1. FARADAY'S LAWS OF ELECTROMAGNETIC INDUCTION AND LENZ'S RULE

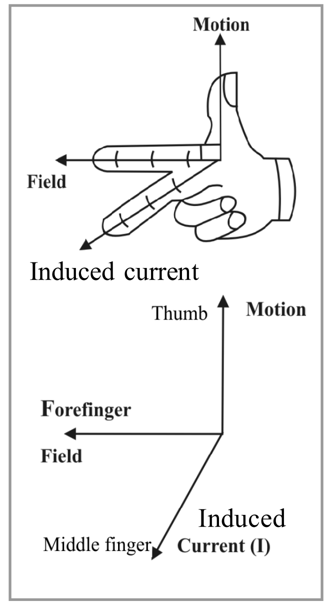
Faraday's Laws of Electromagnetic Induction

(*i*) Whenever magnetic flux linked with a circuit changes, an induced emf is always produced in it. If the circuit is closed, an induced current also flows through it. These induced emf and current lasts as long as the magnetic flux keeps on changing.

(*ii*) The magnitude of the induced emf is directly proportional to the rate of change of the magnetic flux. If $d\phi$ is the change in magnetic flux in a small time interval dt, then induced emf produced is

$$e = -\left(\frac{d\phi}{dt}\right)$$

The negative sign indicates the opposing nature of induced emf. The induced current flows in such a direction, so that it opposes the change in magnetic flux.



Lenz's Rule

According to Lenz's rule, the induced current produced in a closed circuit always flows in such a direction that it always opposes the cause due to which it has been produced.

- Lenz's rule is based on the law of conservation of energy.
- It explains the appearance of negative sign in Faraday's second law of electromagnetic induction.

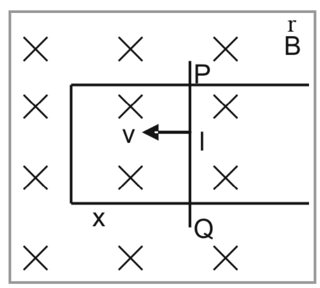
Fleming's Right–Hand Rule

Fleming's right-hand rule gives the direction of induced emf (or current) in a conductor.

If the first finger, central finger and the thumb are stretched outwards in mutually perpendicular directions such that the first finger points along the direction of field, thumb points along the direction of motion of the conductors, then the central finger would point in the direction of induced emf (or current).

2. MOTIONAL EMF

The figure shows a rectangular conductor, one arm (PQ) of which is free to move. The uniform magnetic field of strength B is perpendicular to the plane of the conductor.



The flux through the loop is:

$\phi = Blx$

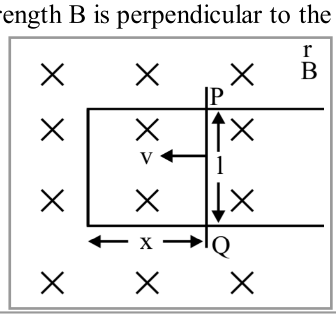
If the arm PQ is moved inwards with a velocity v, then the induced emf will be

$$\varepsilon = -\frac{d\phi}{dt} = -\frac{d(Blx)}{dt} = -Bl\frac{dx}{dt} = Blv \qquad \text{where, } \frac{dx}{dt} = -v$$

The equation, $\varepsilon = Blv$ gives the expression for motional emf.

3. ENERGY CONSIDERATION

The figure shows a rectangular conductor, one arm (PQ) of which is free to move. Let PQ of length *l* move with a uniform speed *v*. The uniform magnetic field of strength B is perpendicular to the plane of the conductor.



Let R be the resistance of the arm PQ and other arms be with negligible resistance.

The current in the loop will be

$$I = \frac{\varepsilon}{R} = \frac{Blv}{R}$$

The presence of the perpendicular magnetic field exerts a force on the arm PQ with a magnitude,

$$F = I\,l\,B = \frac{B^2 l^2 v}{R}$$

The direction of the force coincides with the direction of emf according to the Lenz's law.

The power required to push the arm with velocity v is

$$P = Fv = \frac{B^2 l^2 v^2}{R} \qquad \ldots(i)$$

In the equivalent electrical circuit, the Joule's heat loss is

$$P_j = I^2 R = \left(\frac{Blv}{R}\right)^2 R = \frac{B^2 l^2 v^2}{R} \qquad \ldots(ii)$$

(*i*) and (*ii*) denote the same. It means that the mechanical energy needed to move the arm PQ is converted to electrical energy and then, thermal energy. Law of conservation of energy is verified.

4. EDDY CURRENTS

If a metallic plate is placed in a time varying magnetic field or the plate is moved in a constant magnetic field in such a way that magnetic flux linked with it changes continuously with respect to time, then induced current is produced in the whole volume of the metal. These currents oppose the motion of metallic plate or oppose the change in magnetic flux linked with the plates. These currents are called **Eddy currents** or **Foucault's currents**.

Magnitude of eddy current, $\mathrm{I} = \dfrac{\text{Induced emf}}{\text{Resistance}} = \dfrac{\varepsilon}{\mathrm{R}}$

But, $\varepsilon = -\dfrac{d\phi}{dt}$

Therefore, $\mathrm{I} = -\dfrac{\frac{d\phi}{dt}}{\mathrm{R}}$

Its direction is given by Lenz's law or Fleming's law.

Applications of Eddy Currents

(*i*) **Electromagnetic damping:** This is used in designing dead beat galvanometers. The coil of the galvanometer is wound over a metallic frame. When steady current passed through the coil makes it oscillate, the eddy currents that set up in the metallic frame oppose its motion and an equilibrium position is attained almost instantly. Thus, the motion of the coil is damped.

(*ii*) **Induction furnace:** The substance to be heated is placed in a high frequency magnetic field. The large eddy currents developed in the substance produce so much heat that it melts. Such an arrangement is called induction furnace. It is used for extracting a metal from its ore and also in the preparation of certain alloys.

(*iii*) **Electromagnetic brakes:** Electromagnetic brakes are used in controlling the speed of electric trains. A strong magnetic field is applied to a metallic drum rotating with the axle connecting the wheels. Large eddy currents set up in the rotating drum oppose the motion of the drum and tend to stop the train.

(*iv*) **Induction motor:** A rotating magnetic field produces strong eddy currents in a rotor, which starts rotating in the direction of the rotating magnetic field.

(*v*) Eddy currents are used in speedometers of automobiles and energy metres.

(*vi*) Eddy currents are also used in diathermy *i.e.* in deep heat treatment of the human body.

Drawbacks of Eddy Currents

The production of eddy currents results in the loss of energy in the form of heat. Hence, there occurs a huge loss of energy in the cores of transformers, dynamos etc. Laminated soft iron cores are used to minimise this. The laminated core offers high resistance to eddy currents. As a result, the eddy currents are attenuated.

5. SELF INDUCTANCE

The property of a coil by virtue of which, it opposes any change in the strength of current flowing through it by inducing an emf in itself is called self induction.

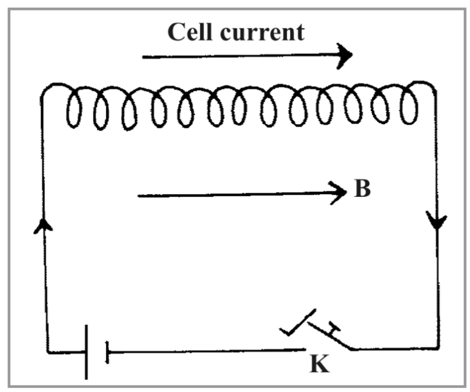
Coefficient of self-induction or self inductance: The magnetic flux (ϕ) linked with a coil that carries a current I is directly proportional to the current flowing through it.

i.e. $\phi \propto I$ *Or* $\phi = LI$ …(*i*)

where L is the coefficient of self-induction or self inductance.

If I = 1A, then $\phi = L$

i.e. self-inductance of a coil is numerically equal to the magnetic flux linked with the coil when a unit current flows through it.



Differentiating equation (*i*) with respect to *t*, we get

$$\frac{d\phi}{dt} = L\left(\frac{dI}{dt}\right) \quad \text{…(ii)}$$

Also, $$\varepsilon = -\frac{d\phi}{dt} \quad \text{…(iii)}$$

The negative sign shows the opposing nature of induced emf.

Using equation (*ii*) and (*iii*)

$$|\varepsilon| = L\left(\frac{dI}{dt}\right) \quad \text{…(iv)}$$

If $\frac{dI}{dt} = 1$, then $|\varepsilon| = L$

Self-inductance can also be defined as the numerical value of induced emf in the coil, when rate of change of current in the coil is unity.

SI unit of self-inductance is **henry** (H).

From equation (*iv*)

$$L = \frac{|\varepsilon|}{\frac{dI}{dt}}$$

If $|\varepsilon| = 1\,V$ and $\frac{dI}{dt} = 1\,As^{-1}$, Then, $L = \dfrac{1\,V}{1\,As^{-1}} = 1\,H$

Self-inductance of a coil is said to be 1 Henry when a current change of 1 As^{-1} through the coil induces an emf of 1 V in the coil.

Note:

1 milli Henry (mH) = 10^{-3} H

1 micro Henry (μH) = 10^{-6} H

Self-inductance of a long solenoid: In a long solenoid, length is very large as compared to its radius of cross section. The magnetic field B at any point inside such a solenoid is practically constant and is expressed by

$$B = \frac{\mu_0 NI}{\ell}$$

where μ_0 is absolute magnetic permeability of free space/air, which forms the core of the solenoid, ℓ is length of the solenoid and N is total number of turns in the solenoid.

Magnetic flux through each turn of the solenoid coil

= B × Area of each turn

$$= \left(\frac{\mu_0 NI}{\ell}\right)A$$

where A is area of each turn of the solenoid.

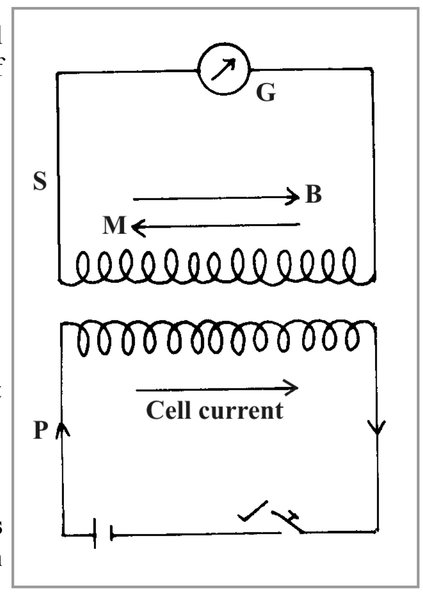
Now, total magnetic flux linked with the solenoid = Flux through each turn × Total number of turns,

i.e. $\phi = \dfrac{\mu_0 NIA}{\ell} \times N$

If L is coefficient of self-inductance of the solenoid, then $\phi = LI$

Then, $LI = \dfrac{\mu_0 NIA}{\ell} \times N$ *Or*, $L = \dfrac{\mu_0 N^2 A}{\ell}$

If core is of any other magnetic material, then μ_0 is replaced by μ such that $\mu = \mu_0 \mu_r$.



6. MUTUAL INDUCTANCE

Mutual induction is the property of two coils by virtue of which each of them opposes any change in the strength of current flowing through the other by developing an induced emf across it.

Coefficient of mutual induction or mutual inductance: Let a current I flow through the primary coil (P) at any instant of time and ϕ be the flux linked with the secondary coil (S) at that instant of time. S is situated in the magnetic filed produced by the current in P. Then,

$\phi \propto I$

Or $\phi = MI$ …(*i*)

where M is the coefficient of mutual induction or mutual inductance of two coils.

If I = 1A, then $\phi = M$

i.e. mutual inductance of the two coils is numerically equal to the magnetic flux linked with one coil when a unit current flows through the neighboring coil.

Differentiating the equation (*i*) with respect to t, we obtain

$$\frac{d\phi}{dt} = M\frac{dI}{dt} \qquad \ldots(ii)$$

Also, $$\varepsilon = -\frac{d\phi}{dt} \qquad \ldots(iii)$$

From (*ii*) and (*iii*)

$$|\varepsilon| = M\left(\frac{dI}{dt}\right) \qquad \ldots(iv)$$

SI unit of mutual inductance is **henry** (H).

From equation (*iv*)

$$M = \frac{|\varepsilon|}{\frac{dI}{dt}}$$

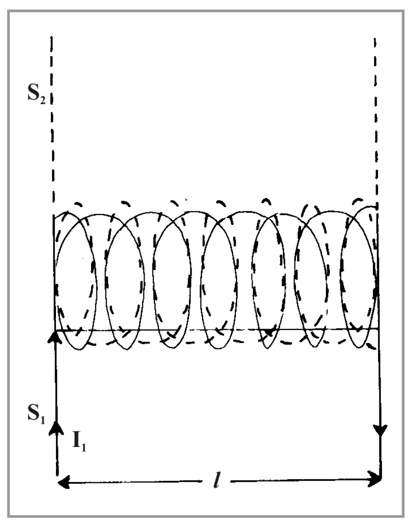
If $\varepsilon = 1\ \text{V}$ and $\frac{dI}{dt} = 1\,\text{As}^{-1}$

Then, $$M = \frac{1\,\text{V}}{1\,\text{As}^{-1}} = 1\,\text{H}$$

Mutual inductance of two coils is said to be 1 henry when a current change of 1 As^{-1} through one coil induces an emf of 1 V in the other.

Mutual inductance of two long solenoids: Consider a long air core solenoid S_1 having N_1 number of turns. Another solenoid S_2 having N_2 numbers of turns is wound over S_1. Let ℓ be the length of each solenoid. The coils of solenoid S_2 are closely wound over S_1 such that both have nearly the same cross-sectional area A.

The magnetic field B_1 at any point inside solenoid S_1 on passing a current I_1 through it is given by



$$B_1 = \mu_0\frac{N_1}{\ell}I_1 \qquad \ldots(i)$$

Now, magnetic flux linked with each turn of solenoid S_2

$= B_1 \times$ Area of each turn $= B_1A$

The total magnetic flux linked with a solenoid S_2 is given by:

$$\phi_2 = B_1A \times \text{Number of turns in solenoid } S_2$$

Or $$\phi_2 = B_1A(N_2) \qquad \ldots(ii)$$

Using equation (*i*)

$$\phi_2 = \left(\mu_0\frac{N_1}{\ell}\times I_1\right)AN_2$$

$$= \frac{\mu_0N_1N_2AI_1}{\ell} \qquad \ldots(iii)$$

The magnetic flux linked with the solenoid S_2 is directly proportional to the current I_1 passing through S_1. If M is the mutual inductance of the two solenoids, then,

$$\phi_2 = MI_1 \qquad \ldots(iv)$$

From (*iii*) and (*iv*)

$$M I_1 = \frac{\mu_0 N_1 N_2 A I_1}{\ell} \qquad Or \qquad M = \frac{\mu_0 N_1 N_2 A}{\ell}$$

If solenoid core is of any other magnetic material, then μ_0 is replaced by μ such that $\mu = \mu_0 \mu_r$.

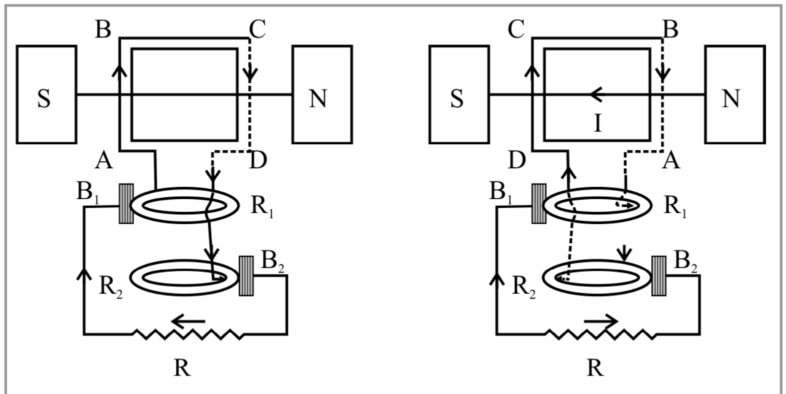
7. AC GENERATOR

AC generator is a device, which converts mechanical energy into electrical current energy.

It works on the principle of electromagnetic induction. An emf is induced in the coil whenever the magnetic flux linked with coil changes. Fleming's right-hand rule indicates the direction of induced current.

Construction

ABCD is a rectangular coil called armature, consisting of large number of turns of insulated copper wire wound over a laminated soft iron core. R_1 and R_2 are two hollow metallic rings such that R_1 is connected to one end of the armature coil and R_2 to the other end. These rings rotate with the rotation of the coil.



(*a*) (*b*)

The armature rotates between the pole pieces (N and S) of a strong electromagnet with the axis of rotation perpendicular to the magnetic field lines. Two flexible carbon rods B_1 and B_2 are used to pass on current from the armature coil to the external load resistance R.

As an armature coil is rotated in the magnetic field, the angle θ between field and normal to the coil changes continuously. Hence, magnetic flux linked with the coil changes and an emf is induced in the coil.

Working

Consider that the coil is perpendicular to the plane of the paper/screen in which the magnetic field is applied. AB is in front and CD is at the back. In this position, amount of magnetic flux linked with coil is maximum.

On moving or rotating the coil anticlockwise, the amount of magnetic flux linked with the coil changes. Current flows from B_2 to B_1 in the external circuit. According to Fleming's right-hand rule, current induced in AB is from A to B and that in CD is from C to D [as shown in figure (*a*)].

At the end of the half rotation, AB is at the back and CD is in the front. On further rotation, AB moves outwards and CD moves inwards. Now, in the external circuit, current flows from B_1 to B_2. Current induced in AB is from B to A and that in CD is from D to C [as shown in figure (*b*)].

That is, after a half rotation of the armature coil the direction of the induced current in the external circuit changes. This repeats for every half rotation and hence, the induced current is alternating in nature.

Calculation for magnitude of emf induced

Magnetic flux linked with the coil,

$$\phi = N\left(\vec{B}.\vec{A}\right) = NBA\cos\theta = NBA\cos\omega t \qquad \ldots(i)$$

where, N is the number of turns of the coil, A is the area enclosed by each turn of the coil, B is the strength of the magnetic field, θ is the angle that the normal to the coil makes with $\vec{B}$ at any instant of time (t) and ω is the angular velocity of the coil.

When coil is rotated and flux ϕ changes, an emf is induced in the coil.

Then,

$$\varepsilon = -\frac{d\phi}{dt} = -\frac{d}{dt}\left(NAB\cos\omega t\right)$$

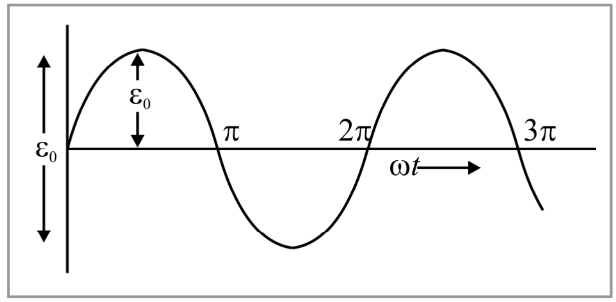
$$= NAB\,\omega\sin\omega t$$

Induced emf ε will be maximum, when $\sin\omega t = 1$.

$\varepsilon_{\max} = \varepsilon_0 = \text{NAB}$ ...(*ii*)

Hence, using equations (*i*) and (*ii*), we can write

$$\varepsilon = \varepsilon_0 \sin\omega t$$



If a graph is plotted between ε and ωt, it is a sine curve as shown in the figure below.

The current supplied by ac generator is also sinusoidal in nature and is given by:

$$I = \frac{\varepsilon}{R} = \frac{\varepsilon_0 \sin\omega t}{R} = I_0 \sin\omega t$$

where, $I_0 = \frac{\varepsilon_0}{R}$ = Maximum value of current

Advantages and Drawback of A.C. Over D.C.

(a) Advantage of a.c. over d.c. are :

(i) Altrnativng current can be transmitted over long distances using step up transformers. The loss of energy is negligible. Direct current cannot be transmitted as such.

(ii) The a.c. voltages can be easily varied using transformers.

(iii) the a.c. can be easily converted into d.c.

(iv) the magnitude of a.c. can be reduced using a choke coil, without involving loss of energy.

(v) the a.c. is easier and cheaper to generate than d.c. the a.c. generators are usually more robust and their efficiency is high.

(b) Drawbacks of a.c. are :

(i) It is more diagerous to work with a.c. at high voltages. The moment the insultation is faulty, one gets a severe shock.

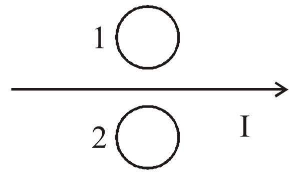
(ii) the shock of a.c. is attractive, whereas that of d.c. is repulsive.

(iii) there are certain phenomena like electroplating, electrorefining, electrotyping etc. where d.c. cannot be used. In such cases, d.c. is needed.

(iv) The a.c. is transmitted more from the surface of conductor than from inside. Therefore, several fine insultated wires (and not a single thick wire) are rquired for the transmission of a.c.

2012

1. Predict the directions of induced currents in metal rings 1 and 2 lying in the same plane where current I in the wire is increasing steadily. **(1 Marks)**

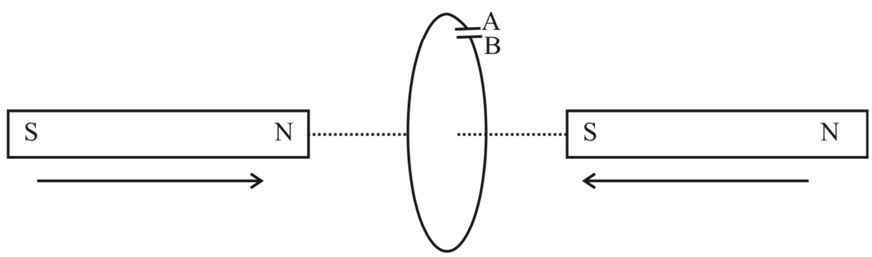


2. Define self-inductance of a coil. Show that magnetic energy required to build up the current I in a coil of self inductance L is given by $\frac{1}{2}LI^2$. **(2 Marks)**

3. A metallic rod of 'L' length is rotated with angular frequency of 'ω' with one end hinged at the centre and the other end at the circumference of a circular metallic ring of radius L, about an axis passing through the centre and perpendicular to the plane of the ring. A constant and uniform magnetic field B parallel to the axis is presents everwhere. Deduce the expression for the emf between the centre and the metallic ring. **(2 Marks)**

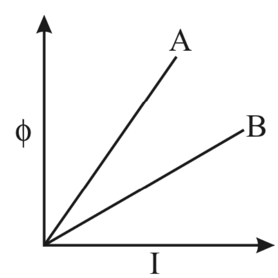
2011

1. Predict the polarity of the capacitor when the two magnets are quickly moved in the directions marked by arrows.



2010

1. A plot of magnetic flux (ϕ) versus current (I) is shown in the figure for two inductors A and B. Which of the two has larger value of self inductance? **(1 Marks)**



2009

1. (*a*) Define self inductance. Write its S.I. units. **(3 Marks)**

(*b*) Derive an expression for self inductance of a long solenoid of length l, cross-sectional area A having N number of turns.

2008

1. When current in a coil changes with time, how is the back emf induced in the coil related to it.

[Ans. $\in = -L\left(\frac{dI}{dt}\right)$**]** **(2 Marks)**

2. Derive an expression for the self-inductance of a long air-cored solenoid of length l and number of turns N. **(3 Marks)**

3. A coil of number of turns N, area A, is rotated at a constant angular speed ω, in a uniform magnetic field B, and connected to a resistor R. Deduce expressions for:

(*i*) Maximum emf induced in the coil

(*ii*) Power dissipation in the coil **(3 Marks)**

4. A jet plane is travelling west at 450 ms^{-1}. If the horizontal component of earths magnetic field at that place is 4×10^{-4} T and the angle of dip is 30°, findthe emf induced between the ends of wings having a span of 30 m. **(3 Marks)**

2007

1. A circular copper disc 10 cm in radius rotates at a speed of 20 rad s^{-1} about an axis through its centre and perpendicular to the disc. A uniform magnetic field of 0.2 T acts perpendicular to the disc.

(*i*) Calculate the potential difference developed between the axis of the disc and the rim. **[Ans.** 0.02 V**]**

(*ii*) What is the induced current if the resistance of the disc is 4 Ω. **[Ans.** 0.005 Amp**]** **(3 Marks)**

2006

1. How is the mutual inductance of a pair of coils affected when:

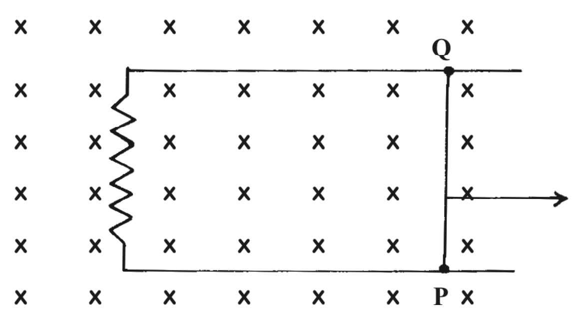
(*i*) separation between the coils is increased.

(*ii*) the number of turns of each coil is increased.

(*iii*) a thin iron sheet is placed between the two coils, other factors remaining the same? Explain your answer in each case. **(3 Marks)**

2. A 0.5 long metal rod PQ completes the circuit as shown in the figure. The area of the circuit is perpendicular to the magnetic field of flux density 0.15 T. If the resistance of the total circuit is 3Ω, calculate the force needed to move the rod in the direction as indicated with a constant speed of 2 ms^{-1}.

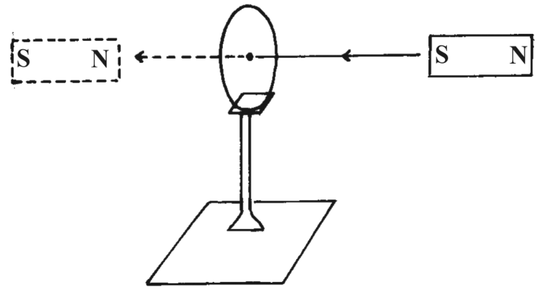
[Ans. 3.75×10^{-3} N**]** **(3 Marks)**



3. What are eddy currents. How are these produced. in what sense are eddy currents considered undesirable in a transformer and how are these reduced in such a device. **(3 Marks)**

2005

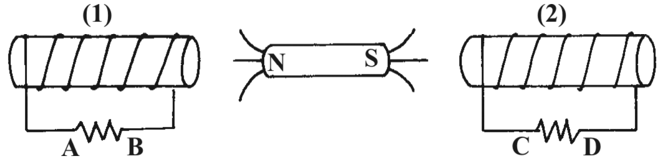
1. Give the direction in which the induced current flows in the coil mounted on an insulating stand when a bar magnet is quickly moved along the axis of the coil from one side to the other as shown in the figure. **(1 Mark)**



2. Two wires of equal lengths are bent in the form of two loops. One of the loops is square shaped whereas the other loop is circular. These are suspended in a uniform magnetic field and the same current is passed through them. Which loop will experience greater torque. Give reasons **(1 Mark)**

3. In the figure given below, a bar magnet moving towards the right or left induces an emf. in the coils (1) and (2). Find giving reason, the directions of the direction of the induced currents through the resistors AB and CD when the magnet is moving

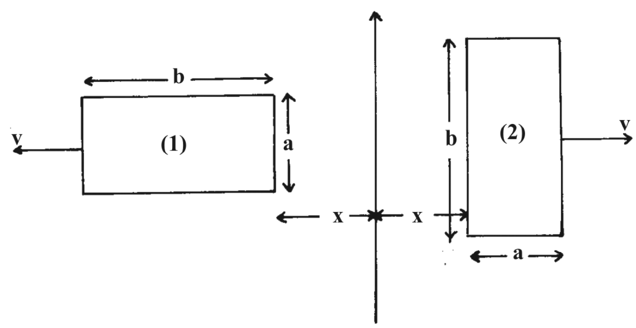
(*a*) towards the right, and (*b*) towards the left. **(2 Marks)**



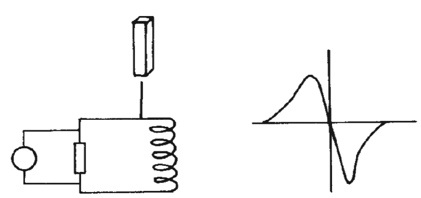
4. The figure shows two identical rectangular loops (1) and (2), placed on a table along with a straight long current carrying conductor between them.

(*i*) What will be the directions of the induced currents in the loops when they are pulled away from the conductor with same velocity U.

(*ii*) Will the e.m.f. induced in the two loops be equal. Justify your answer. **(2 Marks)**



5. Figure shows a bar magnet M falling under gravity through an air cored coil C. Graph shows variation of induced emf (E) with time (*t*). What does the area enclosed by the E-*t* curve depict. **(2 Marks)**



6. A circular coil of radius 8 cm and 20 turns rotates about its vertical diameter with an angular speed of 50 s^{-1} in a uniform horizontal magnetic field of magnitude 3×10^{-2} T. Find the maximum and average value of the emf induced in the coil.

[Ans. $\varepsilon_{max} = 1.92 \times 10^{-2}$ V, $\varepsilon_{avg} = 0$ **]** **(2 Marks)**

