Electromagnetic Induction

The phenomenon of producing induced emf and hence induced current in a closed circuit due to the change in magnetic field or change in magnetic flux linked with the closed circuit is known as electromagnetic induction.

Moving magnets can produce electric current in a nearby conducting loop. Similarly, moving conducting loop in the magnetic field of a magnet gets induced and an electric current starts flowing in it so long as the conducting loop moves in the magnetic field.

Magnetic flux

Magnetic flux (ϕ) through any surface is defined as the total number of magnetic lines passing through that surface.

Consider a small surface of area A. Let $\hat{n}$ be the unit vector which is drawn normal to the plane of the surface. If θ is the angle between $\hat{n}$ and the uniform magnetic field $\vec{B}$ (Fig 1), then the magnetic flux (ϕ) through the surface is given by,

$$\phi_B = \vec{B}\cdot\vec{A} = BA\cos\theta \quad \text{— (1)}$$

$$\phi_B = (B\cos\theta)A \quad \text{(2)}$$

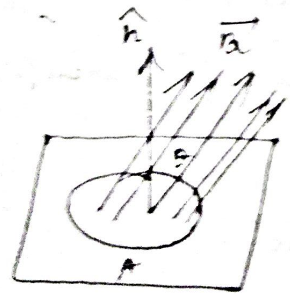


Fig 1

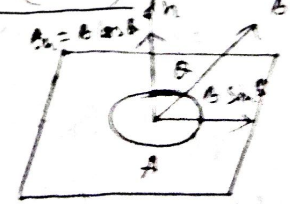


Fig 2

Now $B\cos\theta$ is the component of the magnetic field normal to the plane of the surface and can be represented as B_n (fig 2)

Then eqn (2) can be written as $\phi_B = B_n A$.

Thus, magnetic flux over a given surface is defined as the product of the area of the surface and the component of the magnetic field (B_n) normal to the plane of the surface.

<u>special case</u>

(i) when $\theta = 0°$ $\phi_B = BA$ = maximum.

i.e. maximum number of magnetic field lines pass through the given surface when $\theta = 0°$.

(ii) when $\theta = 90°$ $\phi_B = 0$

Thus the magnetic flux through a given surface is zero, when $\theta = 90°$.

<u>Definition of Magnetic flux density</u> i.e., strength of Magnetic field or Magnetic Induction (B).

$\because$ $\phi_B = BA$ $\therefore B = \frac{\phi_B}{A}$.

Thus, magnetic flux density (B) is defined as the magnetic flux (associated normally) per unit area.

In SI, magnetic flux is measured in weber (Wb)

$\because$ $\phi_B = B_n A$

$\therefore$ 1 weber = 1 tesla × 1 metre^2.

1 Wb = 1 T m^2.

In C.G.S system unit of magnetic flux is maxwell

1 maxwell = 10^{-8} weber.

Laws of electromagnetic induction:

From the experiments conducted by Faraday and others, Faraday deduced the following laws, known as Faraday's Laws.

1. Whenever relative motion exists between a magnetic field and a closed circuit such that the magnetic flux through that circuit changes, an e.m.f is induced in the circuit.

2. The induced e.m.f exists in the circuit as long as the change of flux exists.

3. The magnitude of induced e.m.f is proportional to the rate of change of the magnetic flux through the circuit.

If at any time t the flux lined with a closed coil is ϕ then according to Faraday's law the e.m.f induced in the coil is

$$e \propto \frac{d\phi}{dt} \quad -(1)$$

$$e = k\frac{d\phi}{dt}$$

where k is constant of proportionality. In S.I k=1.

$$\therefore e = \frac{d\phi}{dt}$$

Lenz's law

In the case of electromagnetic induction, the induced current always flows in such a direction as to oppose the very cause to which it is due.

So, Lenz's law gives us the direction of the induced e.m.f or current. The law is expressed

by putting a minus sign before $\frac{d\phi}{dt}$ in eqn (i)
Thus the induced e.m.f is

$$e \propto -\frac{d\phi}{dt}$$

$$e = -K \cdot \frac{d\phi}{dt} \quad [K = \text{constant of proportionality}]$$

$$\therefore e = -\frac{d\phi}{dt} \quad \text{(ii)}$$

Consider a coil or closed loop and a bar magnet.

i) When N pole of a bar magnet is brought near a loop fig A counter clockwise current is produced in the loop (as seen by the advancing N pole). This induced current produces a magnetic field which opposes the magnetic field of the bar magnet i.e. nearer face of the loop (as shown in fig A) behaves as N pole. North pole of the loop will repel the N pole of bar magnet.

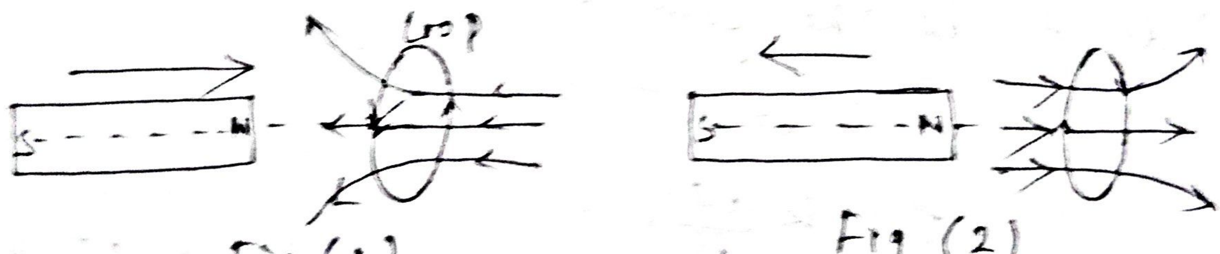


Fig (1) Fig (2)

(ii) When N pole is taken away from the loop, the nearer face of the loop behaves as S pole (fig (2)). It can be concluded that current due to induced e.m.f produces magnetism such that it opposes the cause (i.e. motion of the magnet) of producing e.m.f.

Self Induction and self inductance

Self induction is the property of a coil by virtue of which it opposes the growth or decay of the current flowing through it.

Consider a coil connected to a battery through a key (K).

When the key (K) is pressed, current in the coil starts increasing. Due to increasing current in the coil, the magnetic field and hence flux linkage around the coil also increases. As a result of this, induced e.m.f is set up in the coil. According to Lenz' law the direction of induced e.m.f is such that it opposes the growth of current in the coil. This delays the current to acquire the maximum value.

When the key (K) is released, the current in the coil starts decreasing. So the magnetic flux linked with the coil decreases. As a result of this change in magnetic flux, induced e.m.f is set up in the coil itself. According to Lenz' law the direction of induced e.m.f is such that it opposes the decay of current in the coil. This delays the current to acquire minimum or zero value.

Self Induction is also known as Inertia of electricity as it opposes the growth or decay of the current in the circuit.

Co-efficient of self induction or self Inductance.

Let current I flows through a coil at any instant, then the magnetic flux (ϕ) linked with the coil is found to be proportional to the strength of the current (I).

i.e. $\phi \propto I$ or $\phi = LI$.

Where L is known as co-efficient of self induction.

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

Thus, co-efficient of self Induction of a coil i.e. self inductance is defined as the magnetic flux linked with the coil when unit current flows through it

Also according to Faraday's law of electromagnetic induction, induced e.m.f in the coil is given by

$$\mathcal{E} = -\frac{d\phi}{dt}$$

$$= -\frac{d}{dt}(LI)$$

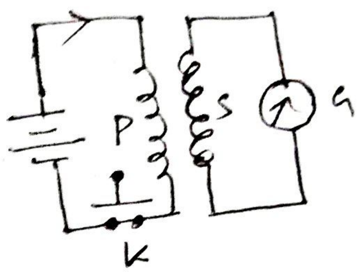
$$\mathcal{E} = -L\frac{dI}{dt},$$

If $-\frac{dI}{dt} = 1$ i.e. rate of decrease of current is unity, then we get $L = \mathcal{E}$.

Thus co-efficient of self induction of a coil is defined as the induced e.m.f produced in the coil through which the rate of decrease of current is unity.

Mutual Induction and mutual Inductance

Mutual induction is the phenomenon of inducing e.m.f in a coil due to the change of current with time in a nearby coil.



Consider a coil connected to a battery through a key (k). This coil is called primary coil (P). Another coil placed near the primary coil and connected to the galvanometer shows a deflection.