

6. Electromagnetic Induction

+ Module 1: Faraday's Laws of Electromagnetic Induction

This module is designed to help you to:

- explain the concept of flux and magnetic flux to solve practical problems based on them;
- state the Faraday laws of electromagnetic induction;
- apply Faraday laws to solve problems based on electromagnetic induction.

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6.1.1 Introduction

Electricity and magnetism were considered as unrelated phenomena for a long time. It was quite a revelation when it was discovered that

1. Current carrying conductors give rise to a magnetic field or in other words, a current carrying conductor is equivalent to a magnet (1820 H.C Oersted).
2. Varying magnetic fields give rise to electric current in a conductor (1831 Michael Faraday).

The historical experiment pertaining to item no.1 above was performed by Oersted and the postulation was done by Ampere. You must have read about Biot-Savart's law and the related applications in devices like galvanometers, cyclotrons, etc. You have also studied about magnetic properties of materials and in the process you have learnt to distinguish between diamagnetism, paramagnetism and ferromagnetism.

You may have to fall back on those concepts while studying electromagnetic induction.

Quite a few interesting features are observed when there is a variation of magnetic field through any conductor which gets exposed to it. Such features can be observed even by keeping the intensity of the magnetic field invariant, but by changing the exposure area of the conductor. This calls for understanding the meaning of magnetic flux, about which we will study in this module.

We will discuss some of the concepts, activities and examples about the relations between varying magnetic flux and the emfs and currents induced by them. We shall come across Faraday's law of electromagnetic induction and its practical applications in our daily life.

6.1.2 Experiments of Michael Faraday demonstrating electromagnetic induction

We shall initiate the topic by discussing a few experiments involving relative motion between a coil and a bar magnet and then between two coils. Let us take a bar magnet, a coil and a galvanometer. The coil and the galvanometer are connected to form a circuit as shown in the Fig 6.1.1 [(a), (b), (c), (d)].

Experiment 1: Coil moving and bar magnet stationary.

Now, follow Fig. 6.1.1 [(a), (b), (c), (d)] carefully. They explain the arrangements and the outcomes of the experiment. The symbols S and N represent South and North Poles respectively. S and N with arrowheads

written in stylised manner within the loops also represent South and North poles respectively. You would recall from your study of magnetic effects of current that a current carrying loop behaves as a magnet. The equivalent magnet is perpendicular to the plane of the coil. While looking towards the loop if the direction of induced current is anticlockwise as in Figs. 6.1.1 (a) and 6.1.1 (d), then the pole of the equivalent magnet facing you is North and it is otherwise South as in Fig. 6.1.1 (b) and 6.1.1 (c).

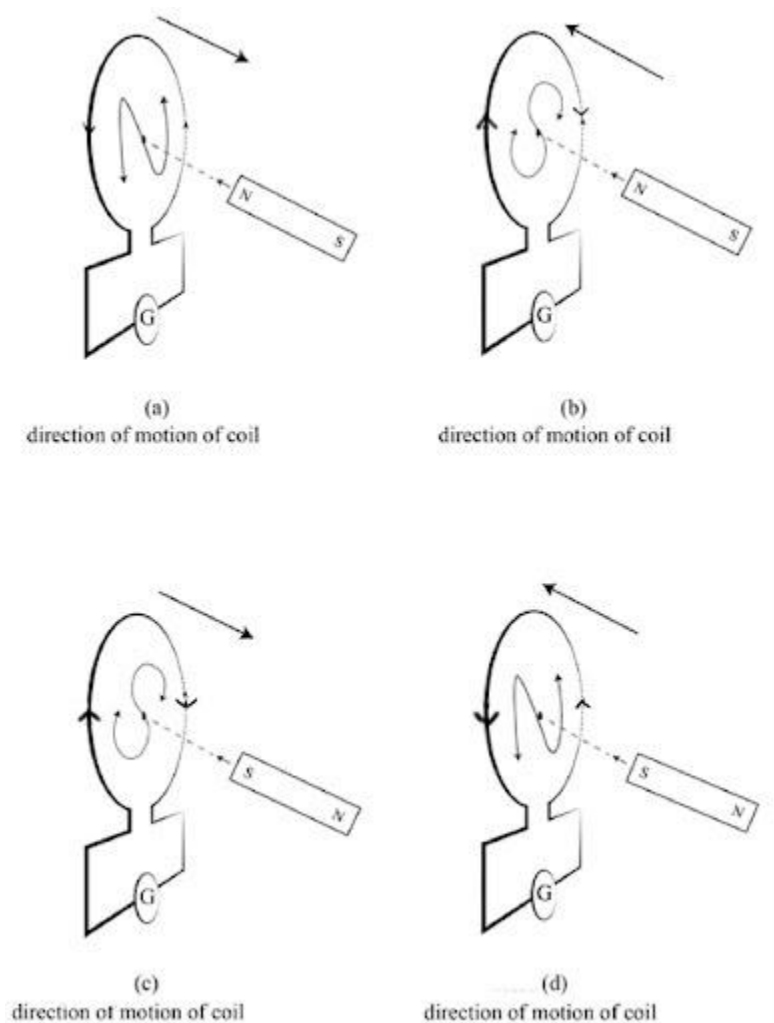


Fig. 6.1.1 [(a), (b), (c), (d)] Showing current induced in moving coil with respect to stationary magnet

In each of the above cases the loop is moving while the bar magnet is stationary. While moving the plane of the coil is perpendicular to the axis of the bar magnet. It is seen that in each case there is a deflection of the galvanometer needle meaning thereby that an e.m.f. is induced. What is the cause behind this induced e.m.f.? The moving loop amounts to the moving charges. Moving charges in a magnetic field cause the charges to experience a force which may be the cause behind the induced e.m.f. in the coil.

Experiment 2: Coil stationary and bar magnet moving.

Through the four Fig. 6.1.2 [(a), (b), (c), (d)] given below the experiment can be summed up. In each case, the magnet is moving perpendicularly to the plane of the coil.

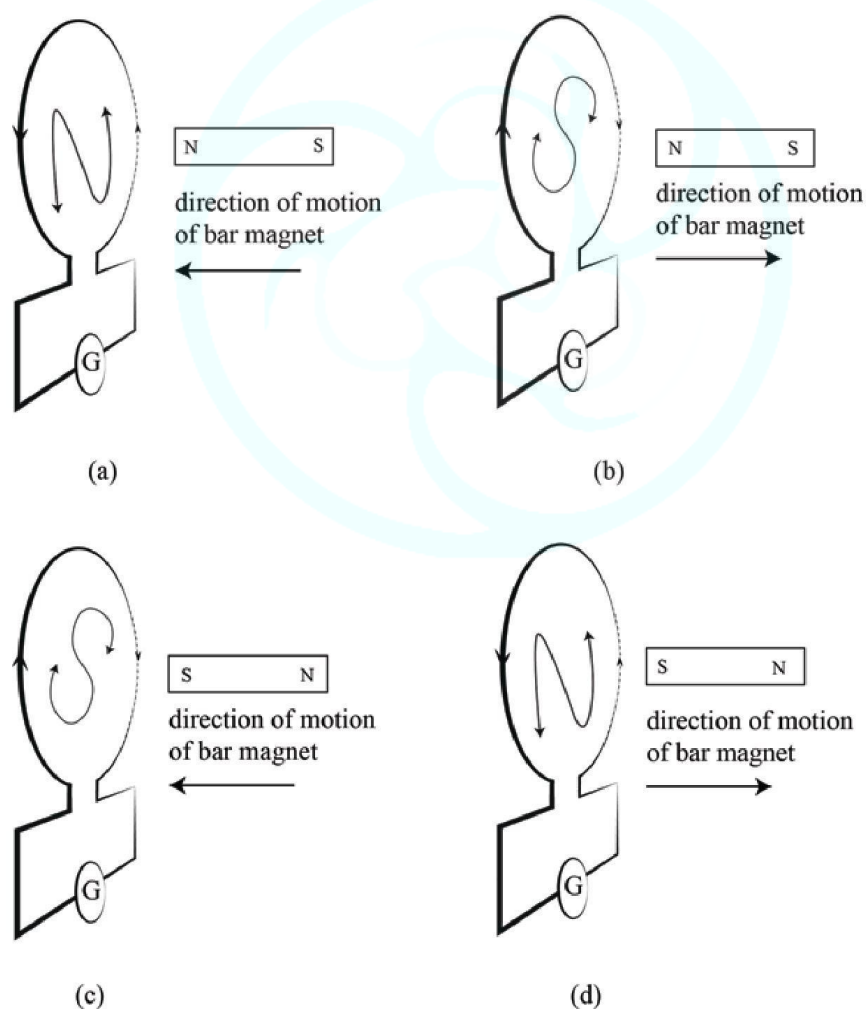


Fig. 6.1.2 [(a), (b), (c), (d)] *Showing current induced in a stationary coil with respect to moving magnet*

Here also in each case the galvanometer needle shows deflection. So, an emf is induced. Now, stationary charges do not experience any magnetic force. Then what is the cause of the induced emf in the coil? Faraday answered this question by concluding that a changing magnetic field induces an electric field. It was this induced electric field that was causing the charges to move through the coil. Now you may revisit experiment 1 and can reconcile with the fact that the cause of the induced electric field is the change in a magnetic field.

We shall now present the case of relative motion between two coils.

Experiment 3: Relative motion between two coils.

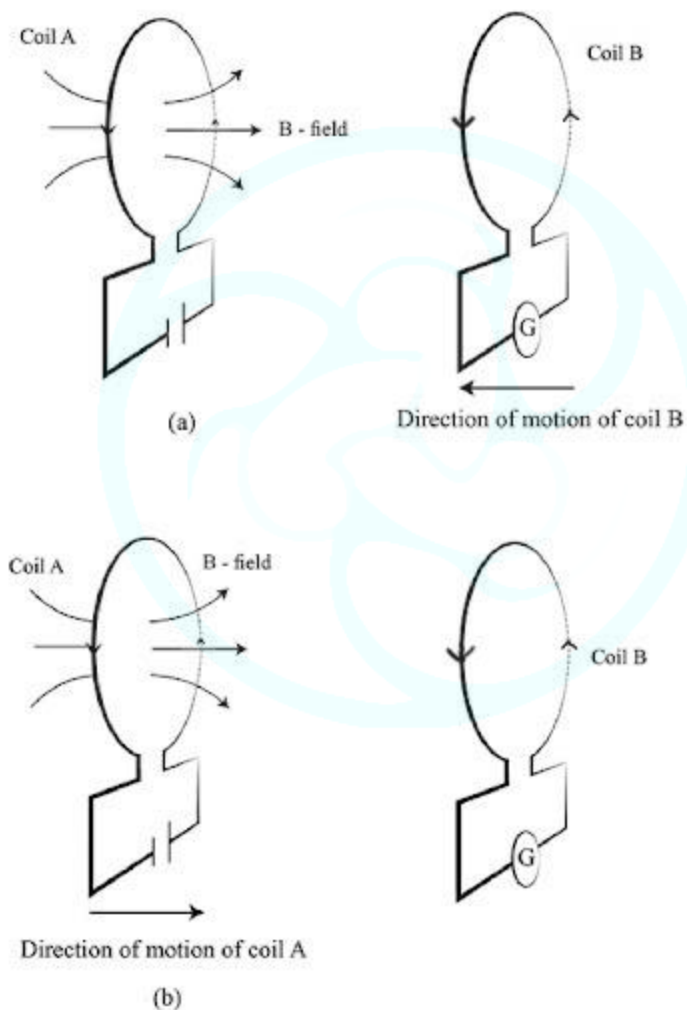


Fig. 6.1.3 (a) Showing induced current in a coil moving with respect to a current carrying coil **(b)** showing current induced in stationary coil due to a current carrying moving coil

In the above experiment with two coils when coil B is moving towards coil A as shown in Fig. 6.1.3(a), the situation is similar to Fig.6.1.1(a) and causes the galvanometer to deflect signifying flow of current in coil B. Similarly, if coil B moves away from coil A then it is similar to Fig.6.1.1(b) and causes the galvanometer to deflect in the opposite direction. Here coil A acts like a magnet because a current carrying coil has a magnetic field associated with it. Similarly, when coil A moves towards coil B as shown by Fig 6.1.3(b) it is similar to Fig 6.1.2(a) and the galvanometer shows a deflection signifying flow of current. When coil A moves away from Coil B then it is similar to Fig 6.1.2 (b) and the galvanometer shows deflection in the opposite direction

signifying that now the induced current in coil B is flowing in the opposite direction. The explanation is the same as that given in the case of Experiment (2).

Now, we shall present a slightly different set-up.

Experiment 4: Two stationary coils and a tapping key.

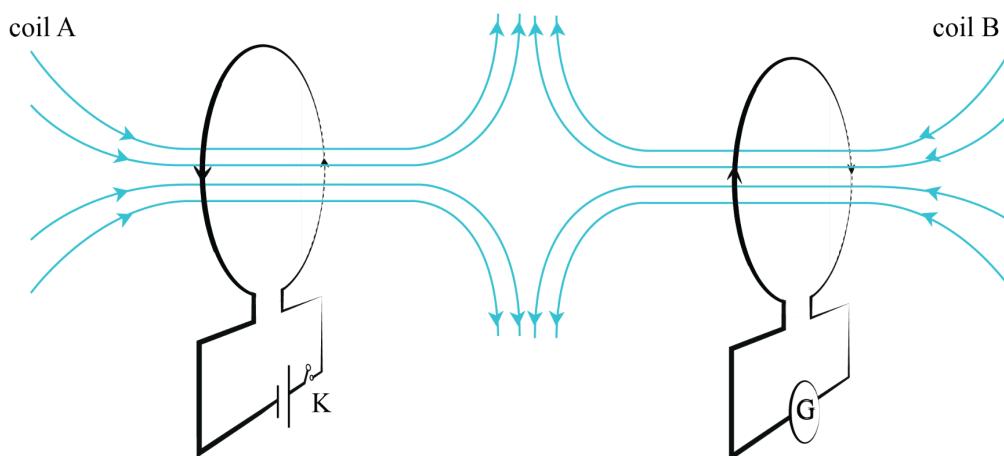


Fig. 6.1.4 showing current induced in coil B due to change in current in coil A

In this experiment (Fig 6.1.4) when the tapping key K is closed in coil A a current starts building up before attaining its maximum value. This causes the galvanometer in coil B to momentarily show a deflection before coming back to its zero deflection position. Similarly, when the tapping key is released the current in coil A drops from its peak value to zero. This again causes the galvanometer in coil B to show momentary deflection but in the opposite direction. This is because now the polarity of the induced current in coil B is reversed. The current is momentarily induced in coil B whenever the tapping key K in coil A is closed or released because building up or decay of current in coil A causes the magnetic field associated with the current flowing in coil A to change. This change in magnetic field associated with coil A causes the intensity of magnetic field lines flowing through coil B to change. This induces an electric field in coil B which causes the current to flow in coil B only during the time in which the magnetic field in coil A changes (either increases or decreases). Note carefully the use of the word 'only' in the previous sentence. It is the crux of the explanation. We shall now see another situation.

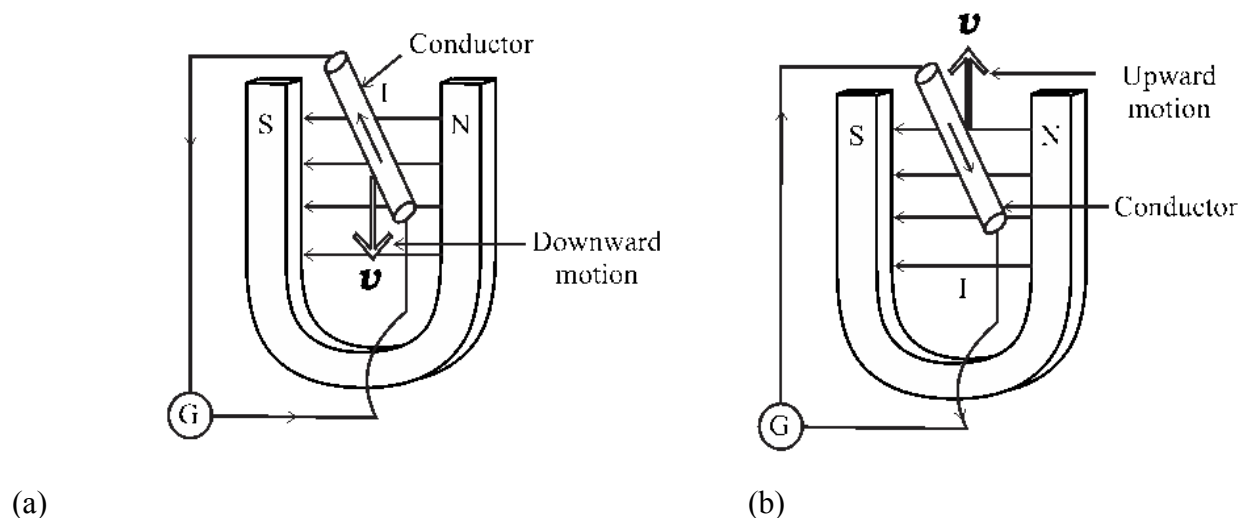
Experiment 5: Cutting of flux by a conductor.

Fig. 6.1.5(a),(b)] Showing current induced in a conductor moving through the magnetic field of a magnet

In the above figures the conductor is either moving down (Fig. 6.1.5(a)) or up (Fig. 6.1.5(b)) through a magnetic field. This amounts to charges in the conductor moving in a magnetic field experiencing a magnetic force. The force experienced by charges (in the rest frame of the conductor) is as if there is an electric field inside the conductor. We say there is an emf induced inside the conductor. This causes the galvanometer to show deflection but the direction of deflection is opposite with reference to the conductor moving up and down thereby signifying that the current flows in the opposite direction for the two cases. Here again, the current flows when there is relative motion between the conductor and the magnet.

Through all the above experiments we can realise that in each case there has been a relative motion between a magnet and a coil or between two coils. So, in effect the magnetic field lines attached with the magnet or the coil, behaving as a magnet, move in space and every time a coil or a conductor gets exposed to them. Since the field lines are moving in space, the intensity of the magnetic field with which they interact with the coil keeps changing with time. The area of exposure of the coil also plays a role. It becomes prudent that we coin a term to understand this phenomenon with more precision. We shall see that in the next section. The force acting on charges moving in a magnetic field is called the Lorentz Force.

6.1.3 Flux- This word originates from the latin word fluxus which means flow. We usually link the word flux with flow rate per unit area.



Fig.6.1.6 Showing direction of flow normal to face

As mentioned earlier, for a better understanding of the concept of electromagnetic induction, its cause and effects, we must get familiar with the concept of flux. The word flow was generally linked with the flow of liquids/fluids. It is easy to realise that if a liquid/fluid were flowing with a uniform velocity v , normally across an area A (Fig 6.1.6), the rate of flow of liquid (volume flowing per unit time) through the area A is $v A$.

If the flow is not normal to the area and making an angle x with the normal then, it is only the component $v \cos \theta$ (normal to the area) that would contribute to the flow through the area (the component $v \sin \theta$, along tangential direction to the area cannot contribute to the flow). Hence the rate of flow, or flux, in such a case, is $v \cos \theta A$.

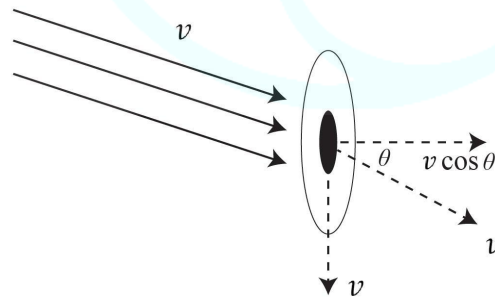


Fig.6.1.7 Showing direction of flow making angle θ with the surface

Regarding area as a vector quantity (direction along the outward normal to the area), we can write flux, for both the above cases as

$$\phi = v \cdot A \quad (6.1.1)$$

If v is not uniform all over the area, we would need to use the above expression for each infinitesimal bit of area and then integrate all over the area. Hence, in general,

$$\phi = \int_A v \cdot dA \quad (6.1.2)$$

We would now try to clarify the above ideas, related to flux, through an activity.

It should be noted that the activity narrated below is not an exact analogy to magnetic flux, however, it gives an idea about it.

Discussion on flux: To get an idea of the factors on which a flux depends, let us do a simple activity.

Make two similarly shaped holes of different sizes on a sufficiently large cardboard. Hold it in front of an electric fan at three different angles (Fig 6.1.8 (a), (b), (c)).

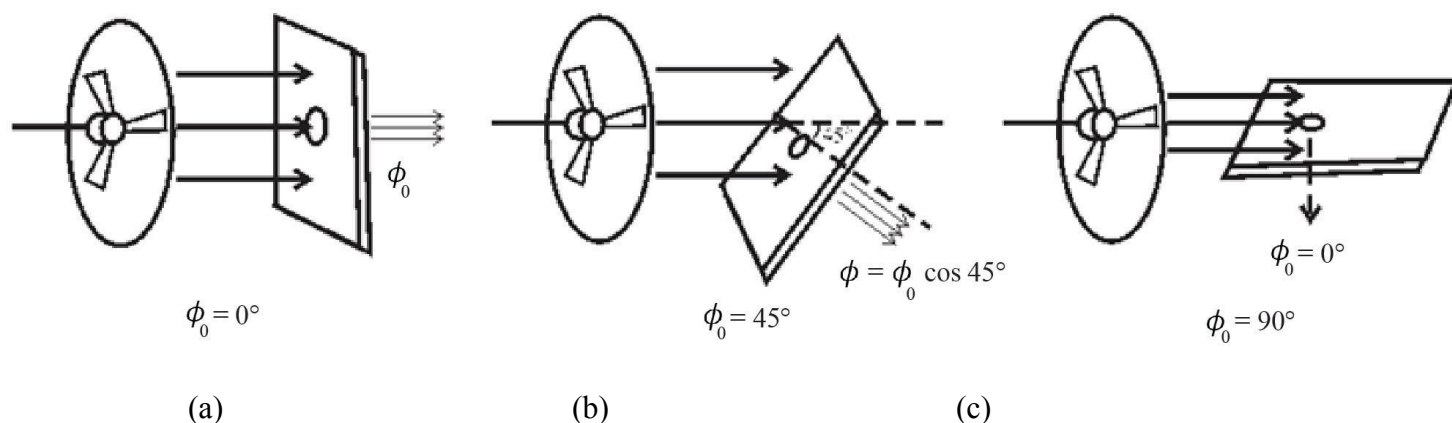


Fig. 6.1.8 [(a), (b), (c)] Showing the amount of air flowing through the hole at different angles

You will find that when the outward normal to the cardboard makes angle $\theta = 0^\circ$ with air flow, a maximum amount of air gushes out from the hole.

Later as the angle increases, a smaller amount of air flows out from it. When the angle is 90° , no air flows out from the hole. Note that, here we are talking only about air flowing from the fan. It is purely a qualitative exercise to understand the concept of flux.

This activity can be repeated with a hole of bigger size to understand the effect of area on the flux.

Points to ponder: area is in general a scalar quantity as it manifests itself through its magnitude only. But in the given example it has a directional role. So it behaves as a vector whose direction is along the outward drawn normal from the area. This happens only in connection with the concept of flux.

6.1.3.1 Magnetic flux

For a magnetic field, magnetic flux through an area A is given by

$$\phi = \int_A B \cdot dA$$

(6.1.3)

Here it needs to be realised that in case of the magnetic field, nothing physical is flowing in or out of the area. We can, however, visualise the magnetic flux in terms of magnetic field lines. Flux of magnetic field, through an area, equals the rate of flow of the magnetic field lines normally through that area. Mathematically, as we have seen, it is given by

$$\phi = \int_A B \cdot dA$$

If B is uniform all over a planar area, we would have

$\phi = B \cdot A = BA \cos\theta$, where θ is the angle between B and A .

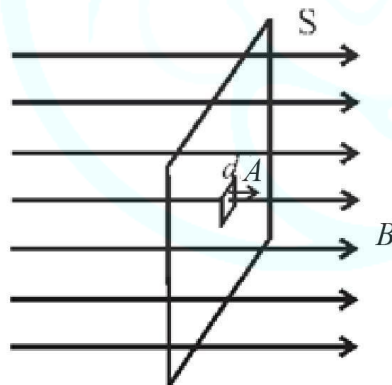


Fig. 6.1.9 showing the flux of magnetic field lines through an area A

dA is area vector of the area element. Flux $d\phi_B = B \cdot dA$ where $d\phi_B$ is the flux of the magnetic field or the number of field lines passing through the surface element with area dA . The flux through the entire surface S is obtained by taking the integral over the entire surface S or

$$\phi_B = \int_S d\phi_B = \int_S B \cdot dA$$

Here in this case (Fig.6.1.9) since dA is along the same direction as B hence the angle between them is 0° . This

$$d\phi_B = B \cdot dA = BdA$$

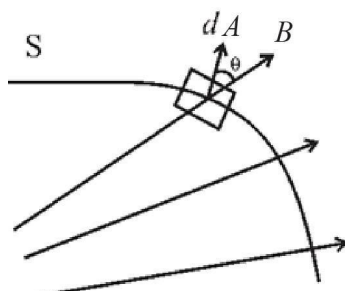


Fig. 6.1.10 flux of magnetic field lines making an angle θ with the area vector of surface element

Here in this case (Fig. 6.1.10) the surface S is a curved surface and the magnetic field lines are not crossing normally through the surface. Considering a small surface area element dA which makes an angle θ with the magnetic field B we have the total magnetic flux associated with this surface given by

$$\phi_B = \int_S d\phi_B = \int_S B \cdot dA \quad (6.1.4)$$

$$\text{and } d\phi_B = B \cdot dA = B \cos \theta dA \quad (6.1.5)$$

Thus here the component of B which is normal to the surface area element or parallel to the surface area element vector is considered for calculating flux.



Q.6.1.1 By what factor does the flux, through a square loop, change if the magnetic field (assumed to be uniform) is doubled and the sides of the loop are halved?

Q.6.1.2 If the magnetic flux, through a loop, is to be half of the maximum possible flux through it, at what angle should the (uniform) magnetic field be inclined to the normal to the plane of the loop?



Answers

A.6.1.1

$$\phi_1 = B_1 l_1^2$$

$$\phi_2 = B_2 l_2^2$$

When magnetic field is doubled, $B_2 = 2B_1$

And when sides of the square loop is halved, $l_2 = \frac{l_1}{2}$

$$\therefore \phi_2 = 2B_1 \frac{l_1^2}{4} = \frac{B_1 l_1^2}{2} = \frac{\phi_1}{2}$$

$$\therefore \frac{\phi_2}{\phi_1} = \frac{1}{2}$$

$$\phi_2 = \phi_1 \times \frac{1}{2}$$

If the magnetic field is doubled and sides of square loop are halved, the magnetic flux reduces to half of its initial value.

A.6.1.2

$$\phi = BA \cos \theta = \phi_{\max} \cos \theta$$

$$\phi = \frac{1}{2} \phi_{\max}$$

$$\therefore \cos \theta = \frac{1}{2} \quad , \quad \theta = 60^\circ$$

6.1.4 To observe changes in the deflection of the galvanometer caused by relative motion between the magnet and the coil

Activity 6.1.1

1. Take a ribbon spool of 3-4 cm of diameter. (If it is not available make a spool like structure with the help of a hard chart paper or use a PVC pipe.)
2. Wind about 100 turns of enamelled copper wire over this spool.
3. Clean both the free ends of enamelled wire and connect the (cleaned) ends to a sensitive galvanometer.
4. Place this spool in a horizontal position on the base as shown in Fig. 6.1.11
5. Keeping a strong magnet at a distance, move its N pole towards the coil. Observe the effect on the galvanometer needle.
6. Now keeping the magnet nearer to the coil, repeat step 5, and observe the difference in its effect on the galvanometer needle.
7. Move the N pole away from the coil and again observe the effect.
8. Now moving the magnet faster, repeat step 7, and observe the difference from the earlier case.
9. Repeat steps 5 to 8 using the south pole of the magnet and observe the corresponding changes.

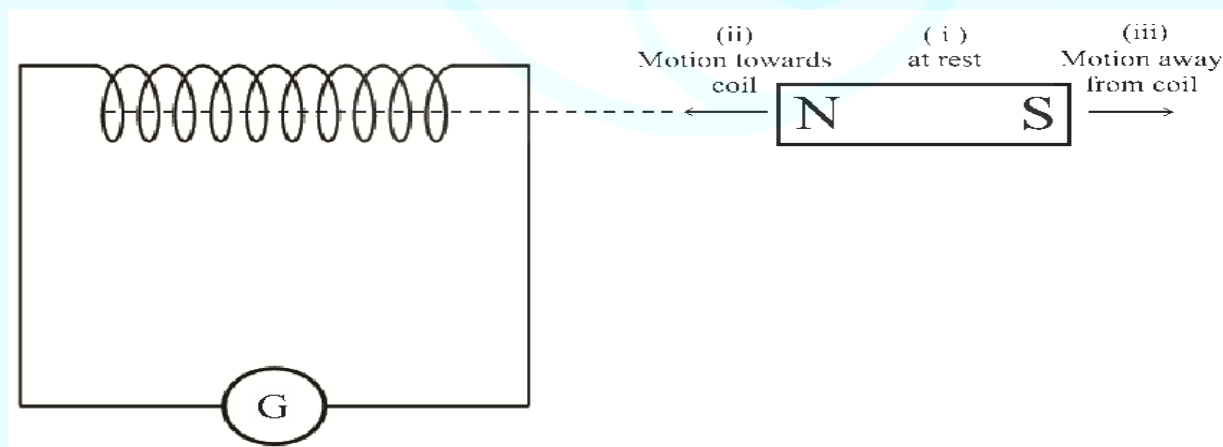


Fig. 6.1.11 Showing the motion of magnet with respect to a copper coil

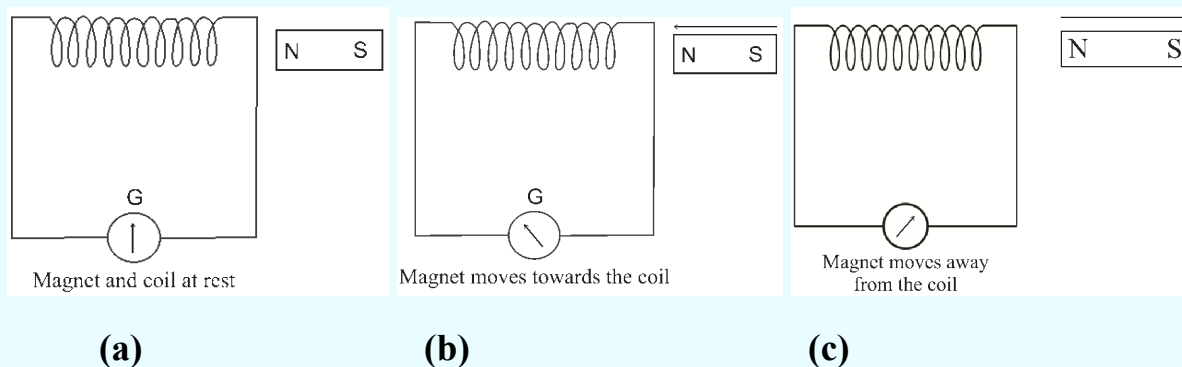


Fig. 6.1.12[(a),(b),(c)] showing the change in galvanometer reading connected with coil due to the motion of magnet with respect to coil

On the basis of your observations tick the correct options in each of the statements given below:

1. We get /do not get deflection when the magnet is stationary or when relative motion between coil and magnet is zero.
2. The deflection increases/decreases/remains same when the magnet is moved from a nearer position.
3. The deflection increases/decreases/remains the same when the magnet moves faster.
4. The deflection is in the same/opposite direction when the north pole is replaced by the south pole.

You may repeat the above activity by moving the coil and keeping the magnet fixed.

Note: The observed changes in the deflection of the galvanometer caused by relative motion between the magnet and the coil are due to electromagnetic induction. *i.e.* production of induced currents due to change in magnetic flux linked with the coil. Let us learn about that through the masterstroke of Michael Faraday.

6.1.5 Faraday's law of electromagnetic induction

Faraday stated his experimental observations in the form of a law called *Faraday's law of electromagnetic induction*. This basic law of electromagnetism specifies how a time-varying magnetic flux can produce an induced emf.

It is stated as “the magnitude of the induced emf, in a circuit, is equal to the time rate of change of magnetic flux through the circuit”.

i.e. $\varepsilon \propto \frac{d\phi_B}{dt}$

We write it as

$$\varepsilon = - \frac{d\phi_B}{dt} \quad (6.1.6)$$

The unit of flux is weber. So from Eq(6.1.6), we get

$$\text{volt} = \frac{\text{weber}}{\text{sec}}$$

The unit of magnetic induction B is tesla and thus tesla = weber m⁻²

$$1 \text{ tesla} = 10^4 \text{ gauss.}$$

where ϕ_B is the magnetic flux given by

$$\phi_B = B.A = BA\cos\theta$$

and the negative sign is due to Lenz's rule which states that the direction of the induced current will be such that the induced EMF will have a polarity so that the direction of induced current will always oppose the change in magnetic flux that is causing it. We shall read about it in detail later.

6.1.5.1 Applications of Faraday's law

Faraday's law is the most basic and important law of electromagnetism. This law is now the basis of all large scale generation of electric energy i.e., electricity. It also finds its application in many electrical machines, industries and medical fields, among others.

- **Simple telephone**

In the microphone of a simple telephone, there is a diaphragm, around which a coil is wrapped. The diaphragm can move back and forth in response to the sound waves incident on it. A stationary bar magnet, placed near the coil, then induces a current in the coil which can then be transmitted (after due amplification) to the loudspeaker of another telephone. When these (amplified) currents reach the loud speaker, (which consists of another coil/diaphragm/magnet combination in the other end of the telephone), the varying current in its coil causes its diaphragm to vibrate and reproduce the original sound waves.

- **Electrical transformers**

It is a static AC device which is used to either step up or step down, AC voltages or currents. It is based on the principle of mutual induction between the primary and secondary coil of transformers. Transformers are used at the generating station, as well as in the transmission and distribution systems of 'power companies'.

- **Electrical generators**

The basic working principle of all electrical generators is Faraday's law of electromagnetic induction. The generator converts mechanical energy into electrical energy.

- **Induction cookers**

They work on the principle of eddy currents which are also induced currents. When an alternating current flows through a copper coil, placed below a cooking container, it produces a changing magnetic field. This alternating or changing magnetic field induces eddy currents in the bottom of the cooking container which is made up of a ferromagnetic material. As the flow of current produces heat in a conductor, the container, and hence the food contained in it, gets heated up and cooked.

- **Electromagnetic flow metres**

They are used to measure the velocity of flow of conducting fluids like blood. When a (changing) magnetic field is applied to an electrically insulated pipe, in which the conducting fluids are flowing an electromotive force is induced in the conducting fluid, as per Faraday's law. This induced emf, being proportional to velocity of the flowing fluid, can be measured to determine the velocity or rate of flow of the conducting fluid.



Let Us Reflect

Q.6.1.3 Find the magnitude of emf induced in a rectangular loop of length 5 cm and breadth 2 cm. When a magnetic field of 0.5 T, directed normal to the plane of the loop, reduces to its half in 0.5 sec.



Answers

A.6.1.3 $\Delta t = 0.5 \text{ sec}$, $A = 10 \times 10^{-2} \text{ m}^2$

$$B_1 = 0.5 \text{ T}, B_2 = 0 \text{ T}$$

$$\phi_1 = BA \cos \theta = 0.5 \times 10^{-1} \times 1 = 5 \times 10^{-2} \text{ Wb}$$

$$\phi_2 = 0$$

$$|\varepsilon| = \frac{\Delta \phi_B}{\Delta t} = \frac{|(5 \times 10^{-2} - 0)|}{0.5} = \frac{5 \times 10^{-2}}{0.5}$$

$$|\varepsilon| = 0.1 \text{ V}$$

6.1.6 Summary

- Michael Faraday (1791-1862) and Joseph Henry (1797-1878) were the pioneers who independently discovered that changing magnetic flux can produce electric current.
- Flux of magnetic field, through an area, measures the rate of flow of the magnetic field lines normally through that area. Mathematically, it is given by

$$\phi = \int_A B \cdot dA$$

- Electromagnetic induction is the phenomenon of generating e.m.f./current in a coil by changing the magnetic flux linked with it. It is the fountainhead of all power generation processes.
- The magnitude of e.m.f. induced in a coil is directly proportional to the rate of change of magnetic flux linked with it and the number of turns in the coil.

- Electromagnetic induction finds many applications in our daily life like induction cooker, induction furnace, electric generators, speedometers of vehicles, brakes of trains and electromagnetic flow meters, etc.

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