Eddy currents

CLASS-XII

SUBJECT : PHYSICS
CHAPTER NUMBER: 06
CHAPTER NAME : ELECTROMAGNETIC INDUCTION

CHANGING YOUR TOMORROW

Lenz’s Law and Law of Conservation of Energy:

- According to Lenz’s law, the induced emf opposes the change that produces it.
- It is this opposition against which we perform mechanical work in causing the change in magnetic flux. Therefore, mechanical energy is converted into electrical energy.
- Thus, Lenz’s law is in accordance with the law of conservation of energy.
- If, however, the reverse would happen (i.e. the induced emf does not oppose or aids the change), then a little change in magnetic flux would produce an induced current which would help the change of flux further thereby producing more current.
- The increased emf would then cause further change of flux and it would further increase the current and so on. This would create energy out of nothing which would violate the law of conservation of energy.

Expression for Induced emf based on both the laws:

$\mathcal{E} = - d\Phi / dt$

$\mathcal{E} = - (\Phi_2 - \Phi_1) / t$

And for 'N' no. of turns of the coil,

$\mathcal{E} = - N\, d\Phi / dt$
$\mathcal{E} = - N (\Phi_2 - \Phi_1) / t$

Note:
Induced emf does not depend on resistance of the circuit where as the induced current and induced charge depend on resistance.

Expression for Induced current:

$I = - d\Phi / (R\, dt)$

Expression for Charge:

$dq / dt = - d\Phi / (R\, dt)$

$dq = - d\Phi / R$

Faraday’s Laws of Electromagnetic Induction:

NOTE:-

- In the case of E.M.I, an emf $|\varepsilon| = \frac{d\phi}{dt}$ always existed, either the circuit is closed or open but the current will exist only if the circuit is closed.
- If the circuit is closed, induced current

  $I = \frac{\varepsilon}{R} = -\frac{Nd\phi}{Rdt}$ (Where R is the total resistance of the circuit)

- Induced charge $dq = Idt = -\frac{Nd\phi}{R}$ (Independent of time)
- $inducedpower(P) = \varepsilon I = \frac{N^2}{R}\left(\frac{d\phi}{dt}\right)^2$
- Induced field: - Time-varying magnetic field induces electric field which is related to induced emf as

$$\varepsilon = \int E_{in}.d\ell$$

Since $\int E.dl \neq 0$this indicate induced electric field is a **non-conservative** field.

NUMERICAL

A square loop of side 10cm and resistance 0.5Ω is placed vertically in the east-west plane. A uniform magnetic field of 0.1 T is set up across the plane in the north-east direction. The magnetic field is decreased to zero in 0.7 s at a steady rate.

(a) Determine the magnitudes of induced emf

(b) Determine the induced current during this internal **[NCERT]**

NUMERICAL

Solution:-

$\phi = BA\cos\theta$

Initial flux = $BA\cos 45^\circ$ [$\therefore$ Area vector makes 45° with field]

$= \left(0.1\times10^{-2}\right)\frac{1}{\sqrt{2}}$

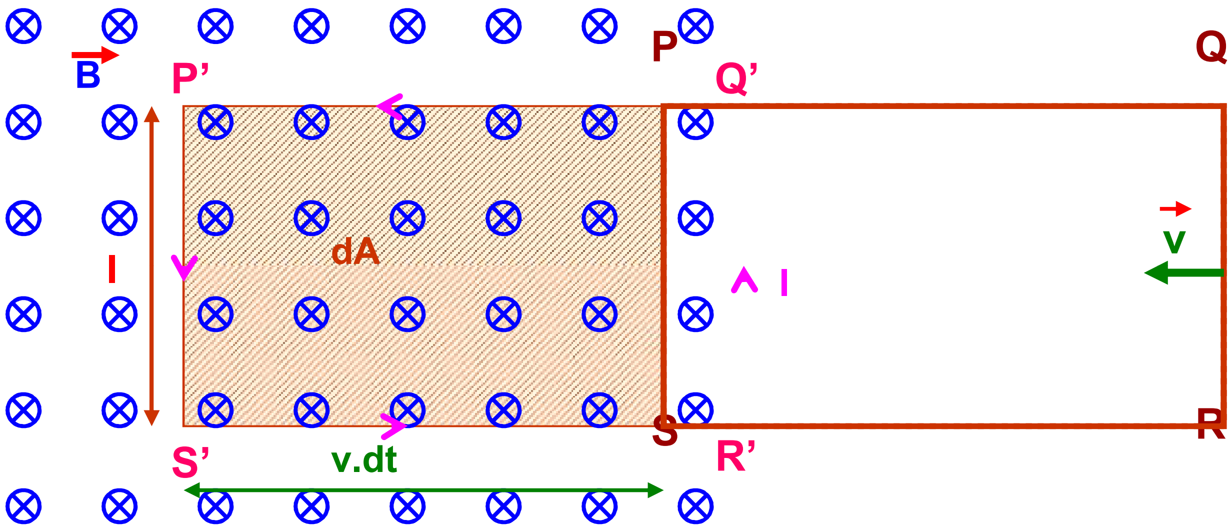
Final flux = 0

(a) $\varepsilon = \frac{\phi_{\text{initial}} - \phi_{\text{final}}}{\Delta t} = 1\,\text{mv}$

(b) $I = \frac{\varepsilon}{R} = \frac{10^{-3}\,\text{v}}{0.5\Omega} = 2\,\text{mA}$

Motional Electromotive Force

Magnetic flux Φ can be changed by changing the area of the loop A which is acted upon by the magnetic field B and hence emf can be induced in the circuit.



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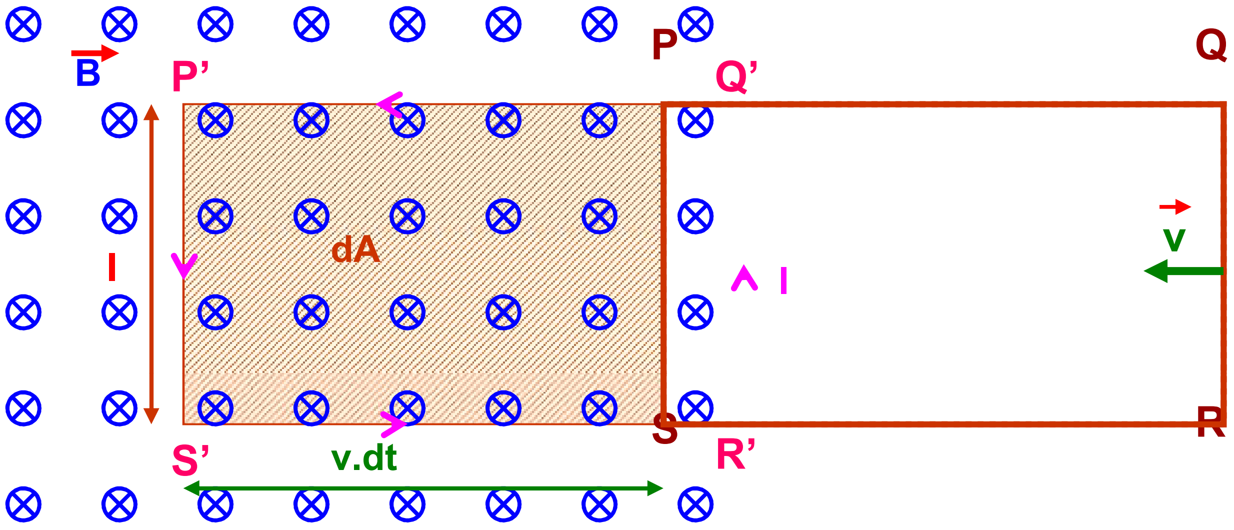


$$d\Phi = B.dA$$

$$= B.l.v.dt$$

$$\varepsilon = - d\Phi / dt$$

$$\therefore \varepsilon = - Blv$$

The loop PQRS is slided into uniform and perpendicular magnetic field. The change (increase) in area of the coil under the influence of the field is dA in time dt. This causes an increase in magnetic flux dΦ.

The induced emf is due to motion of the loop and so it is called 'motional emf'.
If the loop is pulled out of the magnetic field, then $\varepsilon = Blv$
The direction of induced current is anticlockwise in the loop. i.e. P'S'R'Q'P' by Fleming's Right Hand Rule or Lenz's Rule.

Motional Electromotive Force

Magnetic flux Φ can be changed by changing the area of the loop A which is acted upon by the magnetic field B and hence emf can be induced in the circuit.

Method – II, when the conductor moves $\perp rto\vec{B}$, all the charges experience the same force $(= qvB)$ in rod PQ. The work done in moving the charge from P to Q through a distance ℓ, is

$$w = F\ell = qvB\ell$$

Since emf is the work done per unit charge

$$\varepsilon = \frac{w}{q}$$

$$= \frac{qvB\ell}{q}$$

$$= B\ell v$$

Motional Electromotive Force

According Lenz's Rule, the direction of induced current is such that it opposes the cause of changing magnetic flux.

Here, the cause of changing magnetic flux is due to motion of the loop and increase in area of the coil in the uniform magnetic field.

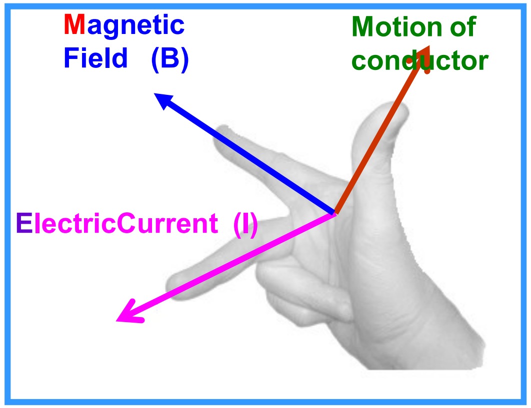
Therefore, this motion of the loop is to be opposed. So, the current is setting itself such that by Fleming's Left Hand Rule, the conductor arm PS experiences force to the right whereas the loop is trying to move to the left.

Against this force, mechanical work is done which is converted into electrical energy (induced current).

NOTE: If the loop is completely inside the boundary of magnetic field, then there will not be any change in magnetic flux and so there will not be induced current in the loop.

Fleming's Right-Hand Rule:

If the central finger, fore finger and thumb of right hand are stretched mutually perpendicular to each other and the fore finger points to magnetic field, thumb points in the direction of motion (force), then central finger points to the direction of induced current in the conductor.



Motional Electromotive Force

Note:-

(a) The induced current in the loop, $I_{in} = \frac{\varepsilon}{R} = \frac{B\ell v}{R}$

(Where r resistance of arm PQ. The total resistance of remaining arm u negligible compared to R)

(b) Magnetic force on the conductor opposing the motion of the rod.

$$F_m = BI_{in}\ell = B\left(\frac{B\ell v}{R}\right)\ell = \frac{B^2 v \ell^2}{R}$$

(c) Rate of doing work (power dissipated) in maintaining the motion of rod by pulling force F.

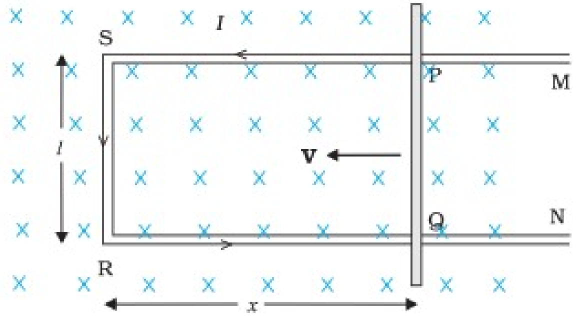
$$P = \frac{dw}{dt} = F.v = \frac{B^2\ell^2 v^2}{R}$$

(d) Electrical power dissipated through the resistor (Joule loss)

$$P_{thermal} = I_{in}^2 R = \left[\frac{B\ell v}{R}\right]^2 R = \frac{B^2 v^2 \ell^2}{R}$$

The phenomenon of electromagnetic induction by Lenz’s law represents the conservation of energy.

Qualitative treatment:-



Suppose the N-pole of the magnet is moved towards the coil, its upper face acquires north polarity. Therefore work has to be done against the force of repulsion in bringing the magnet closer to the coil.

This mechanical work done in moving the magnet w.r.t the coil that changes into electric energy producing induced current.

Hence Lenz’s law obeys the principle of conservation of energy.

Quantitative treatment:-If a conducting rod of length

$$F_m = I\ell B = \left(\frac{B\ell v}{R}\right)\ell B = \frac{B^2\ell^2 v}{R}$$

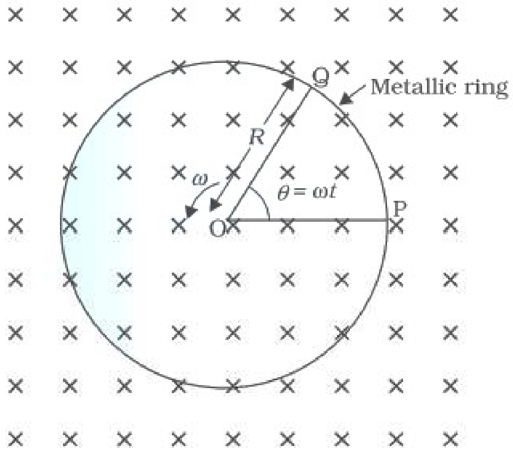
Rate of doing work in maintaining the motion of the rod by pulling force F.

$$\frac{dw}{dt} = P_{much} = Fv = \frac{B^2\ell^2 v^2}{R} = \left[\frac{B\ell v}{R}\right]^2 R = I^2R = P_{thermal}$$

Hence mechanical energy applied to move the conductor is changed into electrical energy which dissipates into thermal energy. This is consistent with the law of conservation of energy.

NUMERICAL

A metallic rod of 1 m length is rotated with a frequency of 50 rev/s, with one end hinged at the centre and the other end at the circumference of a circular metallic ring of radius 1 m, about an axis passing through the centre and perpendicular to the plane of the ring (Fig.). A constant and uniform magnetic field of 1 T parallel to the axis is present everywhere. What is the emf between the centre and the metallic ring

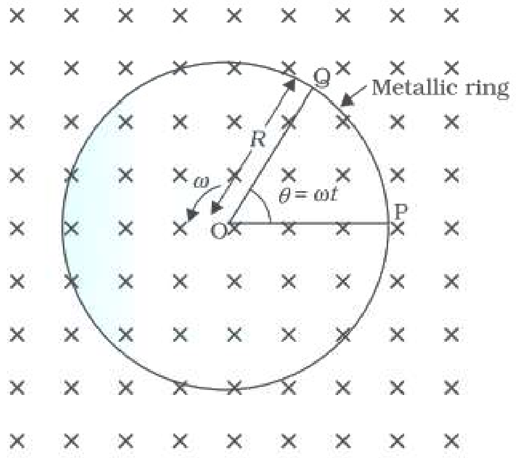


Motional emf induced in a rotating bar:-

As the rod is rotated, free electrons in the rod move towards the outer end due to Lorentz force and get distributed over the ring. Thus, the resulting separation of charges produces an emf across the ends of the rod.

At a certain value of emf, there is no more flow of electrons and a steady state is reached.

The magnitude of the emf generated across a length dr of the rod as it moves at right angles to the magnetic field is given by



Let dr be a segment of the rod at a distance r from o

The induced emf in this segment $d\varepsilon = Bdrv = B(r\omega)dr$

Total emf across the rod

$$\varepsilon = \int d\varepsilon = \int_0^l Br\omega . dr = \frac{B\omega\ell^2}{2}$$

$$\varepsilon = \frac{B\omega\ell^2}{2}$$

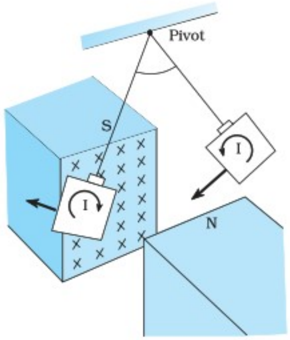
From the right hand rule, we can see o is at a higher potential than P.

Thus $v_0 - v_p = \frac{B\omega\ell^2}{2}$;

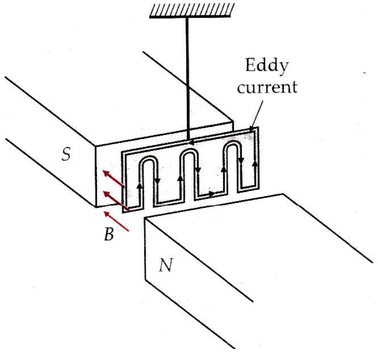
$\omega = 2\pi v$

Eddy Current:-

It is a type of circulating current formed in a bulk piece of conducting material When it is subjected to a changing magnetic flux.



These are circulating currents like eddies in the water



Its magnitude is given by $I = \frac{\varepsilon}{R} = \frac{d\phi}{Rdt}$

Its direction is given by Lenz's law

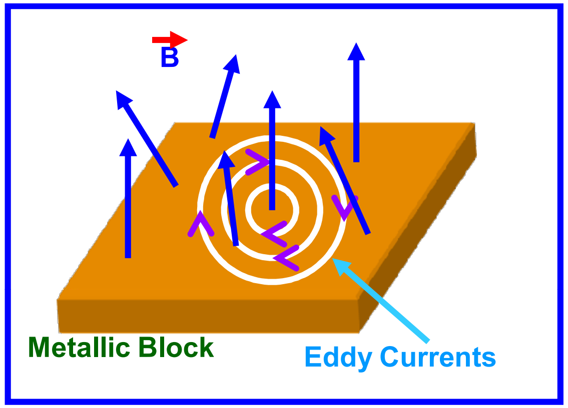
The experimental concept was given by Foucault, hence also normed as Foucault current

Eddy Currents or Foucault Currents:

The induced circulating (looping) currents produced in a solid metal due to change in magnetic field (magnetic flux) in the metal are called eddy currents.

Applications of Eddy Currents:

1. In induction furnace eddy currents are used for melting iron ore, etc.
2. In speedometer eddy currents are used to measure the instantaneous speed of the vehicle.
3. In dead beat galvanometer eddy currents are used to stop the damping of the coil in a shorter interval.



4. In electric brakes of the train eddy currents are produced to stop the rotation of the axle of the wheel.
5. In energy meters (watt – meter) eddy currents are used to measure the consumption of electric energy.
6. In diathermy eddy currents are used for localised heating of tissues in human bodies.

Eddy Current:-

Disadvantages:-

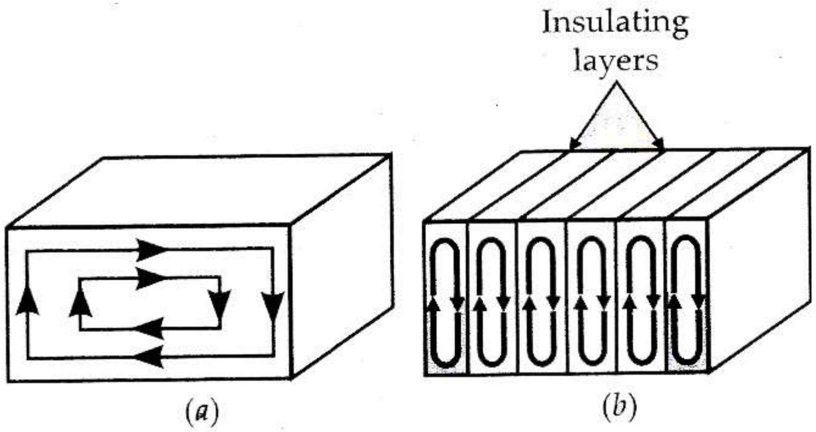
(a) The production of eddy currents in a metallic block leads to loss of electric energy in the form of heat

(b) The heat produced due to eddy currents breaks the insulation in electrical appliances.

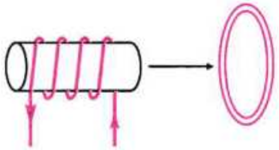
(c) it may cause unwanted damping effect

Minimization of eddy current:-

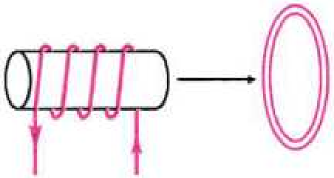
By lamination slotting process



(a) (b)



a current carrying solenoid moving towards a conducting loop. Find the direction of the current induced in the loop as seen from solenoid side.



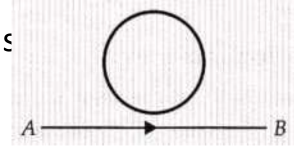
(a) clockwise

(b) anticlockwise

(c) clockwise or anticlockwise

(d) none of these.

2. The current flows from A to B as shown in the figure. The direction of the induced current in the loop is



(a) clockwise

(b) Anticlockwise

(c) none of these

(d) Straight line

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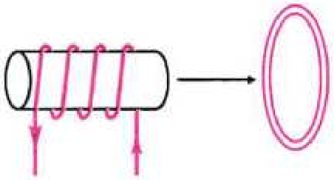
2. Assertion: There may be an induced emf in a loop without induced current.

Reason: Induced current depends on the resistance of the loop as well.

MCQ Ques

1. Figure shows a current carrying solenoid moving towards a conducting loop. Find the direction of the current induced in the loop as seen from solenoid side.



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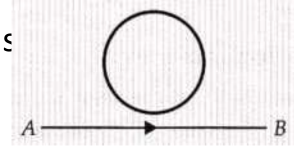

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Answer: B

THANKING YOU

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