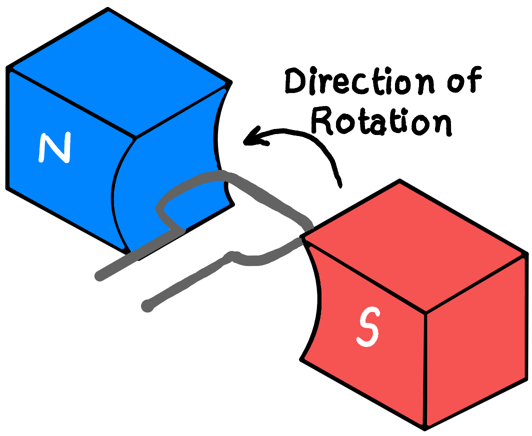
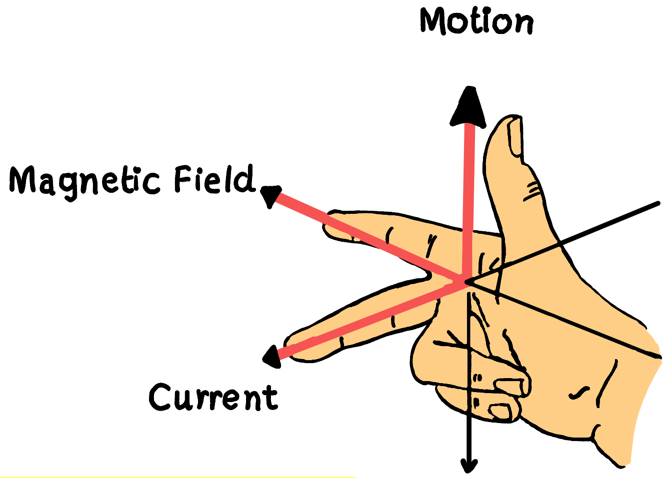
ELECTROMAGNETIC INDUCTION

CLASS 12 PHYSICS





NEW NOTES 2022-23

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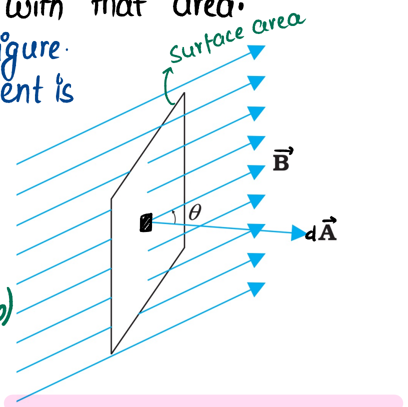
Magnetic flux :→ The total number of magnetic field lines of force passing normally through an area placed in a magnetic field is equal to the magnetic flux linked with that area.

Consider an element of area $d\vec{A}$ on an rectangular shape as shown in figure.
if the magnetic field at this element is $\vec{B}$, the magnetic flux through the element is



$$d\phi_B = \vec{B}\cdot d\vec{A} = B\,dA\cos\theta$$

Total Magnetic flux through the Surface

$$\phi_B = \int \vec{B}\cdot d\vec{A} = \int B\,dA\cos\theta$$

NOTE:→ Magnetic flux is a scalar quantity.
→ SI unit of magnetic flux is tesla-metre² ($1\,Tm^2$), Called as weber ($1\,Wb$)

Electromagnetic Induction.

If the magnetic flux through a circuit changes, an emf and a current are induced in the circuit. This phenomena is called as Electromagnetic Induction.

• Faraday's Law

First Law : Whenever the number of magnetic Lines of force (Magnetic flux) passing through a circuit changes, an emf called induced emf is produced in the Circuit. The induced emf persists as long as there is change or cutting of flux.

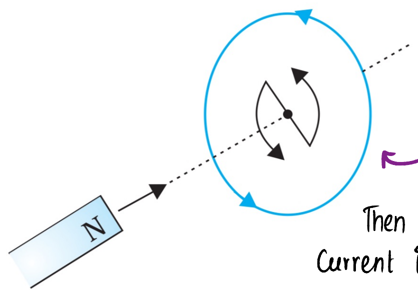
• Second Law : The magnitude of induced emf in a circuit is equal to the time rate of change of magnetic flux through the Circuit. Mathematically, the induced emf is given by

$$\varepsilon = -\frac{d\phi_B}{dt} \quad \text{or for closely wound coil of N turns} \quad \varepsilon = -\frac{N\,d\phi_B}{dt}$$

−ve sign indicates the direction of ε and hence direction of Current in the Circuit.

LENZ'S LAW :→ It states that the direction of the induced current is such that it opposes the change that has induced it.

NOTE: If a Current is induced by an increasing flux, it will weaken the original flux. If a current is induced by a decreasing flux, it will strengthen the original flux.

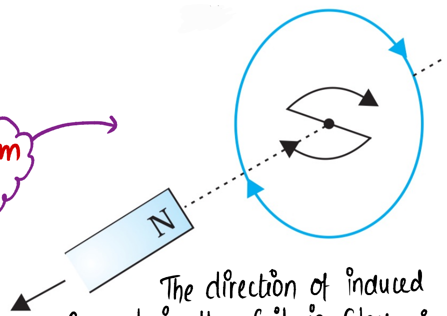


When North Pole of Magnet is moving

Toward Coil

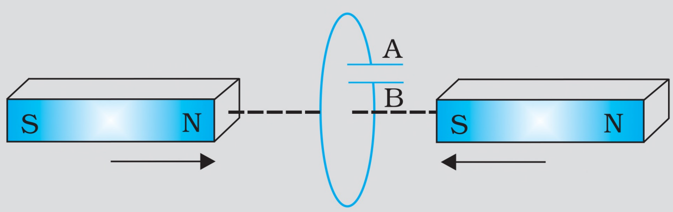
Then direction of induced Current in the Coil is Anticlock wise

Away from Coil



The direction of induced Current in the Coil is Clockwise.

Predict the polarity of the capacitor in the situation described by Fig. 6.9.



Do yourself

Motional Electromotive Force : The emf induced across the ends of a conductor due to its motion in a magnetic field is called motional emf.

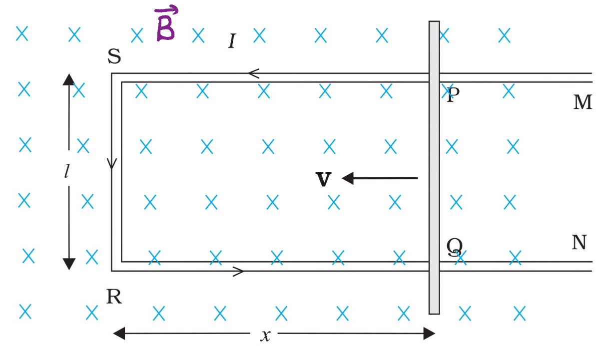


Figure shows a rectangular conductor PQRS in which the conductor PQ is free to move. The rod PQ is moved towards the left with a constant velocity v.

The magnetic flux enclosed by the loop PQRS will be

$\phi_B = \vec{B}\cdot\vec{A} \Rightarrow \phi_B = BA\cos\theta \qquad A = lx$

So $\quad \phi_B = Blx\cos 0^\circ \qquad \theta = 0^\circ \qquad \vec{B} \parallel \vec{A}$ (in same direction)

$\phi_B = Blx$

And the induced emf is given by $\qquad \mathcal{E} = -\dfrac{d\phi_B}{dt}$

So $\mathcal{E} = -\dfrac{d(Blx)}{dt} \Rightarrow \mathcal{E} = -Bl\dfrac{(dx)}{(dt)}$ since x is changing with Time.

Here

$\dfrac{dx}{dt} = -v$ (speed of the conductor PQ) $\qquad$ Hence $\boxed{\mathcal{E} = Blv}$

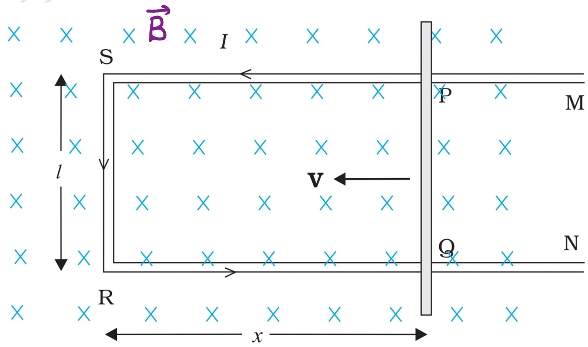
Another Method For Motional EMF

When the rod moves with speed v, the charge will also be moving with speed v in the magnetic field $\vec{B}$. The Lorentz force on this charge is $\boxed{qvB}$ in magnitude, and its direction is towards Q. All charges experience the same force, in magnitude and direction, irrespective of their position in the rod PQ. The work done in moving the charge from P to Q is

$W = qvBl$ and emf is $\mathcal{E} = \dfrac{W}{q}$, emf is work done per unit charge. $\qquad \dfrac{qvBl}{q} \Rightarrow \boxed{\mathcal{E} = Bvl}$

• Energy Consideration : A Quantitative Study

Let r be the resistances of movable arm PQ of the rectangular consider. The remaining arms QR, RS and SP have negligible resistances compared to r. Thus overall resistance of loop is r. and does not change as PQ is moved. The current i in the loop is $\quad I = \dfrac{\mathcal{E}}{r} \Rightarrow I = \dfrac{Blv}{r}$, Due to magnetic field, there will be a force on the arm PQ. This force is $\boxed{F = ilB}$ put value of i



So $\quad F = \dfrac{B^2l^2v}{r}$

The arm PQ is being pushed with a constant speed v, the power required to do this is

$P = Fv$

$P = \dfrac{B^2l^2v^2}{r}$ The agent that does this work is mechanical. where does this mechanical energy go? The answer is : it is dissipated as joule heat.

Relation between the charge flow through the circuit and the change in magnetic flux.

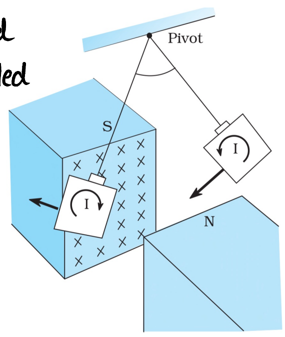
From Faraday's law we have learnt $\quad |\mathcal{E}| = \dfrac{\Delta\phi_B}{\Delta t}$ However $|\mathcal{E}| = Ir = \dfrac{\Delta Q}{\Delta t}r \Rightarrow \boxed{\Delta Q = \dfrac{\Delta\phi_B}{r}}$

Eddy Current : When a changing magnetic flux is applied to a piece of conducting material, circulating currents called eddy current are induced in the material.

These eddy current often have large magnitudes and heat up the conductor.

Advantages of Eddy Current

- Magnetic braking in trains
- Electromagnetic damping
- Induction furnace
- Electric Power meters.



Eddy currents are generated in the copper plate, while entering and leaving the region of magnetic field.

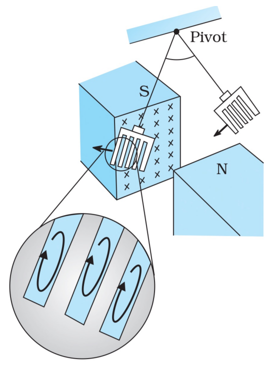


FIGURE . Cutting slots in the copper plate reduces the effect of eddy currents.

Inductance

Self Inductance

Whenever the electric Current passing through a coil or circuit changes, the magnetic flux linked with it also change, an emf is induced in the Coil or the circuit which opposes the change that Causes it. This phenomenon is called "self induction". and the emf induced is called back emf. Current so produced is called induced Current.

* Coefficient of Self Induction

Number of flux linkages with the Coil is proportional to the Current i i.e $N\phi \propto i$ or $N\phi = Li$

Hence $L = \frac{N\phi}{i}$ = coefficient of self induction

- By Faraday's law, induced emf $e = -N\frac{d\phi}{dt}$

i.e $e = -L\frac{di}{dt}$

if $\frac{di}{dt} = 1$ amp then $|e| = L$

Hence coefficient of self induction is equal to the emf induced in the coil when the rate of change of current in the coil is unity.

- SI unit of L = Henry (H)

Mutual Inductance

- Whenever the current passing through a coil or circuit changes, the magnetic flux linked with a neighbouring coil or circuit will also change. Hence an emf will be induced in the neighbouring coil or circuit. This phenomenon is called 'mutual induction'.

* Coefficient of mutual induction.

Total flux linked with the Secondary due to current in the primary is $N_2\phi_2$ and $N_2\phi_2 \propto i_1$

$N_2\phi_2 = M i_1 \Rightarrow M = \frac{N_2\phi_2}{i_1}$ = coefficient of mutual induction.

Acc. to Faraday's law

$e_2 = N_2\frac{d\phi_2}{dt} \Rightarrow e_2 = -M\frac{di_1}{dt}$

if $\frac{di_1}{dt} = 1$ amp then $|e_2| = M$

Hence Coefficient of Mutual induction is equal to the emf induced in the secondary coil when rate of change of current in primary coil is unity.

Inductance of a Solenoid :→

Let us find the inductance of a uniformly wound Solenoid having N turns and length l. Assume that l is much longer than the radius of the windings and that the core of the solenoid is air. Magnetic field due to a Current i is uniform and given by

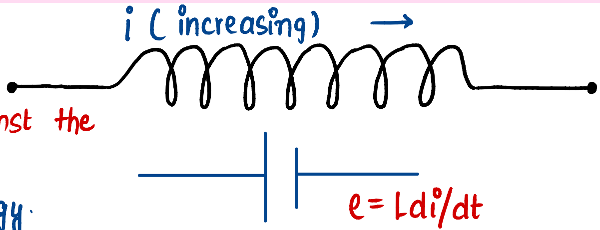
$B = \mu_0 n i \Rightarrow B = \mu_0\left(\frac{N}{l}\right)i$ $\quad \frac{N}{l}$ = number of turns per unit length

The magnetic flux through each turn is $\phi_B = BA = \mu_0 \frac{N}{l} A i$, where A = cross-sectional area of the Solenoid.

$L = \frac{N\phi_B}{i} = \frac{N}{i} \times \frac{\mu_0 N A i}{l} \Rightarrow \boxed{L = \frac{\mu_0 N^2 A}{l}}$ $\quad N = nl \quad L = \frac{\mu_0 n^2 l^2 A}{l} \Rightarrow \boxed{L = \mu_0 n^2 l A}$ $\quad Al = V$ (Volume of the Solenoid)

Energy stored in an inductor

An increasing current in an inductor causes an emf between its terminals. Work needs to be done against the back emf (E) in establishing the Current.



This work done is stored as magnetic potential energy.

For the Current i at any instant in a circuit, the rate of work done per unit time is

$\frac{dW}{dt} = |e| i \Rightarrow \frac{dW}{dt} = L\frac{di}{dt} i \Rightarrow dW = L i\, di$

For Total work done $\int_0^W dW = \int_0^i L i\, di \Rightarrow W = L\int_0^i i\,dt \Rightarrow W = \frac{1}{2}Li^2$

W = U = Potential energy stored in an inductor.

Magnetic energy density (u)

u = energy stored per unit volume

$u = \frac{U}{V} \Rightarrow \boxed{u = \frac{1}{2}\frac{B^2}{\mu_0}}$

Mutual inductance of two long co-axial solenoid.

Figure shows a solenoid S_2 of N_2 turns and Radius r_2 surrounding a long solenoid of length l, radius r_1 and number of turns N_1. (length of both Solenoid is same).

When a current I_2 is set up through S_2, it in turn sets up a magnetic flux through S_1. Let us denote it by Φ_1. The corresponding flux linkage with solenoid S_1 is

$$N_1\Phi_1 = M_{12} I_2 \quad \text{—①}$$

M_{12} is called the *mutual inductance* of solenoid S_1 with respect to solenoid S_2. It is also referred to as the *coefficient of mutual induction.*

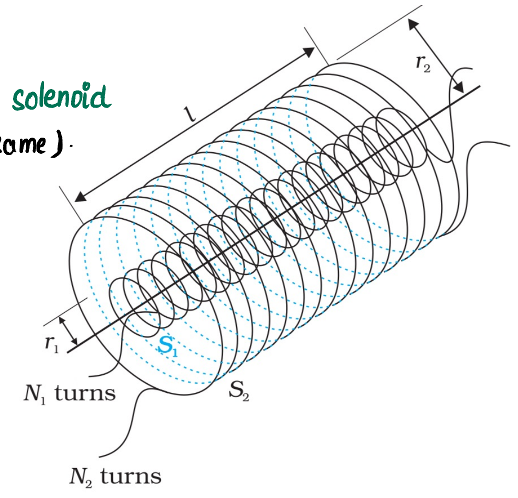


FIGURE Two long co-axial solenoids of same length l.

The resulting flux linkage with Coil S_1 is

$N_1\phi_1 = (N_1) B_2 A_1 \qquad B_2 = \mu_0 n_2 i_2 \qquad A_1 = \pi r_1^2 \qquad N_1 = n_1 l$

i.e $N_1\phi_1 = n_1 l \mu_0 n_2 i_2 \pi r_1^2$

From ① eq we get

$M_{12} I_2 = \mu_0 n_1 n_2 l I_2 \pi r_1^2 \Rightarrow \boxed{M_{12} = \mu_0 n_1 n_2 \pi r_1^2 l}$

Similarly $M_{21} = \mu_0 n_1 n_2 \pi r_1^2 L$

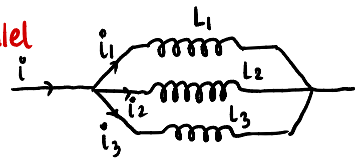
also $M_{12} = M_{21} = M = \mu_r \mu_0 n_1 n_2 \pi r_1^2 l$ For a medium of Relative Permeability μ_r i.e $\mu = \mu_0 \mu_r$

Combination of inductances

In Series

Then $\boxed{L = L_1 + L_2 + L_3}$

In Parallel



$$\boxed{\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}}$$

• NOTE: If the flux from one inductance links another, mutual inductance term becomes important. This mutual interaction may increase or decrease the flux due to the self induction. The equivalent inductance of the pair of coils in series is, $L = L_1 + L_2 \pm 2M$

A.C Generator (Dynamo): A dynamo converts mechanical energy (rotational kinetic energy) into electrical energy.

It consists of a coil rotating in a magnetic field. Due to rotation of the coil magnetic flux linked with it changes, so an emf is induced in the coil.

Principle: when a closed coil is rotated rapidly in a strong magnetic field, the number of magnetic flux-lines passing through the coil changes continuously. Hence, an emf is induced in the coil and a current flows in the circuit connected to the coil.

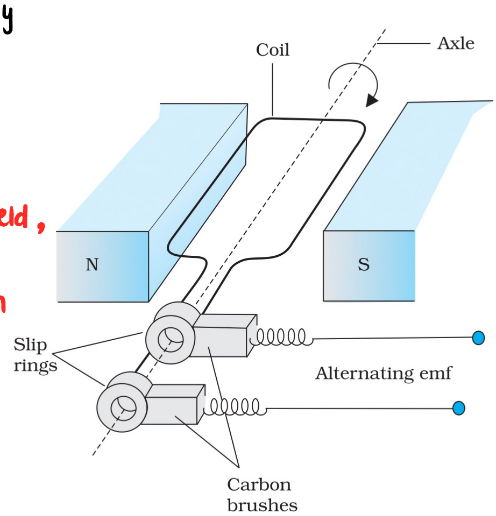


FIGURE AC Generator

working

when the coil is rotated with a constant angular speed ω, the angle θ between the magnetic field vector $\vec{B}$ and the area vector $\vec{A}$ of the coil at any instant t is $\theta = \omega t$

(assuming $\theta = 0°$ at $t = 0$)

As a result the effective area of the coil exposed to the magnetic field lines changes with time.

NOTE:

As the armature coil rotates, the magnetic flux linked with changes. Hence, an emf is induced in the coil and current flow in it.

Suppose at $t=0$, plane of coil is perpendicular to the magnetic field.

The flux linked with it at any time t will be given by

$$\phi = NBA\cos\omega t$$

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

$\frac{d}{dt}(\cos\omega t) = -\sin\omega t\,\omega$

$$e = -\frac{d}{dt}(NBA\cos\omega t)$$

$$\Rightarrow e = NBA\omega\sin\omega t$$

$$\text{or} \quad \boxed{e = e_0 \sin\omega t}$$

where $e_0 = NBA\omega$ = max value of induced emf.

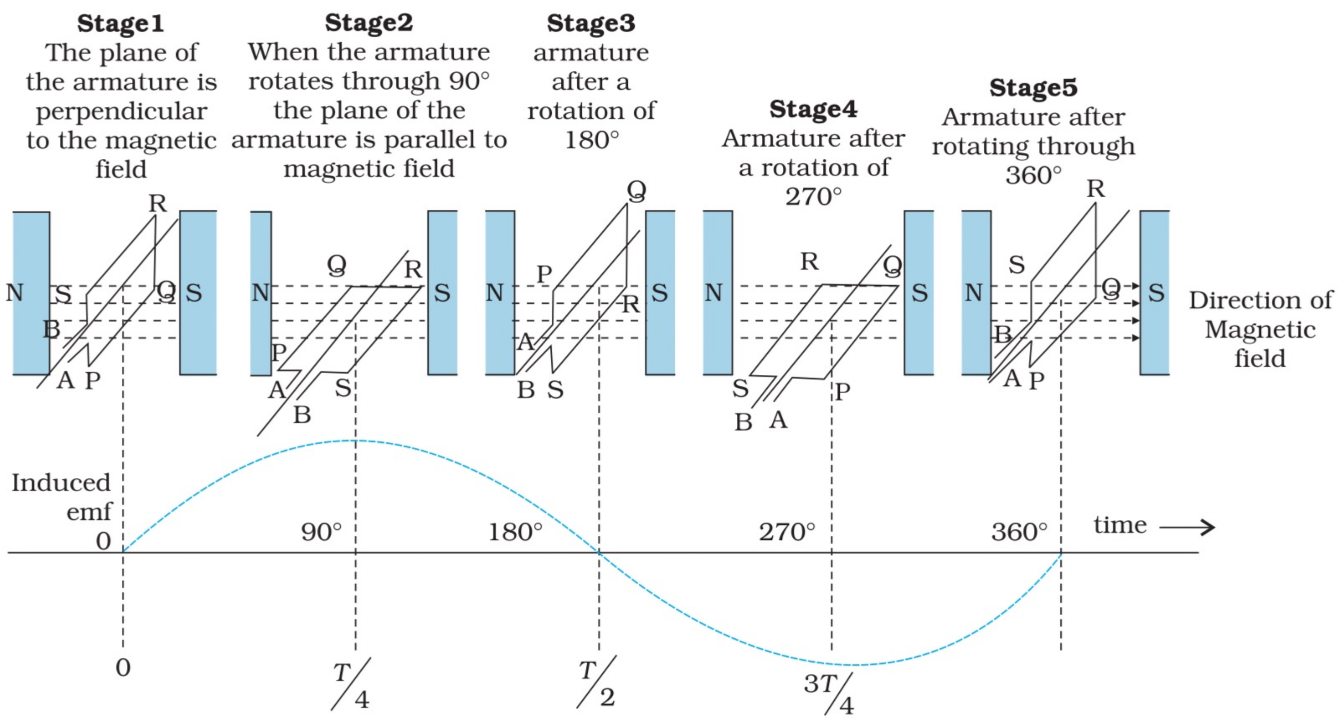


FIGURE 6.17 An alternating emf is generated by a loop of wire rotating in a magnetic field.