CHAPTER **06**

Electromagnetic Induction

1. **Magnetic Flux** The magnetic flux linked with any surface is equal to total number of magnetic lines of force passing through it. It is a scalar quantity.

   SI unit of magnetic flux is weber (Wb). CGS unit of magnetic flux is maxwell (Mx).

   $$1 \text{ Wb} = 10^8 \text{ Mx}$$

2. **Faraday's Law of Electromagnetic Induction**

   First Law Whenever magnetic flux linked with the closed loop or circuit changes, an emf is induced in the loop or circuit which lasts so long as change in flux continues.

   Second Law The induced emf in a closed loop or circuit, is directly proportional to the rate of change of magnetic flux linked with the closed loop or circuit.

   i.e. $$e \propto \frac{d\phi}{dt} \Rightarrow e = -N\frac{d\phi}{dt}$$

   where, N = number of turns in loop. Negative sign indicates the Lenz's law.

3. **Lenz's Law** The direction of induced emf or induced current is such that it always opposes the cause that produced it i.e. change in magnetic flux linked with the circuit.

   Lenz's law is a consequence of the law of conservation of energy.

   Induced current, $$I = \frac{e}{R} = -\frac{N}{R}\cdot\frac{d\phi_B}{dt}$$

4. **Motional Emf** The emf ε induced in a conductor of length l moving with velocity v in a direction perpendicular to magnetic field B is given by

   $$\varepsilon = vBl$$

5. The induced emf developed between two ends of conductor of length l rotating with angular velocity ω about one end in a direction perpendicular to magnetic field B is given by

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

6. Emf can be induced in a coil by
   (i) putting the coil/loop/circuit in varying magnetic field.
   (ii) changing the area A of the coil inside the magnetic field.
   (iii) changing the angle (θ) between **B** and **A**.

7. **Eddy Currents** These are loops of electric current induced within bulk pieces of conductors by a changing magnetic field in the conductor, according to Faraday's law of induction. It causes the heating of conductor.

8. **Self-Induction** The phenomenon of production of induced emf in a coil itself when a current passes through it

   $\because$ Total flux linked with coil $N\phi \propto I$

   $\therefore$ $$N\phi = LI$$

   where, ϕ = flux linked with each turn and

   L = coefficient of self induction.

   Also, induced emf, $$e = -L\frac{dI}{dt}$$

   SI unit of self-induction is henry (H).

   $$1 \text{ henry (H)} = 1 \text{ V-s/A} = 1 \text{ WbA}^{-1}$$

9. **Mutual Induction** The phenomenon of generation of induced emf in secondary coil when current linked with primary coil changes

   $$N_2\phi_2 = MI_1$$

   where, $N_2\phi_2$ = flux linked with secondary coil

   I_1 = current in primary coil,

   M = constant = mutual inductance or coefficient of mutual induction

   Also, $$e_2 = -M\frac{dI_1}{dI_2}$$

   SI unit of mutual inductance is henry (H).

   $$1 \text{ henry (H)} = 1 \text{ V-s/A} = 1 \text{ WbA}^{-1}$$

10. Self-inductance of a long solenoid, $L = \dfrac{\mu N^2 A}{l}$

    where, μ = magnetic permeability of the medium inside the solenoid,

    N = number of turns,

    A = area of solenoid and

    l = length of solenoid.

11. Mutual inductance (M) of closely wound solenoids,

    $$M = \frac{\mu_0 N_1 N_2 A}{l}$$

where, N_1 and N_2 = number of turns in primary and secondary solenoids, A = area of solenoid and l = length of solenoid.

12. Two inductors are in parallel combination, then equivalent inductance is given by $\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2}$

13. Two inductors are in series combination $L = L_1 + L_2$

14. Magnetic energy stored in an inductor $U = \frac{1}{2} LI^2$

where, I is the current in inductor.

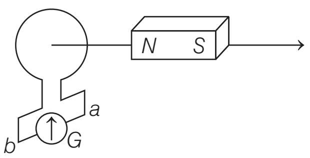
15. Energy density in magnetic field $= \frac{u}{V} = \frac{1}{2} \frac{B^2}{\mu_0}$.

Practice Questions

1 The phenomenon in which electric current is generated by varying magnetic field is appropriately known as electromagnetic

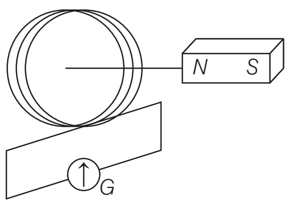
(a) conduction (b) induction
(c) pressure (d) radiation

2 The direction of deflection of pointer of galvanometer when the bar magnet is pulled away from the coil as shown in figure, is



(a) towards a (b) no deflection
(c) towards b
(d) indicator oscillates between a and b

3 Current in the coil is larger, when the magnet is



(a) pushed towards the coil faster
(b) pulled away from the coil faster
(c) Both (a) and (b)
(d) Neither (a) nor (b)

4 A circular loop of radius R carrying current I lies in xy-plane with its centre at origin. The total magnetic flux through xy-plane is

(a) directly proportional to R
(b) directly proportional to I
(c) inversely proportional to I
(d) zero

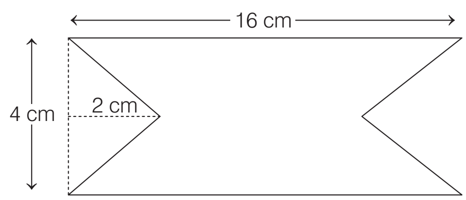
5 Consider a circular coil of wire carrying constant current I, forming a magnetic dipole. The magnetic flux through an infinite plane that contains the circular coil and excluding the circular coil area is given by ϕ_i. The magnetic flux through the area of the circular coil area is given by ϕ_o. Which of the following option is correct ?

(a) $\phi_i > \phi_o$ (b) $\phi_i < \phi_o$
(c) $\phi_i = \phi_o$ (d) $\phi_i = -\phi_o$

6 A circular disc of radius 0.2 m is placed in a uniform magnetic field of induction $(1/\pi)$ Wbm^{-2} in such a way that its axis makes an angle of 60° with **B**. The magnetic flux linked with the disc is

(a) 0.02 Wb (b) 0.06 Wb
(c) 0.08 Wb (d) 0.01 Wb

7 At time $t = 0$ magnetic field of 1000 G is passing perpendicularly through the area defined by the closed loop shown in the figure. If the magnetic field reduces linearly to 500 gauss, in the next 5 s, then induced emf in the loop is



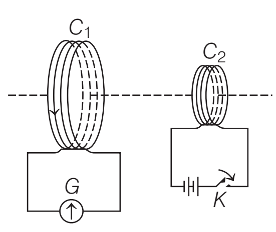
(a) 48 μV (b) 28 μV (c) 56 μV (d) 36 μV

8 According to Faraday's law of electromagnetic induction, the magnitude of the induced emf in a circuit is equal to the time rate of change of

(a) magnetic field induction (b) magnetising field intensity
(c) magnetic flux (d) electric flux

9 As shown in the figure, it is observed that the galvanometer shows a momentary deflection when the tapping key K is pressed.

When the key is released, the current in coil C_2 and the resulting magnetic field is



(a) increase from zero to maximum value
(b) first increase, then decrease
(c) remains same
(d) decreases from the maximum value to zero

10 The magnetic flux linked with the coil varies with time as $\phi_B = 3t^2 + 4t + 9$. The magnitude of the induced emf at 2s is

(a) 9 V (b) 16 V
(c) 3 V (d) 4 V

11 A varying magnetic flux linking a coil is given by $\phi_B = xt^2$. If at time $t = 3$ s, the emf induced is 9 V, then the magnitude of x is

(a) 0.66 Wbs^{-2} (b) 1.5 Wbs^{-2}
(c) – 0.66 Wbs^{-2} (d) None of the above

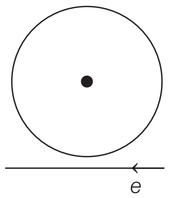
12 The polarity of induced emf is such that it tends to produce a current which opposes the change in magnetic flux that produce it, is the statement of

(a) Faraday's law
(b) Lenz's law
(c) Biot-Savart's law
(d) Fleming's left hand rule

13 An infinitely long cylinder is kept parallel to an uniform magnetic field B directed along positive Z-axis. This direction of induced current as seen from the Z-axis will be

(a) clockwise of the positive Z-axis
(b) anti-clockwise of the positive Z-axis
(c) zero, no current is induced
(d) along the magnetic field

14 Near a circular loop of conducting wire as shown in the figure an electron moves along a straight line. The direction of the induced current, if any in the loop is

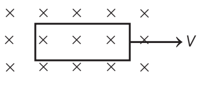


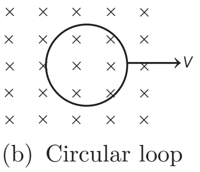
(a) variable (b) clockwise
(c) anti-clockwise (d) zero

15 A closed loop moves normal to the constant electric field between the plates of a large capacitor. Is the current induced in the loop when it is wholly inside the region between the capacitor plates?

(a) Yes (b) No
(c) May be possible (d) May not be possible

16 A rectangular loop and a circular loop are moving out of a uniform magnetic field region in the given figure, to a field free region with a constant velocity v. In which loop do you expect the induced emf to be constant during the passage out of the field region?





(a) Rectangular loop (b) Circular loop
(c) Both (a) and (b) (d) Neither (a) nor (b)

17 The north pole of a bar magnet is moved towards a coil along the axis passing through the centre of the coil and perpendicular to the plane of the coil.
The direction of the induced current in the coil when viewed in the direction of the motion of the magnet is

(a) clockwise (b) anti-clockwise
(c) no current in the coil
(d) Either clockwise or anti-clockwise

18 A conducting rod of length l is moving in a transverse magnetic field of strength B with velocity v. The induced voltage across the conducting rod is

(a) $\sqrt{\dfrac{Bvl}{2}}$ (b) $\sqrt{2Bvl}$ (c) Bvl (d) $\dfrac{Bvl}{2}$

19 A horizontal straight wire 20 m long extending from east to west is falling with a speed of 5.0 ms^{-1} at right angles to the horizontal component of the earth's magnetic field 0.30×10^{-4} Wbm^{-2}. The instantaneous value of the emf induced in the wire will be

(a) 6.0 mV (b) 3 mV (c) 4.5 mV (d) 1.5 mV

20 A conducting rod of length L is moving in a transverse magnetic field of strength B with velocity v. The resistance of the rod is R. The current in the rod is

(a) $\dfrac{BLv}{R}$ (b) BLv (c) zero (d) $\dfrac{B^2v^2L^2}{R}$

21 In which of the following devices, the eddy current effect is not used?

(a) Magnetic braking in train (b) Electromagnet
(c) Electric heater (d) Induction furnace

22 In induction furnace, heat is produced due to

(a) eddy current (b) resistance
(c) capacitor (d) None of these

23 The shiny metal disc in the electric power meter rotates due to

(a) continuously decreasing current
(b) motor fitted inside
(c) continuously increasing current
(d) eddy current

24 Which of the following is equivalent to self-induction?

(a) Inertia of mass (b) Inertia of energy
(c) Inertia of moment (d) Inertia of current

25 An electric current can be induced in a coil by flux change produced by another coil in its vicinity or flux change produced by the same coil. In both cases, the flux through a coil is

(a) proportional to the square of current
(b) inversely proportional to the square of current
(c) proportional to the current
(d) inversely proportional to the current

26 The mutual inductance M_{12} of coil 1 with respect to coil 2

(a) increases when they are brought nearer
(b) depends on the current passing through the coils
(c) increases when one of them is rotated about an axis
(d) is different from M_{21} of coil 2 with respect to coil 1

ANSWERS

1 (b)	**2** (c)	**3** (c)	**4** (d)	**5** (d)	**6** (a)	**7** (c)	**8** (c)	**9** (d)	**10** (b)
11 (b)	**12** (b)	**13** (c)	**14** (a)	**15** (b)	**16** (a)	**17** (b)	**18** (c)	**19** (b)	**20** (c)
21 (c)	**22** (a)	**23** (d)	**24** (a)	**25** (c)	**26** (a)				

Hints & Solutions

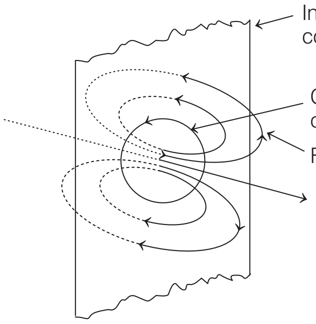
2 (*c*) When the magnet is pulled away from the coil, then according to Lenz's law, a current in induced in the coil such that it opposes the motion of the magnet. Therefore, direction of induced current in the coil will be in clockwise direction. Hence, deflection in the galvanometer will be towards *b*.

3 (*c*) Current will be larger, when the magnet is pushed towards or pulled away from the coil faster, because rate of change of magnetic flux increases and hence induced emf across the coil increases.

4 (*d*) As the circular loop lies in *xy*-plane, so the magnetic field or flux is perpendicular to its plane, i.e. in *z*-direction. Therefore, the total magnetic flux through *xy*-plane is

$$\phi = BA\cos\theta = BA\cos 90^\circ \quad [\because B \perp A]$$
$$= 0$$

5 (*d*) We are given with following situation,



From the diagram of field lines, we can observe that whatever be the number of field lines emitted from coil, all of them goes back into the infinite plane only.

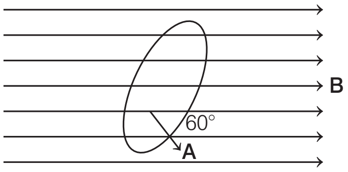
So, magnetic flux emanating from coil is equal and opposite to the flux linked with infinite plane.

So, $\phi_i = -\phi_o$

6 (*a*) The magnetic flux ϕ_B passing through a plane surface of area A placed in a uniform magnetic field B is given by

$$\phi_B = BA\cos\theta$$

where, θ is the angle between the direction of B and the normal (axis) to the plane.



Given, $\theta = 60^\circ$, $B = (1/\pi)\ \text{Wbm}^{-2}$, $A = \pi(0.2)^2$

$$\therefore \quad \phi_B = \frac{1}{\pi} \times \pi(0.2)^2 \times \cos 60^\circ = (0.2)^2 \times \frac{1}{2} = 0.02\ \text{Wb}$$

7 (*c*) Induced emf in the loop,

$$E = -\frac{\Delta\phi}{\Delta t} = -\left(\frac{\Delta B}{\Delta t}\right)(A) \qquad [\because \phi = BA]$$
$$= -\left(\frac{B_2 - B_1}{\Delta t}\right)A \qquad \ldots\text{(i)}$$

Here, $B_2 = 500\ \text{G} = 500 \times 10^{-4}\ \text{T}$,

$B_1 = 1000\ \text{G} = 1000 \times 10^{-4}\ \text{T}$,

$\Delta t = 5\text{s}$

$\therefore \quad A$ = area of loop

= Area of rectangle − Area of two triangles

$$= \left(16 \times 4 - 2 \times \frac{1}{2} \times 4 \times 2\right)\text{cm}^2$$
$$= 56 \times 10^{-4}\ \text{m}^2$$

Using Eq. (i), we get

$$E = \frac{(1000 - 500) \times 10^{-4} \times 56 \times 10^{-4}}{5}$$
$$= 56 \times 10^{-6}\ \text{V}$$
$$= 56\,\mu\text{V}$$

9 (*d*) When the tapping key K is pressed, the current in the coil C_2 and the resulting magnetic field rises from zero to a maximum value in a short time. So, the galvanometer shows a momentary deflection due to the change in flux along C_1. If the key is held pressed continuously, there is no deflection in the galvanometer as the current is constant. So, no change in flux occur across C_1.

When the key is released, a momentary deflection is observed again, but in opposite direction due to change in the direction of field or flux across C_1.

It is due to the fact that the current in coil C_2 and the resulting magnetic field decreases from the maximum value to zero in a short time.

10 (*b*) Magnitude of induced emf,

$$|\varepsilon| = \frac{d\phi_B}{dt} = \frac{d}{dt}(3t^2 + 4t + 9) = 6t + 4 + 0$$

At $t = 2\text{s}$, $|\varepsilon| = 6 \times 2 + 4 = 16\ \text{V}$

11 (*b*) From Faraday's law, induced emf,

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

Given, $\phi_B = xt^2$

$$\therefore \quad \varepsilon = \frac{-d(xt^2)}{dt} = -2tx$$

Given, $t = 3\text{s}$ and $\varepsilon = 9\text{V}$

$$\therefore \text{ Magnitude of } x = \frac{|\varepsilon|}{2t} = \frac{9}{2 \times 3} = 1.5 \text{ Wbs}^{-2}$$

13 (*c*) In uniform magnetic field, change in magnetic flux is zero. Therefore, induced current will be zero.

14 (*a*) Since, electron is moving from right to left, the flux linked with loop will first increase and then decrease as the electron passes. Therefore, induced current I in the loop will be first clockwise and then will move in anti-clockwise direction. Hence, direction of induced current is variable.

15 (*b*) According to question, there can be two cases as follows

Case I Closed coil is moving inside constant electric field.

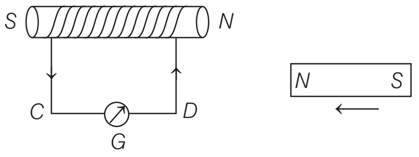
Case II Closed coil is wholly inside constant electric field.

However, no current is induced in either case because current cannot be induced by changing the electric flux.

16 (*a*) The induced emf is expected to be constant only in the case of the rectangular loop.

In the case of circular loop, the rate of change of area of the loop during its passage out of the field region is not constant, hence induced emf will vary accordingly.

17 (*b*) When the north pole of the magnet is brought towards one end of the coil, the induced current flows in the coil in such a direction, so as to oppose the motion of the north pole of the magnet towards the coil. Thus, direction of induced current is anti-clockwise as shown below.



19 (*b*) Given, $B_H = 0.30 \times 10^{-4}$ Wbm^{-2},

$l = 20\,\text{m}$

and $v = 5.0\,\text{ms}^{-1}$

Induced emf across the ends of wire,

$$\varepsilon = B_H lv$$
$$= 0.30 \times 10^{-4} \times 20 \times 5.0 = 3 \text{ mV}$$

20 (*c*) Emf across rod is induced and charges get accumulated across its ends. But current flowing in it is zero, because circuit is open.

21 (*c*) Electric heaters are not based on the eddy current effect. Rather their working is based on Joule's heating effect of current. According to this effect, the passage of an electric current through a resistor produces heat.