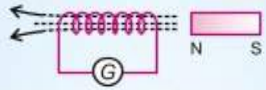
Electromagnetic Induction

Chapter 6

1 FARADAY'S EXPERIMENTS

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



(b) 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.

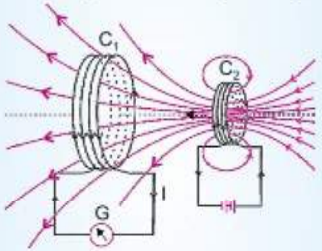
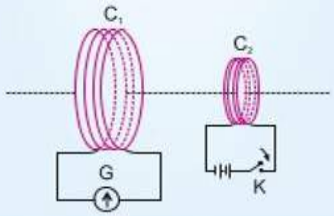


Fig. : Current is induced in coil C_1 due to motion of the current carrying coil C_2.

(c) Third experiment : Galvanometer shows a momentarily deflection when tapping key K is pressed



2 MAGNETIC FLUX

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

For non-uniform magnetic field

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

3 FARADAY'S LAWS OF INDUCTION

Conclusion of experiments was formulation of 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

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

- 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.

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

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

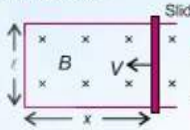
4 LENZ'S LAW

- **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.

5 MOTIONAL EMF

(1) Straight conductor in motion: In uniform and time independent magnetic field.



$e = Blv$ (emf across rod)

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

- Mechanical energy which is needed to move arm is converted into electric energy and then to thermal energy.

(2) Rod rotated about one end :

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

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 along field, thumb along direction of motion of conductor then central finger will give the direction of induced current.

6 EDDY CURRENTS

Electric currents are induced in well defined path in a conductor like circular loops, when bulk piece of conductor is subjected to changing magnetic flux, induced currents are produced in them known as eddy currents.

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

- The changing magnetic flux induces current.
- These currents are used to advantage 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

7 INDUCTANCE

The current can be induced in a coil by the flux change produced by same coil OR another coil.

- In both cases, flux through a coil is proportional to current

$$\frac{d\phi_B}{dt} \propto \frac{dI}{dt}$$

- Constant of proportionality is called inductance.
- Inductance is the ratio of flux linkage and current.
- This inductance depends on geometry of the coil and intrinsic material properties.

SELF INDUCTANCE

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

Total flux linkage = Li

L is called self inductance.

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

- 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 meter of solenoid length.
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.
- Unit of self inductance is henry (H) in SI units.
- 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.

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

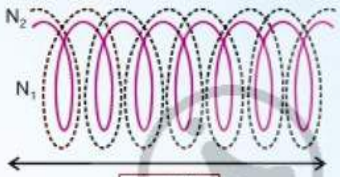
The magnitude of induced emf depends on rate of change of current and mutual inductance of two coils:

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

For two long co-axial solenoids each of length l

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

M_{12} is coefficient of mutual induction



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

- Mutual inductance of a pair of coils, solenoids depends on their separation as well as their relative orientations.
- For two concentric circular coils with radius r and R ($R >> r$) coils are coplanar also.

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

8 MAGNETIC POTENTIAL ENERGY

- Energy required to built any current I in a system of self inductance L

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

- This work done gets stored as magnetic potential energy.

$$U_B = \frac{1}{2}LI^2 = \frac{B^2 A\ell}{2\mu_0}$$

- Magnetic energy per unit volume.

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

9 AC GENERATOR

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

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

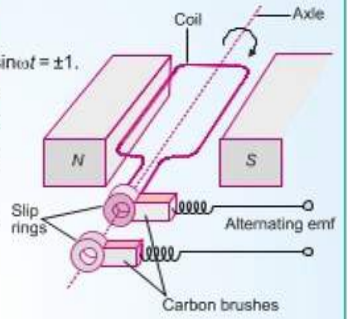
$NBA\omega$ is the maximum value of emf when $\sin\omega t = \pm 1$.

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

ω is angular speed of rotor of ac generator.

The direction of current and emf changes periodic with time

$$\varepsilon = \varepsilon_0 \sin(2\pi\nu t)$$



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

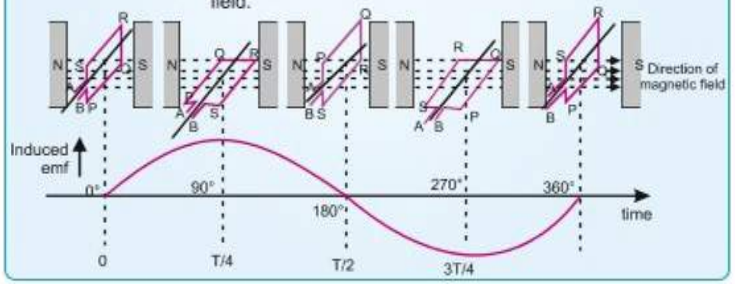
Stage-1 : The plane of the armature is perpendicular to the magnetic field.

Stage-2 When the armature rotates about 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°



Sharpen Your Understanding

1. Direction of current induced in a wire by moving it in a uniform magnetic field is found using [NCERT Pg. 215]
   (1) Newton's laws
   (2) Lenz's law
   (3) Ampere's rule
   (4) Right hand grip rule
2. A metallic plate is getting heated. It cannot be due to [NCERT Pg. 218]
   (1) A direct current passing through plate
   (2) An alternating current passing through it
   (3) It is placed static in space varying magnetic field but does not vary with time
   (4) It is placed in time varying magnetic field
3. A rectangular coil expands on pulling from two diagonal edges in a region of magnetic field and no emf is induced in the coil. This can be because of [NCERT Pg. 230]
   (1) Magnetic field is constant
   (2) Magnetic field is in the plane of rectangular coil
   (3) Magnetic field has a perpendicular component to the plane of coil whose magnitude is decreasing
   (4) There is a uniform magnetic field perpendicular to plane of coil
4. The self-inductance L of a solenoid of length l and area of cross section A, with fixed number of turns per unit length increases as [NCERT Pg. 223]
   (1) l and A increases
   (2) l decreases and A increases
   (3) Both l and A decreases
   (4) l increases and A decreases
5. The mutual inductance of pair of co-axial neighbouring coils [NCERT Pg. 220]
   (1) Increases when they are brought nearer
   (2) Increases when one of them is rotated about an axis
   (3) Is independent of current passing through coils
   (4) Both (1) and (3) are correct
6. A square loop of side length L meter lies in x-y plane in a region, where the magnetic field is given by $\vec{B} = B_0(\hat{i} + 2\hat{j} + 3\hat{k})\ T$, B_0 is positive constant. The magnitude of magnetic flux passing through square is [NCERT Pg. 207]
   (1) $5\,B_0L^2$ Wb
   (2) $3\,B_0L^2$ Wb
   (3) $\sqrt{14}\,B_0L^2$ Wb
   (4) B_0L^2 Wb

NCERT Based MCQs

7. A 20 cm long conductor carrying a current of 10 A is kept perpendicular to magnetic field of 0.6T. The mechanical power required to move conductor with a speed of 1 ms^{-1} is [NCERT Pg. 215]
   (1) 1.2 W (2) 1.5 W
   (3) 0.6 W (4) 0.4 W
8. A square loop of edge 20 cm and resistance of 1 Ω is placed vertically in horizontal plane. A uniform magnetic field of 0.5T is set up across the plane in the direction at 45° to the plane. The magnetic field is decreased to zero in 0.2 s, at a steady rate. Calculate magnitude of current induced in this time interval. [NCERT Pg. 208]
   (1) 20 mA (2) 50 mA
   (3) 60 mA (4) 70 mA
9. A circular loop with its plane parallel to plane of paper is entering into uniform magnetic field directed into the plane of paper perpendicularly. The loop is moved at constant speed V. Then [NCERT Pg. 212]
   (1) No. emf will be induced in the coil
   (2) Induced emf is constant in magnitude only
   (3) Induced emf is varying with time
   (4) Induced emf is constant in magnitude as well as in direction

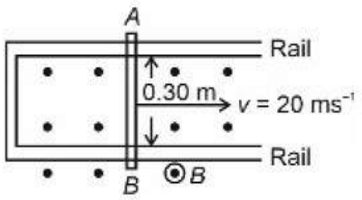
10. A metallic rod of length 20 cm is rotated with, frequency of 50 rev/s with one end pivoted at the centre and other end at circumference of circular metallic ring of radius 20 cm about an axis passing through centre and perpendicular to plane of the ring. A constant and uniform magnetic field 1.5 T parallel to axis is present everywhere. What is emf induced between centre and periphery of circular ring. [NCERT Pg. 214]

(1) 2.6 V (2) 9.4 V
(3) 4.7 V (4) 12.3 V

11. A cycle wheel with 20 metallic spokes each 1 m long is rotated with speed of 60 rad/s in a plane normal to horizontal component of earth's magnetic field B_H = 0.5 G at a place. The emf induced between axle and rim of wheel is [NCERT Pg. 215]

(1) 1.5 mV (2) 12.3 mV
(3) 3.0 mV (4) 0.75 mV

12. A conducting arm AB of length 30 cm moves on conducting rails held parallel. A uniform magnetic field B = 0.2 T exists perpendicular to planes of rails. Only the conducting arm has resistance of 0.5 Ω. The arm is pulled out with constant speed of 20 ms^{-1}, how much force is required parallel to rails to keep it moving at same speed. [NCERT Pg. 216]



(1) 0.14 N (2) 8 N
(3) 16 N (4) 0.25 N

13. Which statement regarding eddy currents among the following is incorrect? [NCERT Pg. 218]

(1) If rectangular slots are made in copper plate, the magnitude of eddy currents will decrease
(2) Dissipation of heat produced is proportional to strength of eddy currents
(3) Dead beat galvanometer has fixed core made of non-magnetic metallic material
(4) Magnetic brakes in train use the application of eddy current

14. Two circular coils one of small radius r and other of larger radius R ($r << R$) are placed co-axially with centres coinciding. The mutual inductance of the arrangement is [NCERT Pg. 221]

(1) $\frac{\mu_0 \pi R^2}{2r}$ (2) $\frac{\mu_0 \pi r^2}{2R}$
(3) $\frac{\mu_0 \pi rR}{(r+R)}$ (4) $\frac{2\mu_0 \pi r^2}{R}$

15. A long solenoid is of length 1.25 m and 600 turns per unit length. It is connected to a source which establishes a current of 2A in circuit. Magnetic energy stored in the solenoid coil with cross-sectional area 0.1 m^2 is [NCERT Pg. 224]

(1) 0.1 J (2) 0.4 J
(3) 0.6 J (4) 1.2 J

16. A rectangular coil of 100 turns with area 0.1 m^2 is rotated at 10 revolution per second and placed in a uniform magnetic field of 0.01 T perpendicular to axis of rotation of the coil. The maximum voltage generated in coil is [NCERT Pg. 226]

(1) 3.14 V (2) 6.28 V
(3) 9.42 V (4) 31.4 V

17. Two thin cylindrical pipes of equal internal diameters made of aluminum and plastic are taken. The pipes are kept vertical. A small cylindrical magnet without touching sides of wall of pipe is allowed to fall one by one. Then correct observations are [NCERT Pg. 219]

(1) Magnet takes longer time to cross aluminum pipe
(2) Magnet takes longer time to cross plastic pipe
(3) Eddy currents are generated in aluminum pipe but not in plastic
(4) Both (1) and (3) are correct

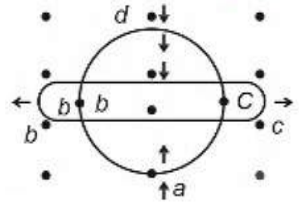
18. Which of the following statement is wrong? [NCERT Pg. 225]

(1) In ac generator when flux through coil is maximum, emf induced is minimum
(2) Maximum emf is induced when plane of coil is parallel to magnetic field
(3) The emf induced changes periodically with time if coil is rotated at uniform rate
(4) The frequency of rotation of armature coil is 60 Hz in India and 50 Hz in USA

19. A pair of adjacent coils has mutual inductance of 1.5 H. If the current in one coil changes from 0 to 10 A in 0.5 s, the rate of change of flux linkage with other coil is [NCERT Pg. 219]

(1) 20 V (2) 30 V
(3) 4 V (4) 5 V

20. A circular coil is being deformed into a narrow straight wire at regular stretch. Then [NCERT Pg. 230]



(1) The direction of induced current is clockwise
(2) The direction of induced current is anticlockwise
(3) Magnetic flux through coil increases
(4) The amount of charge flowing in coil depends on time

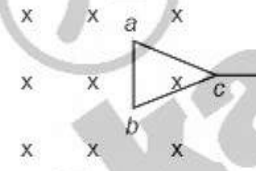
Thinking in Context

1. The relative motion between a magnet and a coil is responsible for generation of _____ in coil. [NCERT Pg. 205]

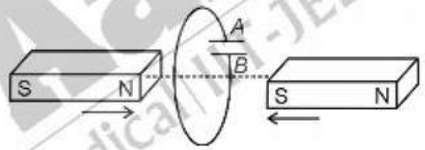
2. SI units of magnetic flux is _____. [NCERT Pg. 207]

3. The polarity of induced emf is such that it tends to produce a current which apposes the change in _____ that produced it. [NCERT Pg. 210]

4. A magnetic field is directed normal to plane of triangular loop away from reader. Due to outward motion, magnetic flux through loop decreases due to which induced current flows along path *cabc*. This statement is [NCERT Pg. 211]



(1) True (2) False

5. 

Due to motion of the magnets, the polarity of plate *A* of capacitor will be positive with respect to plate *B*. This statement is [NCERT Pg. 212]

(1) True (2) False

6. We are able to produce induced emf by moving a conductor instead of varying the magnetic field, that is, by changing magnetic flux enclosed by the circuit. This statement is [NCERT Pg. 213]

(1) True (2) False

7. A charge in motion can exert force on a stationary magnet. Conversely a bar magnet in motion can lead to a force on stationary charges. This statement is [NCERT Pg. 213]

(1) True (2) False

8. Lenz's law is consistent with the law of conservation of _____ [NCERT Pg. 215]

9. Relation between total charge flowing through closed circuit of resistance R and change in magnetic flux through it, is_____ [NCERT Pg. 216]

10. When bulk pieces of conductors are subjected to changing magnetic flux, induced currents are produced in them. These currents are called _____ [NCERT Pg. 218]

11. Eddy currents are minimized using laminations of metal. The laminations are separated by an insulating material like lacquer. This statement is [NCERT Pg. 218]

(1) True (2) False

12. Galvanometer has a fixed core made of _____ metallic material. When coil oscillates, the eddy currents generated in core oppose the motion and bring the coil to rest quickly. [NCERT Pg. 218]

13. Inductance is a scalar quantity. It has the dimensions of _____ [NCERT Pg. 220]

14. Mutual inductance of a pair of coils, solenoids depends on their separation as well as on their _____ [NCERT Pg. 221]

15. It is possible that emf is induced in a single isolated coil due to change of flux through coil by means of varying current through same coil. This phenomenon is called _____ [NCERT Pg. 222]

16. Self-inductance plays the role of inertia. It is electromagnetic analogue of _____ in mechanics. [NCERT Pg. 223]

17. The expression of magnetic energy stored in a solenoid in terms of magnetic field B length and area of solenoid is _____ [NCERT Pg. 224]

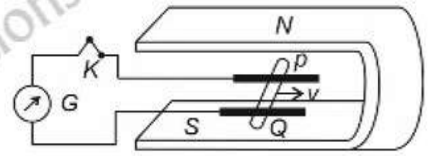
18. The basic principle behind ac generator machine is of changing magnetic flux by rotating coil in a magnetic field. An ac generator converts _____ energy into _____ energy [NCERT Pg. 225]

19. In an ac generator, the coil has N turns and A area rotated at f revolutions per second in a uniform magnetic field B, then peak value of motional emf is directly proportional to frequency and area. This statement is _____ [NCERT Pg. 228]

(1) True

(2) False

20. In the shown experiment excess positive charge is built at end P of the metal rod. This statement is



[NCERT Pg. 231]

(1) True (2) False

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