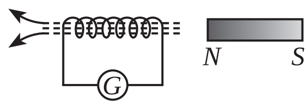
CHAPTER

6 Electromagnetic Induction

Faraday's Experiments

- **First experiment:** Relative motion between a bar magnet and wire loop produces a small amount of current.



- **Second experiment:** If one coil is connected to a battery and another coil is moved towards or away from it, electric current is produced in neighbouring coil.

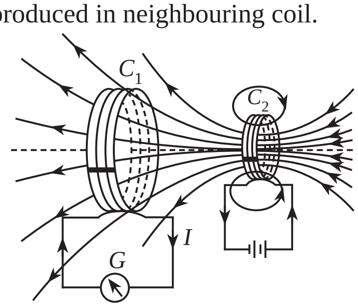
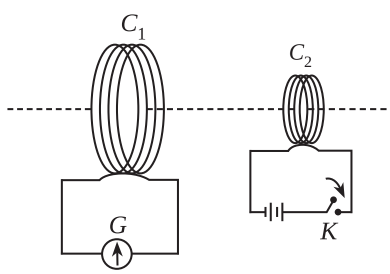


Fig.: Current is induced in coil C_1 due to motion of the current carrying coil C_2.

- **Third experiment:** Galvanometer shows a momentary deflection when tapping key K is closed or opened.



Magnetic Flux

Magnetic flux through a surface of area $\vec{A}$ placed in uniform magnetic field $\vec{B}$ is written as $\phi_\theta = \vec{B}\cdot\vec{A} = BA\cos\theta$

For non-uniform magnetic field

$$\phi = \int \vec{B}\cdot d\vec{A}$$

Faraday's Laws of Induction

Conclusion of experiments was formulation of following laws:

1. The magnitude of the induced emf in a circuit is equal to the time rate of change of magnetic flux through the circuit.
2. Mathematically the emf induced is given by

$$\boxed{\varepsilon = -\frac{d\phi_B}{dt}}$$

- Negative sign indicates the direction of ε and hence the direction of current in the closed loop.
- If loop contains N turns, change of flux is associated with each turn.

$$\boxed{\varepsilon = -N\left(\frac{d\phi_B}{dt}\right)}$$

- The induced emf can be increased by increasing the number of turns of closed coil.

Lenz's Law

- **Lenz's law:** This law gives the polarity of induced emf. The polarity of induced emf is such that it tends to produce a current which opposes the change in magnetic flux that produced it.
- The law is in accordance with the law of conservation of energy.

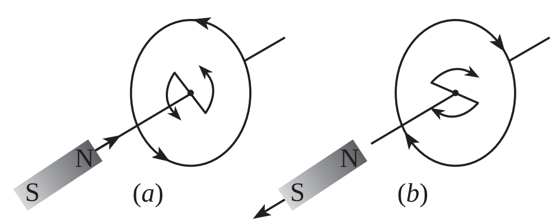
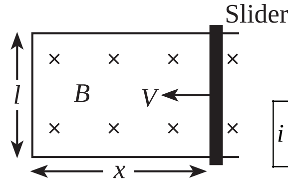


Fig.: Illustration of Lenz's law

Motional EMF

- **Straight conductor in motion:** In uniform and time independent magnetic field.

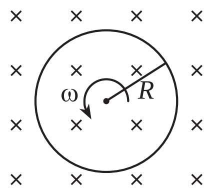


$\boxed{e = Blv}$ (emf across rod)

$$\boxed{i = \frac{\varepsilon}{R} = \frac{Blv}{R}} \quad \boxed{\Delta Q = \frac{\Delta\phi_B}{R}} \quad \boxed{P = \frac{B^2l^2v^2}{R}}$$

Mechanical energy which is needed to move the rod is converted into electric energy and then to thermal energy.

❖ Rod rotated about one end:



$$\boxed{\varepsilon = \frac{B\omega R^2}{2}}$$

Fleming's right hand rule: This gives the direction of induced emf or current in a conductor moving in a magnetic field. If we stretch forefinger, central finger and thumb of our right hand in mutually perpendicular directions such that forefinger is along magnetic field, thumb along direction of motion of the conductor then central finger will give the direction of induced current.

Eddy Currents

Electric currents are induced in well defined paths in a conductor like circular loops, when bulk piece of conductor is subjected to changing magnetic flux. This circular induced current is knwon as eddy current.

The eddy currents are also called Foucault currents after its discoverer.

❖ These currents are used in many applications.
1. Magnetic braking of trains
2. Electromagnetic damping
3. Induction furnace

❖ Eddy currents dissipate energy in the form of heat energy.

❖ Eddy currents are minimized using laminations of metal to make a metal core.

Self Inductance

Phenomenon of induced EMF in a single isolated coil due to changing magnetic flux through the coil by means of varying the current through same coil is self induction.

Total flux linkage = Li [L is the self inductance.]

Emf induced in the coil is

$$\varepsilon = -L\frac{di}{dt}$$

❖ Self induced emf always opposes any change of current in the coil.

Self inductance of a solenoid is $L = \mu_0 n^2 Al$

n is number of turns per unit length of the solenoid.

When solenoid is filled with some material.

$$L = \mu_0\mu_r n^2 Al$$

❖ Self inductance plays the role of inertia. It is electromagnetic analogue of mass in mechanics.

❖ SI unit of self inductance is henry (H).

❖ Self inductance of the coil depends on its geometry and on the permeability of the medium.

Mutual Inductance

❖ Varying current in one coil can induce emf in neighbouring coil.

$$\varepsilon_1 = M\frac{di_2}{dt}$$

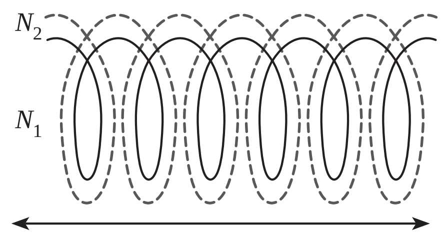
The magnitude of induced emf depends on rate of change of current and mutual inductance of two coils:

❖ SI unit of mutual inductance is henry and is denoted by H. Its dimensional formula is $ML^2T^2A^{-2}$.

For two long co-axial solenoids each of length l

$$M_{12} = \mu_0 n_1 n_2 Al$$

where, M_{12} is coefficient of mutual induction



$$M_{12} = M_{21}$$

❖ Mutual inductance of a pair of coils, depends on their separation as well as their relative orientations.

❖ For two concentric circular coils with radius r and $R(R >> r)$ coils which are concentric as well as coplanar.

$$M_{12} = M_{21} = \frac{\mu_0\pi(r)^2}{2R}$$

Magnetic Potential Energy

❖ Energy required to build any current I in a system of self inductance L

$$W = \frac{1}{2}\times L\times l^2$$

❖ This work done gets stored as magnetic potential energy.

$$U_B = \frac{1}{2}U^2 = \frac{B^2 Al}{2\mu_0}$$

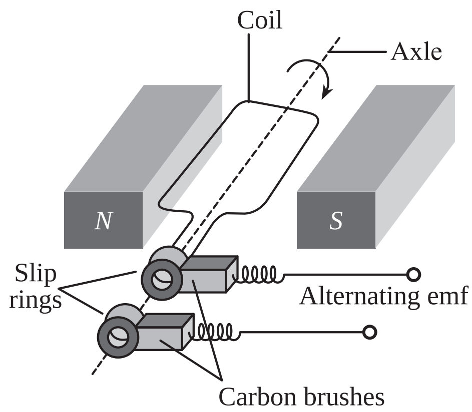
❖ Magnetic energy per unit volume.

$$u_B = \frac{B^2}{2\mu_0} \rightarrow \text{Energy is proportional to square of field strength}$$

AC Generator

❖ AC generator is based on the phenomenon of electromagnetic induction.
- ✦ Modern A.C. generator has output capacity upto 100 MW.
- ✦ This machine converts mechanical energy into electric energy.
- ✦ The emf induced is sinusoidal.

$$\varepsilon = NBA\omega\sin\omega t$$



NBA ω is the maximum value of emf when $\sin\omega t = \pm 1$.

Let $\varepsilon_0 = NBA\omega$

$\Rightarrow \; \varepsilon = \varepsilon_0 \sin \omega l$

ω is angular speed of rotor of ac generator.

The direction of current and emf changes periodically with time.

$\therefore \; \varepsilon = \varepsilon_0 \sin(2\pi v t)$

- v in India is 50 Hz
- v in USA is 60 Hz

Stage-1: The plane of the armature is perpendicular to the magnetic field.

Stage-2: When the armature rotates through 90° the plane of the armature is parallel to magnetic field.

Stage-3: Armature after a rotation of 180°

Stage-4: Armature after a rotation of 270°

Stage-5: Armature after a rotation through 360°