the plane, is given by

$$\Phi = BA \cos\theta.$$

- What is the flux through the plane taken parallel to the field?
- What is the use of introducing the ideas of magnetic flux and magnetic flux density?

  Later in this chapter, you will see how these ideas are used.
- Are there any sources of magnetic field other than magnets?
- Do you know how old electric calling bells work?

  Let us see

Magnetic field due to currents

In activity 1 we observed that the compass needle is deflected when current flows through the circuit. This observation helps us to conclude that, "Current carrying wire produces magnetic field."

Let us discuss about the magnetic fields produced by a current carrying wire.

(i) Magnetic field due to straight wire carrying current

Activity 4

Take a wooden plank and make a hole as shown in figure 4(a). Place this plank on the table. Now place a retort stand on the plank as shown in figure 4(a). Pass 24 gauge copper wire through hole of the plank and rubber knob of the retort stand in such a way that the wire be arranged in a vertical position and not touch the stand. Connect the two ends of the wire to a battery via switch. Place 6 to 10 compass needles in a circular path around the hole so that its centre coincides with the hole. Use 3 (or 9) volt battery in the circuit. Switch on. Current flows through the wire.

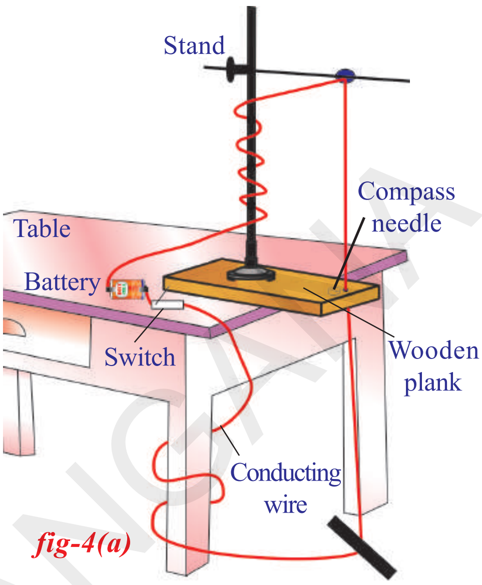


fig-4(a)

- How do the directions of the compass needles change?

  You may notice that they are directed as tangents to the circle.

- What is the shape of the magnetic field line around wire?

It must be a circular line. So we conclude that magnetic field lines are closed lines. The magnetic field lines due to straight wire carrying the current is shown in figures 4(b) and 4(c). This can be verified by sprinkling iron filings around the wire when current flows in the wire.

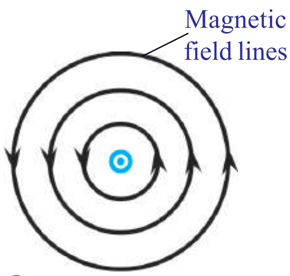


fig-4(b)

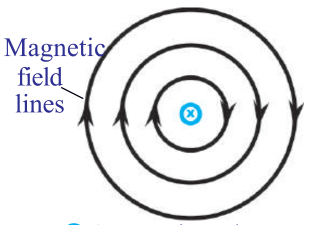


fig-4(c)

- What is the direction of magnetic field induction at any point on the field line?

If the current flow is vertically upwards (out of the page), the field lines are in anticlockwise direction, as shown in figure 4(b). If current flows into the page, in downward direction, the field lines are in clockwise direction as shown in figure 4(c). How do we determine the direction of field lines? It can be easily determined with **right hand thumb rule**. If you grab the current carrying wire with your right hand in such way that thumb is in the direction of current, then the curled fingers show the direction of the magnetic field as shown in figure 4(d).

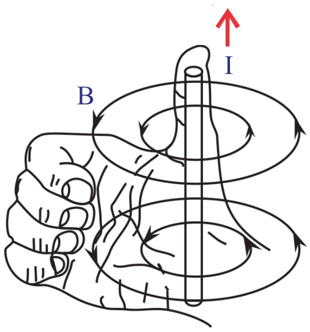


fig-4(d)

(ii) Magnetic field due to circular coil

Activity 5

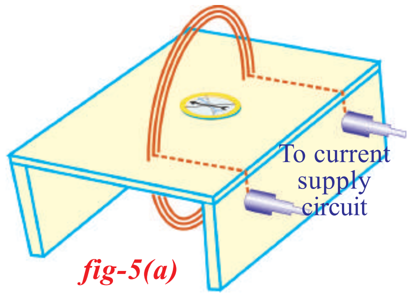


fig-5(a)

Take a thin wooden plank covered with white paper and make two holes on its surface as shown in figure 5(a). Pass insulated copper wire (24 gauge) through the holes and wind the wire 4 to 5 times through holes such that it looks like a coil (figure 5(a)). The ends of the wire are connected to terminals of the battery through a switch. Now switch on the circuit. Place a compass needle on the plank at the centre of the coil. Put dots on either side of the compass. Again place compass at one of the dots, put other dot further. Do the same till you reach the edge of the plank. Now repeat this for the other side of the coil from the centre. Then draw a line joining the dots, you will get a field line of the circular coil. Do the same for the other points taken in between the holes. Draw corresponding lines. You will get field lines of the circular coil.

- Can you tell the direction of the magnetic field of the coil?

This could be answered from the orientation of the compass needle. You can observe this when the compass needle is kept at the centre of the coil. The direction in which the compass needle comes to rest indicates the direction of the field due to the coil. Thus the direction of the field is perpendicular to the plane of the coil.

- Why does the compass needle point in the direction of field?

Place the compass in front of one of the faces of the coil and observe the orientation of the compass needle. Note the pole of the needle that faces the coil. We know that south pole is attracted to the north pole. The needle is oriented in such a way that its south pole points towards the north pole of the coil. So we can say that the direction of magnetic field, due to coil, points towards you when the current in the coil is in anticlockwise direction. Verify this in your experiment (do not touch the wires of the coil). When the current in the coil is in clock-wise direction, the direction of magnetic field due to the coil points away from you. The direction of the field due to coil is determined by using right hand rule, which states that,

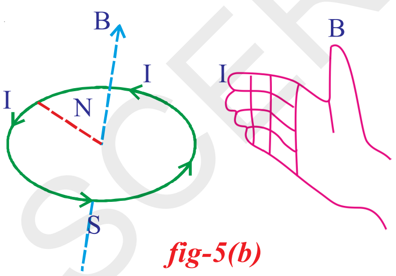


fig-5(b)

"When you curl your right hand fingers in the direction of current, thumb gives the direction of magnetic field."

Observe the direction of magnetic field in figure 5(b).

(iii) Magnetic field due to solenoid

Activity 6

Take a wooden plank covered with white paper. Make equidistant holes on its surface as shown in figure 6(a). Pass copper wire through the holes as shown in figure 6(a). This forms a coil. Join the ends of the coil to a battery through a switch. Switch on the circuit. Current passes through the coil. Now sprinkle iron filings on the surface of the plank around the coil. Give a small jerk to it. An orderly pattern of iron filings is seen on the paper.

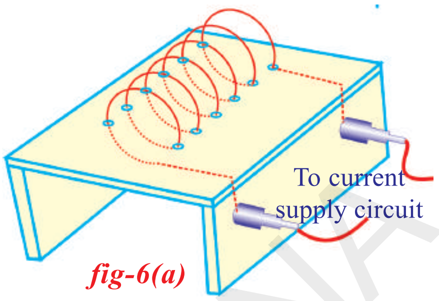


fig-6(a)

- How do they adjust in such an orderly pattern?

This long coil is called solenoid. A solenoid is a long wire wound in a close packed helix. The field of solenoid is shown in the figure 6(b). The magnetic field lines set up by solenoid resemble those of a bar magnet indicating that a solenoid behaves like a bar magnet. The direction of the field due to solenoid is also determined by using right hand rule. One end of the solenoid behaves like a north pole and other behaves like a south pole. The field lines outside the solenoid are continuous with those inside. Outside the solenoid the direction of the field lines is from north to south while inside the direction is from south to north. Thus the magnetic field lines are closed loops. This is so for the bar magnet too!

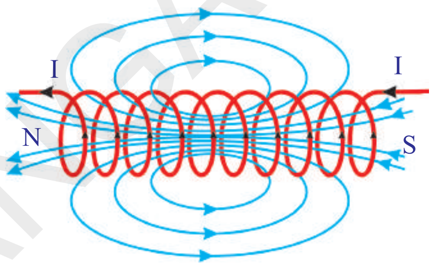


fig-6(b)

We have seen that current carrying wires produce magnetic field. So, electric charges in motion produce magnetic fields.

- What happens when a current carrying wire is kept in a magnetic field? Let us see.

Magnetic Force On Moving Charge And Current Carrying Wire

Activity 7

Take a bar magnet and bring it near the TV screen (The old CRT type TV). What do you observe?

You can observe that the picture on the screen is distorted.

- Why does the picture get distorted?
- Is the motion of electrons reaching the screen affected by the magnetic field of the bar magnet?

Move the bar magnet away from the screen. Now you will get a clear picture. Repeat this to confirm that the motion of electrons is affected by the field produced by the bar magnet. This must be due to the fact that the magnetic field exerts a force on the moving charges. This force is called magnetic force.

- Can we calculate the force experienced by a charge moving in a magnetic field?

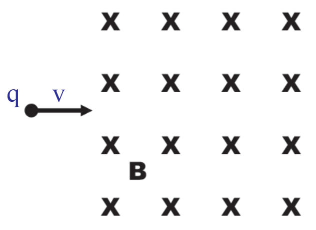


fig-7

Let a charge 'q' move with a velocity 'v' perpendicular to the magnetic field 'B' as shown in figure 7. The value of magnetic force on the moving charge can be found experimentally and it is given by,

$$F = q\,v\,B$$

Magnetic force on the charge is the product of three quantities charge, speed and magnetic flux density. The equation for magnetic force acting on a charge 'q' is $F = q\,v\,B$ and holds well only when the direction of velocity of charged particle 'v' is perpendicular to the direction of the magnetic field 'B'.

Generalize the equation for magnetic force on charge when there is an angle 'θ' between the directions of field **B** and velocity **v**.

It is experimentally proved that when there is an angle between direction of field and velocity, the magnetic force experienced by the charge is given by,

$$F = q\,v\,B \sin\theta.$$

When charge moves parallel to the magnetic field (along the magnetic field or against the field) the value of θ becomes zero. In the above equations θ is 0^0 so that $\sin\theta = 0$.

Thus the charge experiences no force when it is moving parallel to the magnetic field (along field direction or against field direction).

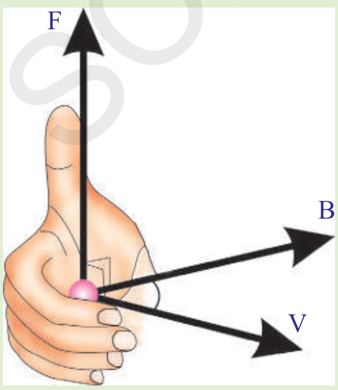


fig-8(a)

We have an easy method to find out the direction of magnetic force acting on a charge moving in a magnetic field. Keep your right hand fingers along the direction of velocity of moving charge and next curl your fingers towards the direction of magnetic field then the thumb gives the direction of magnetic force as shown in figure 8(a). This rule is applied for any case of angle between directions of velocity and field. The direction of magnetic force is always perpendicular to the direction of both velocity and magnetic field.

Generally right hand rule is used when velocity and field are perpendicular to each other. This law states that, "If the fore-finger points towards the direction of velocity of charge or current, middle finger points to the direction of field (B) then thumb gives direction of force when the three fingers are stretched in such a way that they are perpendicular to each other as shown in figure 8(b)."

This rule is applicable to positive charge.

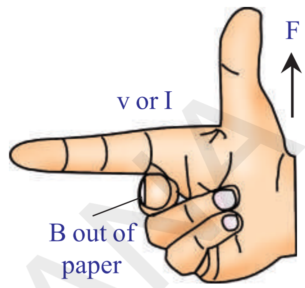


fig-8(b):Right hand rule for positive charge

- What is the direction of force acting on a negative charge moving in a field?

First find the direction of force acting on a positive charge. Next reverse its direction. This new direction is the direction of force acting on the negative charge.

Let us see an example of force acting on a charged particle.

Example 1

A charged particle 'q' is moving with a speed 'v' perpendicular to the magnetic field of induction B.

Find the radius of the path and time period of the particle.

Solution: Let us assume that the field is directed into the page as shown in figure E-1. Then the force experienced by the particle is F = q v B. We know that this force is always directed perpendicular to velocity. Hence the particle moves along a circular path and the magnetic force on a charged particle acts like a centripetal force.

Let r be the radius of the circular path.

We know that centripetal force $= \frac{mv^2}{r}$

$$q\,v\,B = \frac{mv^2}{r}$$

Solving this equation, we get; $r = \frac{mv}{Bq}$

Time period of the particle; $T = \frac{2\pi r}{v}$

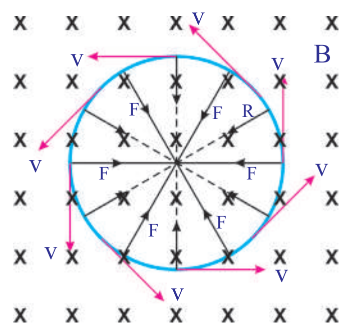


fig-E-1

Substituting r in above equation, we get $T = \frac{2\pi m}{Bq}$

- What happens when a current carrying wire is placed in a magnetic field?

Electric current is charges in motion. We know that each charge experiences a magnetic force. Thus the current carrying wire (constituting collection of charges in motion) experiences magnetic force when it is kept in a magnetic field.

- Can you determine the magnetic force on a current carrying wire which is placed along a magnetic field?

We know that each charge experiences no magnetic force because they are moving parallel to the direction of field along the field. So the force acting on wire is zero when it is kept along a magnetic field.

Let us find the magnetic force on a straight wire carrying current which is kept perpendicular to a uniform magnetic field 'B'. This 'B' is directed into the page. It is represented by 'x' as shown in the figure 9. Let the field be confined to the length L. So only the part of the wire of the length 'L' is inside the magnetic field. Remaining wire is outside the magnetic field. We know that the electric current means charges in motion hence they move with a certain velocity called drift velocity 'v'.

The magnetic force on a single charge is given by,

$$F_0 = q\,v\,B$$

Let total charge inside the magnetic field be Q. So magnetic force on the current carrying wire is given by

$$F = Q\,v\,B \quad \text{..................(1)}$$

The time taken by the charge (Q) to cross the field be

$$t = \frac{L}{v} \Rightarrow v = \frac{L}{t} \quad \text{..................(2)}$$

substituting this in equation 1, we get,

$$F = \frac{QLB}{t} \Rightarrow F = \frac{Q}{t}\,LB \quad \text{..................(3)}$$

We know that $\frac{Q}{t}$ is equal to the electric current in the wire,

$$I = \frac{Q}{t}$$

Assume that the ends of the wire is connected to the terminals of the battery

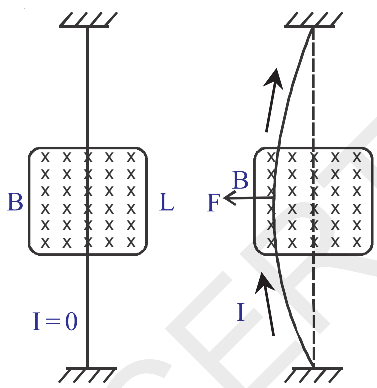


fig-9

Substituting 'I' in the equation 3, we get

$$F = ILB \quad \text{.................(4)}$$

Note: This equation holds well only when direction of electric current is perpendicular to magnetic field.

In fig.-9, you can observe the bending in the wire due to the force applied on it.

- What is the force on the wire if its length makes an angle 'θ' with the magnetic field?

  Let 'θ' be the angle between direction of current and magnetic field, then the force acting on the current carrying wire is given by

  $F = ILB \sin\theta$ (at any angle) ....(5)

- How could you find its direction?

  You can use right hand rule to find out the direction of force on the current carrying wire.

  Let us see the result of force applied on a current carrying wire by an experiment.

Activity 8

Take a wooden plank. Fix two long wooden sticks on it. These wooden sticks are split at their top ends.

A copper wire is passed through these splits and the ends of the wire are connected to battery of 3 volt, through a switch. Close the switch to make the circuit. Current passes through the wire. Now bring a horseshoe magnet near the copper wire as shown in figure 10.

- What happens to the wire?
- In which way does it deflect?

  Use the right thumb rule to find the direction of force.

- Is the direction of deflection observed experimentally same as that of the theoretically expected one?

  Change polarities of the horse shoe magnet. Again observe the deflection. Repeat this by changing the direction of current in the circuit.

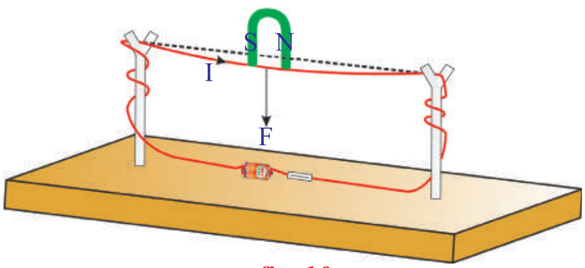


fig-10

- Does the right hand rule give the explanation for the direction of magnetic force exerted by magnetic field on the wire?

  Right hand rule helps you to find the direction of magnetic force exerted by the magnetic field on current carrying wire. It does not help you explain the reason for deflection of wire.

- Can you give a reason for it?

  Imagine a situation where there is no current in the wire. Then there exists only magnetic field due to external source (horse shoe magnet). When there is a current in the wire, it also produces a magnetic field. These fields overlap and give non- uniform field. Let us see this clearly with diagrams.

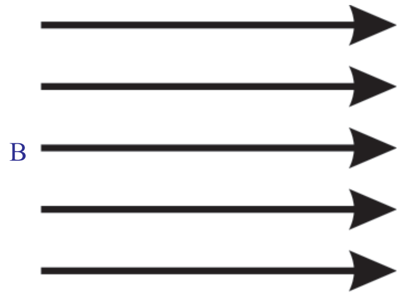


fig-11(a): Field lines due to horseshoe magnet between its poles

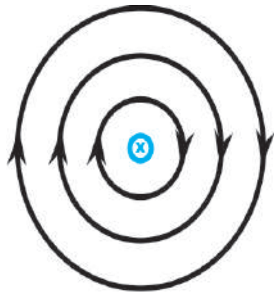


fig-11(b): Current into the page

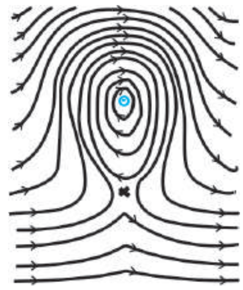


fig-11(c)

The field in between north and south pole of horse shoe magnet is shown in the figure 11 (a). Let us imagine a wire passing perpendicular to the paper. Let the current pass through it (into the page). It produces a magnetic field as shown in figure 11(b). Now let us try to sketch the resultant field by observing the field lines. We can see that the direction of the field lines due to the wire in upper part (of circular lines) coincides with the direction of the field lines of horse shoe magnet. The direction of field lines by wire in lower part (of circular lines) is opposite to the direction of the field lines of horse shoe magnet. So that the net field in upper part is strong and in lower part it is weak. Hence a non-uniform field is created around the wire. This non uniform field is shown in figure 11 (c). Therefore the wire tries to move to the weaker field region.

- Does this deflection fit with the direction of magnetic force found by right hand rule?
- What happens when a current carrying coil is placed in a uniform magnetic field?
- Can we use this knowledge to construct an electric motor?

Let us try to answer.

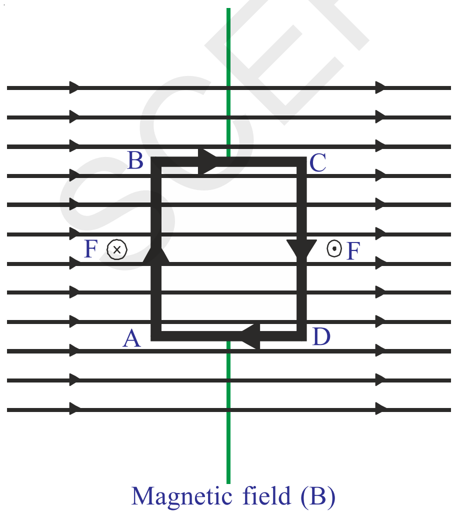


fig-12(a)

Electric Motor

To understand the working of an electric motor we need to understand the behaviour of a current carrying coil kept in a uniform magnetic field.

Consider a rectangular coil kept in a uniform magnetic field as shown in figure 12(a). Switch on the circuit so that the current flows through the rectangular coil. The direction of current in the coil is shown in figure 12(a).

- What is the angle made by AB and CD with magnetic field?

You will notice that they are always at right angles to the magnetic field.

- Can you draw the direction of magnetic force on sides AB and CD?

Apply right hand rule to get the direction of magnetic force. At AB, the magnetic force acts inward perpendicular (F⊗) to field of the magnet and on CD, it acts outward (F⊙).

The force on the sides BC and DA varies because they make different angles at different positions of the coil in the field.

- What are the directions of forces on BC and DA?

In the direction of currents in BC and DA are parallel to the field. magnetic force does't act on them. If the direction of currents in BC and DA are perpendicular to the field at BC, magnetic force pulls the coil up and at DA magnetic force pulls it down.

- What is the net force on the rectangular coil?

The force on AB is equal and opposite to the force on CD due to external magnetic field because they carry equal currents in the opposite direction. Sum of these forces is zero; similarly the sum of the forces on sides BC and DA is also zero for the same reason. So, net force on the coil is zero. But there is rotation of the coil. How is it possible?

- Why does the coil rotate?

Let us consider opening a cap of the bottle as an example where two equal and opposite forces act on the cap. Two forces equal in magnitude but opposite in direction must act on the either side of cap of the bottle as shown in figure 12 (b). These forces bring the cap into rotation. Similarly the rectangular coil comes into rotation in clockwise direction because of equal and opposite pair of forces acting on the two sides of the coil.

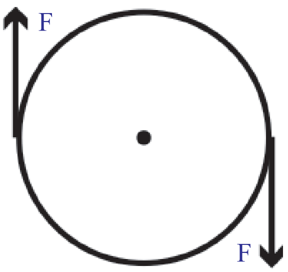


fig-12(b)
Couple action on bottle cap

- What happens to the rotation of the coil if the direction of current in the coil remains unchanged?

If the direction of current in the coil is unchanged, it rotates up to a vertical position then due to its inertia it rotates further in clockwise direction. But now the sides of the coil experience forces which are in the opposite direction to the previous case. Hence these forces try to rotate it in anti clockwise direction. As a result, this coil comes to halt and rotates in anti clock wise direction, this will go on if the direction of current remains unchanged.

- How could you make the coil rotate continuously?

If the direction of current in the coil, after the first half rotation, is reversed, the coil will continue to rotate in the same direction. Thus if the direction of current through the coil is reversed every half rotation, the coil will rotate continuously in one and the same direction.

- How can we achieve this?

To achieve this, brushes B_1 and B_2 are used, as shown in figure 12 (c). These brushes are connected to the battery. The ends of the coil are

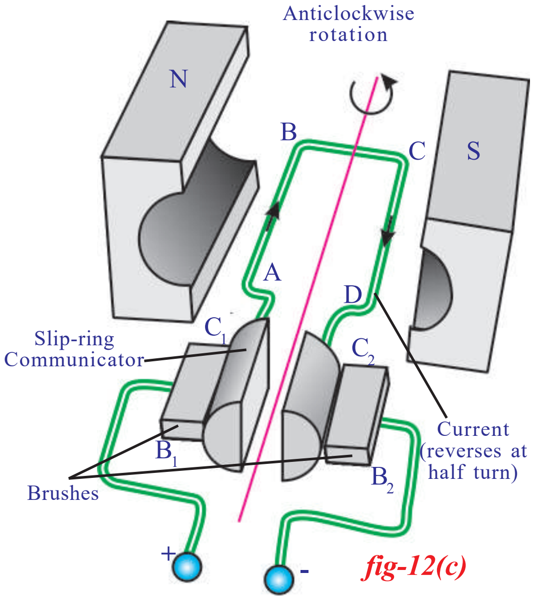


fig-12(c)

connected to slip rings C_1 and C_2, which rotate along with the coil. Initially C_1 is in contact with B_1 and C_2 is in contact with B_2. After half rotation, the brushes come into contact with the other slip rings in such a way that the direction of current through the coil is reversed. This happens every half rotation. Thus the direction of rotation of the coil remains the same. This is the principle used in "electric motor."

In electric motors, electrical energy is converted into mechanical energy.

We have learned that a current carrying coil rotates when it is kept in a uniform magnetic field.

- What happens when a coil without current is made to rotate in magnetic field?
- How is current produced?

Do you know?

- The relation between direction of induced current, magnetic field and force can also be explained by Flemings left hand rule. Stretch the left hand thumb, middle finger and forefinger in such a way that they are mutually perpendicular to each other. The forefinger indicates the direction of magnetic field, the middle finger indicates the direction of current and thumb indicates direction of force. By using the Flemings left hand rule we can explain the working of electric motor.

Electromagnetic induction

Ativity 9

The discovery and understanding of electromagnetic induction are based on a long series of experiments carried out by Faraday and Henry. Let us try to do one of those experiements.

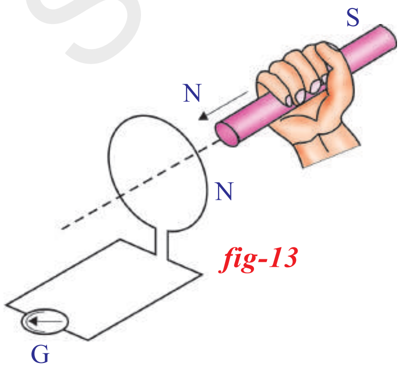


fig-13

Connect the terminals of a coil to a sensitive ammeter or a galvanometer as shown in the fig.-13. Normally, we would not expect any deflections of needle in the galvanometer because there is no electromotive force in this circuit. Now if we push a bar magnet towards the coil, with its north pole facing the coil, a remarkable thing happens. While the magnet is moving towards the coil, the needle in galvanometer deflects, showing that a current has been set up in the coil, the galvanometer does not deflect if the magnet is at rest. If the magnet is moved away from the coil, the needle in the galvanometer again deflects, but in the opposite direction, which means that a current is set up in the coil in the opposite direction.

If we use the end of south pole of a magnet instead of north pole in the above activity, the experiment works just as described but the deflections are exactly reversed.

Further experimentation enables us to understand that the relative motion of the magnet and coil set up a current in the coil. It makes no difference whether the magnet is moved towards the coil or the coil towards the magnet.

Faraday's Law

"Whenever there is a continuous change of magnetic flux linked with a closed coil, a current is generated in the coil."

This is one form of Faraday's law.

The current generated is called induced current and is set up by an induced electromotive force (induced EMF). This phenomenon of getting induced current is called electromagnetic induction.

Faraday observed that the changes in the magnetic flux through the coil are responsible for the generation of current in the coil. He also observed that the rapid changes in flux through coil generate greater induced current or induced EMF. After observing this important factor, he proposed a law of electromagnetic induction, which is as follow,

"The induced EMF generated in a closed loop is equal to the rate of change of magnetic flux passing through it."

In mathematical form, we can write this as

$$\text{Induced EMF} = \frac{\text{change in flux}}{\text{time}}$$

$$\varepsilon = \frac{\Delta\Phi}{\Delta t} \qquad \text{.....................(6)}$$

The equation is called Faraday's law of induction where Φ (phi) is the flux linked with coil. Let Φ_0 be the flux linked with single turn. If there are N turns in the coil, the flux linked with the coil is N Φ_0.

$$\Phi = N\,\Phi_0 \qquad \text{.....................(7)}$$

So far we have not specified the direction of the induced EMF or induced current. In the previous example, we have observed that an induced current is set up in the loop.

- What is its direction?
- Can you apply conservation of energy for electromagnetic induction?

Lenz Law

When we push the bar magnet towards the coils, current is generated, in other word electromagnetic induction takes place and mechanical energy is converted into electrical energy.

Let us discuss it in detail.

We know that when a bar magnet is pushed towards a coil with its north pole facing the coil an induced current is set up in the coil. Let the direction of current in the coil be in clockwise direction with respect to north pole of the bar magnet. Then this current carrying loop behaves like a magnet, with its south pole facing the north pole of bar magnet. In such a case, the bar magnet attracts the coil. Then it gains kinetic energy. This is contradictory to conservation of energy. So our assumed clockwise direction of induced current is wrong. Hence the correct direction of induced current has to be in anticlockwise direction with respect to north pole of the bar magnet. In such a case, the north pole of the coil faces the north pole of the bar magnet as shown in figure 14. Then north pole of bar magnet is repelled by the north pole of the coil. Hence we need to do work to overcome this force. This work done on the magnet is converted into electrical energy in the coil. In this way conservation of energy takes place in electromagnetic induction.

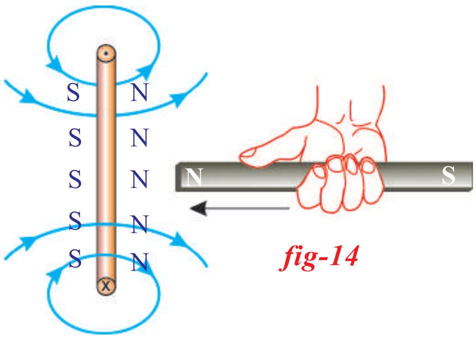


fig-14

Let us see a case where the bar magnet is pulled away from the coil, with north pole facing the coil. In such case, the coil opposes the motion of bar magnet to balance the conversion of mechanical energy into electric energy. This happens only when the north pole of the magnet faces the south pole of the coil.

- Can you guess what could be the direction of induced current in the coil in such case?

Invariably the direction of induced current in the coil must be in anti clock wise direction. In simple terms, when flux increases through coil, the coil opposes the increase in the flux and when flux decreases through coil, it opposes the decrease in the flux. This is discovered by a Russian Physist **Heinrich Lenz**.

Lenz's law states that "the induced current will appear in such a direction that it opposes the changes in the flux in the coil."

- Could we get Faraday's law of induction from conservation of energy?

Derivation of Faraday's Law

Let us arrange an apparatus as shown in figure 15. It consists of a pair of parallel bare conductors which are spaced *l* meters apart in uniform magnetic field of 'B'. We can hold another bare conductor in such a way that it is in contact with the two parallel wires(see figure-15). A galvano meter is connected to the ends of parallel conductors to complete an electric circuit. Now if the cross wire (cross conductor) placed across parallel conductors is moved to the left, galvanometer needle will deflect in one direction.

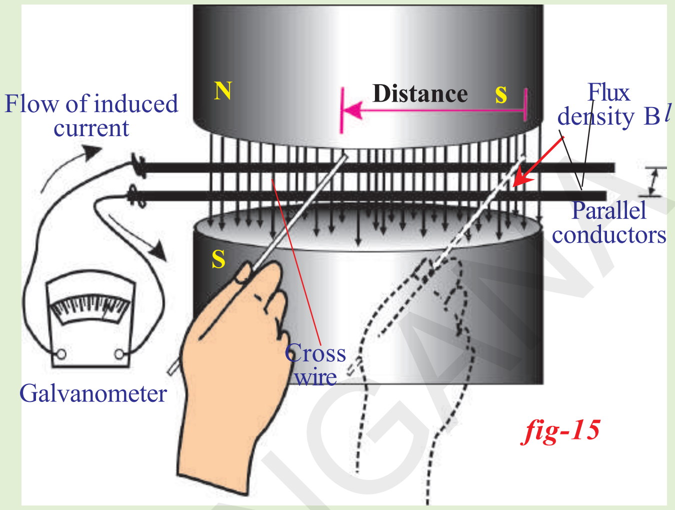


fig-15

If this cross wire is moved to the right, its needle deflects in a direction opposite to the previous deflection. Suppose that the crosswire is moved to the left to a distance of 's' meters in a time of 'Δ t'. Then the reading of galvanometer gives us the amount of current that flows in the circuit. A current will be set up in the circuit only when there is an EMF in the circuit. Let this EMF be 'ε'. The principle of conservation of energy tells us that this electric energy (associated with flow of current) must come from the work that we have done in moving the crosswire. If we ignore friction everywhere, in the arrangement, the work done by this applied force = Fs. It is evident that there is a current of 'I' amperes flowing through the length of *l* meters of the cross wire, and the cross wire is in a magnetic field. With this information,

- Can you derive an expression for the force applied on crosswire by the field B?

We know that it is equal to BI*l*, from equation-4 of previous discussion (see page 220).

i.e., $F = BIl$ ....(8)

This force must oppose the applied force. The direction of applied force determines the direction of current through the cross wire. Here we are doing positive work. The work done by us in moving the cross wire converts into electric energy. So the work done is given by,

$W = Fs = BIls$ ....(9) (using equation-8)

When we put the cross wire across parallel conductors it makes a complete electrical circuit which encloses a certain amount of magnetic flux. Now as we move the cross wire to the left, the area of the loop (formed by the parallel conductors and cross wire) decreases and the flux through the loop also decreases. The decrease in flux is given by,

$$\Delta\Phi = Bls \qquad \text{.............................(10)}$$

Here B is perpendicular to the area (ls). From equations 9 and 10

$W = (\Delta\Phi)\, I$

Let us divide both sides of this equation by Δt

$$\frac{W}{\Delta t} = \frac{I\,\Delta\Phi}{\Delta t} \qquad \text{.............................(11)}$$

Electric power, $P = \dfrac{I\,\Delta\Phi}{\Delta t}$

We know that electric power is the product of current and emf or voltage. $\varepsilon = \dfrac{\Delta\Phi}{\Delta t}$ is obviously equal to induced EMF.

Electric power, $P = \varepsilon I$ ....(12)

Thus the electric power generated in the circuit is equal to product of induced EMF and the current. Thus the mechanical energy utilised to move the cross wire in one second is converted into electric power $\dfrac{\Delta\Phi}{\Delta t}$ I. This is nothing but conservation of energy.

Dividing equation (9) by Δt, we have

$$\frac{W}{\Delta t} = \frac{Fs}{\Delta t} = \frac{BIls}{\Delta t} \qquad \text{..................(13)}$$

Here $\dfrac{s}{\Delta t}$ gives the speed of the cross wire, let it be taken as v. Then we get, Electric power $P = \dfrac{W}{\Delta t} = Fv = BIlv$ ......(14)

Power is also given as force times velocity. From equations (12) and (14), we get $\dfrac{W}{\Delta t} = \varepsilon I \Rightarrow \varepsilon I = BIlv$

We get,

$\varepsilon = Blv$ This is called motional EMF.

The above equation is not Faraday's law of induction because it is not related to the loop. It is useful when a conductor moves in a uniform magnetic field.

Let us see a few examples on induced emf.

Example 1

The magnetic flux inside a coil of 400 turns changes for each single turn with time as shown in figure

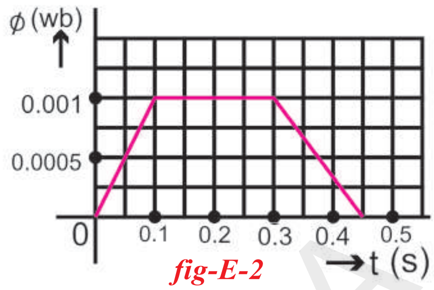


fig-E-2

Determine the maximum induced emf generated in the coil. Is there any change in induced EMF from t = 0.1 second to 0.3 second?

Solution: From the given graph, the increase in magnetic flux through one turn of coil in 0.1 second is 0.001 Wb. According to Faraday's law, the maximum induced emf generated in the coil is given by,

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

Substituting the values, we get

$$\varepsilon = \frac{400 \times 0.001}{0.1} = 4V$$

From graph, there is no change in magnetic flux through coil from t = 0.1s to 0.3s hence no emf is generated.

Example 2

Find the length of the conductor which is moving with a speed of 10 m/s in the direction perpendicular to the direction of magnetic field of induction 0.8T, if it induces an emf of 8V between the ends of the conductor.

Solution: Given that B = 0.8T, v = 10 m/s and ε = 8V.

Using $\varepsilon = Blv$

$8 = 0.8(l)(10)$

l (length of the conductor) = 1m

Applications of Faraday's law of electromagnetic induction

Electromagnetic induction is all around us.

- You might have seen that, during security check, people are made to walk through a large upright coil of wire which produces a weak AC (alternating) magnetic field. If we are carrying any significant quantities of iron, the magnetic flux linked with the large coil changes and the induced current generated in coil triggers an alarm.
- The tape recorder which we use to listen to songs (or) record voices works on the principle of electromagnetic induction. It consists of a piece of plastic tape coated with iron oxide and is magnetised more in

some parts than in others. When the tape is moved past as a small coil of wire (head of the tape recorder), the magnetic field produced by the tape changes, which leads to generation of current in the small coil of wire.

- How could we use the principle of electromagnetic induction in the case of using ATM card when its magnetic strip is swiped through a scanner? Discuss with your friends and your teacher.
- An induction stove works on the principle of electromagnetic induction. A metal coil is kept just beneath the cooling surface. It carries alternating current (AC) so that AC produces an alternating magnetic field. When you keep a metal pan with water on it, the varying magnetic field beneath it crosses the bottom surface of the pan and an EMF is induced in it. Because the pan is metal the induced EMF generates an induced current in it. Since the pan has a finite resistance, the flow induced current in it produces heat in it and this heat is conducted to the water. That's why we call this stove as induction stove.

Have you ever thought, from where do we get electrical energy?

Let us learn about it.

Magnetic Levitation

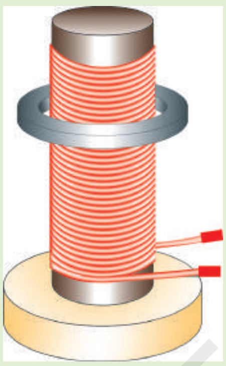


fig-16(a)

Take a wooden base as shown in figure 16(a). Fix a soft iron cylinder on the wooden base vertically. Wind copper wire around the soft iron as shown in figure 16(a). Now take a metal ring which is slightly greater in radius than the radius of the soft iron cylinder and insert it through the soft iron cylinder on the wooden base. Connect the ends of the coil to an AC source and switch on the current.

- What do you notice?

You notice that the metal ring is levitated on the coil.

Switch off the current, the ring will jump into the air very dramatically. Remove the AC supply and connect a DC supply. Observe what happens.

- Why is there a difference in behaviour in these two cases?
- What force supports the ring against gravity when it is being levitated?
- Could the ring be levitated if DC is used?

The metal ring levitates when AC is used, therefore the net force on it should be zero according to Newton's second law. The free body diagram of metal ring is shown in figure 16 (b). Weight (w) acts down. To balance it, a force (F) equal in magnitude and opposite in direction should act as shown in figure 16 (b).

- What is this unknown force acting on the metal ring?

In this activity AC is used. AC changes both its magnitude and direction in regular time intervals. We know that the current through the coil, produces a magnetic field so that one end of the coil behaves like north pole and other end behaves like south pole for a certain time interval. For the next interval, coil changes its polarities. Hence we can say that coil undergoes changes in its poles in the same intervals of time. The levitation of metal ring is possible only when the metal ring behaves like a magnet and should change its polarities in the same time intervals but in a sense opposite to that of the solenoid (coil) as shown in figure 16(c). Assume that the current flows in an clockwise direction in the solenoid as viewed from the top. Then the upper end becomes a south pole. An upward force is applied on the ring only when the upper side of the ring becomes a north pole (i.e. south pole of the ring faces towards the south pole of solenoid). It is only possible when there exists a anticlockwise current (viewed from the top) in the ring. After certain intervals, solenoid changes its polarities, so that the ring should also change its polarities in the same intervals. This is the reason why the metal ring is levitated.

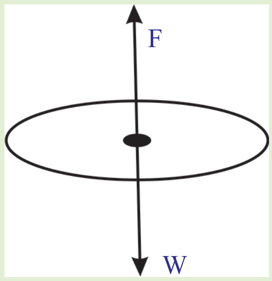


fig-16(b)

- What is responsible for the current in the metal ring?

AC is not a constant current. So that, the magnetic induction changes in both magnitude and direction in the solenoid and in the ring.

Here the area of the metal ring is constant. But the field through the metal ring changes so that flux linked with the metal ring changes.

- If DC is used, the metal ring lifts up and falls down immediately. Why?

The flux linked with metal ring is zero when no current flows through the solenoid. When the current is allowed to flow through the solenoid, it behaves like bar magnet. So the flux is linked to the metal ring when the switch is on. At that instant there is a change in flux linked with ring. Hence the ring rises up. There after, there is no change in flux linked with coil, hence it falls down. If the switch is off, the metal ring again lifts up and falls down. In this case also, there is a change in flux linked with ring when the switch is off.

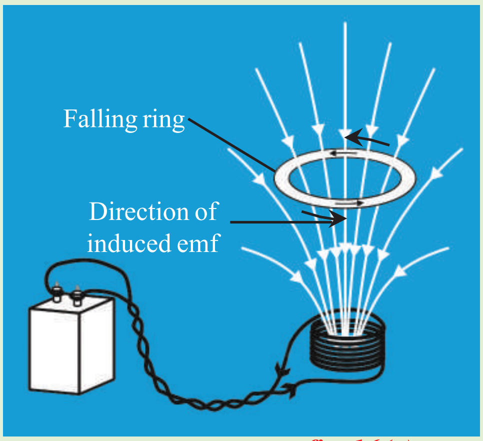


fig-16(c)

- What could you conclude from the above analysis?

Electric Generator and Alternating - Direct Currents

- What happens when a coil is continuously rotated in a uniform magnetic field?
- Does it help us to generate electric current?

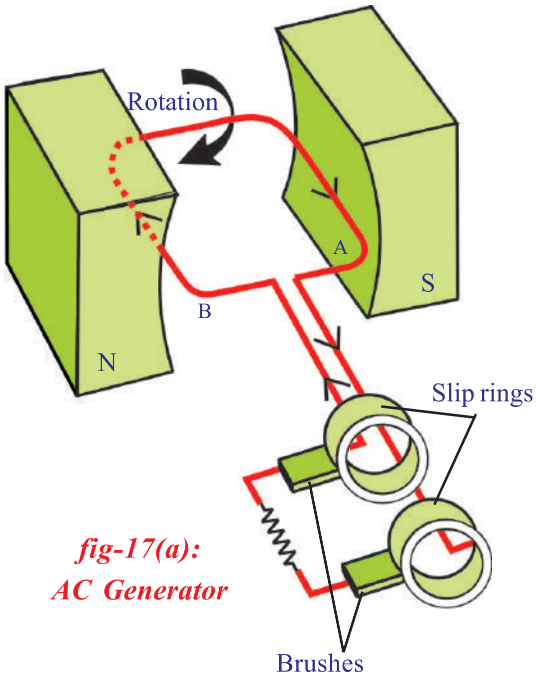


fig-17(a): AC Generator

Let us see:

Consider a rectangular coil. Let it be held between the poles of Curve- shaped permanent magnet as shown in fig.-17(*a*). As the coil rotates, the magnetic flux passing through the coil changes. According to the law of electro magnetic induction an induced current is generated in the coil.

- Is the direction of current induced in the coil constant? Does it change?

1. Consider initially the coil, positioned in such a way that magnetic flux passes through it. When the coil is at rest in vertical position, with side A of coil at top position and side B at bottom position, no current will be induced in it. Thus current in the coil is zero at this position.

2. When the coil is rotated in clockwise direction, current will be induced in it and it flows from A to B. During the first quarter of rotation, the current increases from zero to a maximum and reaches peak value when the coil is in horizontal position.

3. If we continue the rotation of coil, current decreases during the second quarter of the rotation and once again becomes zero when coil comes to vertical position with side B at top A at bottom position. During the second part of the rotation, current gener-ated follows the same pattern as that in the first half except that the direction of current is reversed. (see fig.-17(*b*))

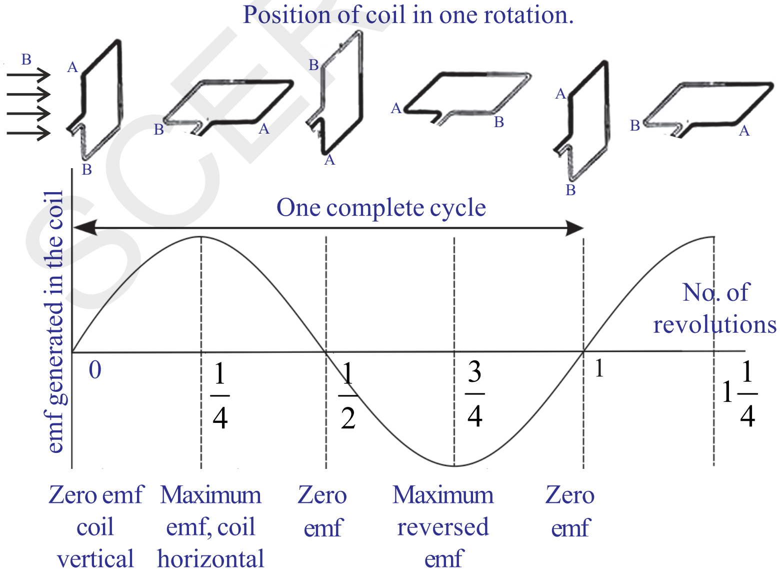


fig-17(b)

- Can you guess the reason for variation of current from zero to maximum and vice-versa during the rotation of coil?
- Can we make use of this current? If so, how?

Let us find out.

As shown in fig.-17(*a*) the ends of the coil are connected to two slip rings. Two carbon brushes arranged in such a way that they press the slip rings to obtain current from the coil. When these brushes are connected to external devices like TV, radio, we can make them work with current supplied from ends of carbon brushes.

The current obtained by this process changes its direction alternatively for each half cycle as shown in fig.-17(*b*).

This current is called alternating current (AC) in which, the direction of charge flow reverses periodically. So AC possesses certain frequency. The generator that we discussed here is called AC generator.

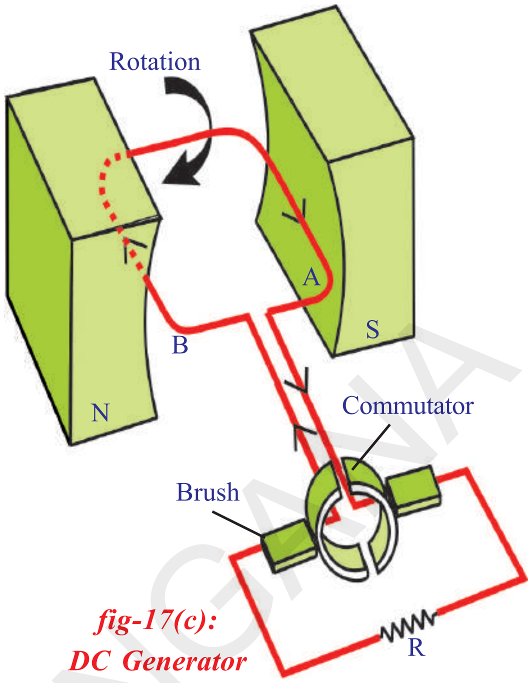


fig-17(c): DC Generator

- How can we get DC current using a generator?
- What changes do we need to make in an AC generator to be converted into a DC generator?

Let us find out.

If two half slip rings are connected to ends of the coil as shown in fig.-17(*c*), the AC generator works as DC generator to produce DC current.

Let us see how it works.

When the coil is in the vertical position the induced current generated during the first half rotation, rises from zero to maximum and then falls to zero again. As the coil moves further from this position, the ends of the coil go to other slip rings. Hence during the second half rotation, the current is reversed in the coil itself, the current generated in the second half rotation of the coil is identical with that during the first half of direct current (DC) as shown in fig.-17(*d*) for one revolution.

In generators, mechanical energy is converted into the electrical energy.

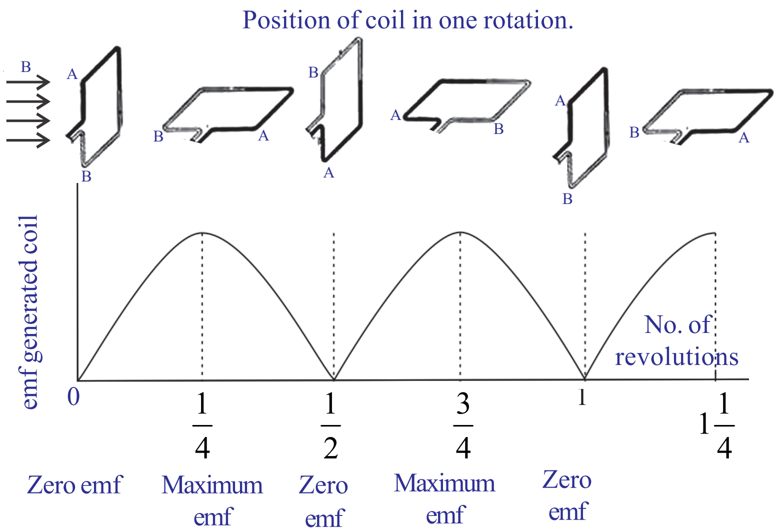


fig-17(d)

Key words

Magnetic flux, Magnetic flux density, Electric motor, Slip rings, Induced current, Induced EMF, Electric generator, DC and AC currents, rms values

What we have learnt

- A measure of strength of magnetic flux by taking account of number of field lines is called magnetic flux.
- Magnetic flux density (B) is defined as the ratio of flux passing through a plane perpendicular to field and the area of the plane.
- Current carrying wire produces magnetic field.
- $F = qvB \sin\theta$ and $F = ILB \sin\theta$
- In electric motor, electrical energy is converted into mechanical energy.
- The production of electric current due to relative motion between a coil and a magnetic field is called electromagnetic induction.
- Faraday's law: The induced EMF generated in a closed loop is equal to the rate of change of magnetic flux passing through it.
- Lenz's law: the induced current set up in the coil is in such a direction that it opposes the changes in the flux.
- When a conductor of length 'l' moves perpendicular to field B with a speed v then potential difference (voltage) developed between the ends of conductor is Blv. This EMF is called motional EMF.
- In generators, mechanical energy is converted into electrical energy.

Improve your learning

Reflections on Concepts

1. Are the magnetic field lines closed? Explain. (AS_1)

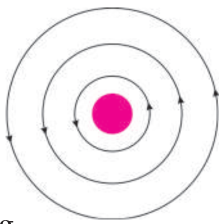


fig- Q2

2. See fig-Q2, magnetic lines are shown. What is the direction of the current flowing through the wire?(AS_1)

3. A bar magnet with North Pole facing towards a coil moves as shown in fig-Q3. What happens to the magnetic flux passing through the coil? (AS_1)

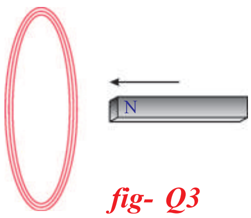


fig- Q3

4. A coil is kept perpendicular to the page. At P, current flows into the page and at Q it comes out of the page as shown in fig-Q3. What is the direction of magnetic field due to the coil?(AS_1)

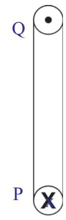


fig- Q4

Application of Concepts

1. The direction of current flowing in a coil is shown in fig-Q. What type of magnetic pole is formed at the face that has flow of current as shown in fig-Q? (AS_1)

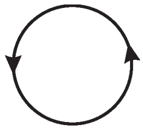


fig- Q

2. Why does the picture appear distorted when a bar magnet is brought close to the screen of a television? Explain (AS_1)
3. Symbol 'X' in fig.Q3 indicates the direction of a magnetic field into the page. A straight long wire carrying current along its length is kept perpendicular to the magnetic field. What is the magnitude of force experienced by the wire? In what direction does it act? (AS_1)

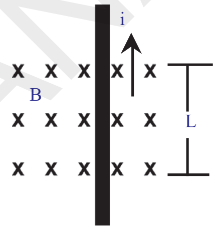


fig- Q3

4. An 8N force acts on a rectangular conductor 20cm long placed perpendicular to a magnetic field. Determine the magnetic field induction if the current in the conductor is 40A. (Ans: 1tesla) (AS_1)
5. As shown in the fig-Q5, both coil and bar magnet moves in the same direction. What happens? (AS_2)
6. Give a few applications of Faraday's law of induction in daily life. (AS_7)

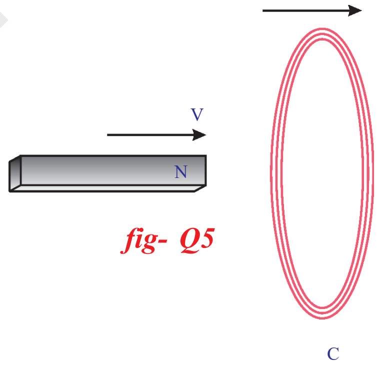


fig- Q5

Multiple choice questions

1. Which of the following converts electrical energy into mechanical energy [ ]
   a) motor b) battery
   c) generator d) switch
2. Which of the follwing converts mechanical energy into electrical energy [ ]
   a) motor b) battery
   c) generator d) switch
3. The magnetic force on a current carrying wire placed in uniform magnetic field if the wire is oriented perpendicular to magnetic field is [ ]
   a) 0 b) ILB
   c) 2ILB d) $\frac{ILB}{2}$

4. One Tesla = [ ]

   a) Newton/Coloumb b) Newton / ampere - meter

   c) Ampere / meter d) Newton / ampere second

5. Magnetic flux [ ]

   a) dyne b) Oersterd c) Guass d) Weber

6. No force works on the conductor carrying electric current when kept [ ]

   a) parallel to magnetic field b) perpendicular to magnetic field

   c) in the magnetic field d) away from magnetic field

Suggested Experiments

1. Explain with the help of two activities that current carrying wire produces magnetic field. (AS_3)
2. How do you verify experimentally that the current carrying conductor experiences a force when it is kept in magnetic field? (AS_3)
3. Explain Faraday's law of induction with the help of activity. (AS_3)
4. What experiment do you suggest to understand Faraday's law? What instruments are required? What suggestions do you give to get good results of the experiment? Give precautions also. (AS_3)
5. How can you verify that a current carrying wire produces a magnetic field with the help of an experiment? (AS_3)

Suggested Projects

1. Collect information about generation of current by using Faraday's law. (AS_4)
2. Collect information about material required and procedure of making a simple electric motor from internet and make a simple motor on your own. (AS_4)
3. Collect information of experiments done by Faraday. (AS_4)