6 Electromagnetic Induction

Fastrack Revision

- **Magnetic Flux:** Magnetic lines of force passing through a surface area is called magnetic flux. The magnetic flux passing through an area in a magnetic field is given by

$$\phi = \oint \vec{B} \cdot d\vec{S}$$

where, $\vec{B}$ = magnetic field

$d\vec{S}$ = area or $\phi = \vec{B} \cdot \vec{S}$

or $\phi = BA \cos\theta$

It is scalar quantity.

SI unit of ϕ is weber or Tm^2 (tesla meter squared) and its dimension is $[ML^2T^{-2}A^{-1}]$.

$$1\,Tm^2 = 1\,Wb = 10^8\,\text{Maxwell}$$

- **Electromagnetic Induction:** When magnetic flux changes through a coil, an e.m.f. is induced which is called electromagnetic induction.
- **Faraday's Laws of Induction**

First Law: When a magnetic flux associated with closed circuit changes , an e.m.f is induced which lasts as long as flux changes.

Second Law: The magnitude of the induced emf in a circuit is equal to the time rate of change of magnetic flux through the circuit.

$$\varepsilon = -\frac{d\phi}{dt} \quad \text{or} \quad \varepsilon = \frac{\phi_2 - \phi_1}{t}$$

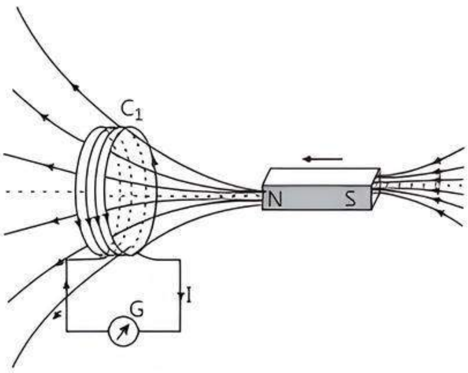
Negative sign shows that the emf induced opposes the cause by which it is produced.

If N is the number of turns of the coil, then

$$\varepsilon = -\frac{N d\phi}{dt}$$

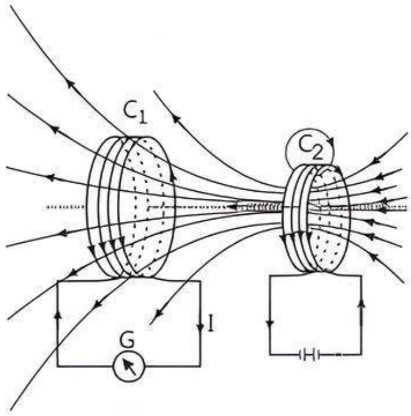
- **The Experiments of Faraday and Henry**

Experiment 1: It shows that it is the relative motion between the magnet and the coil that is responsible for generation or induction of electric current in the coil.



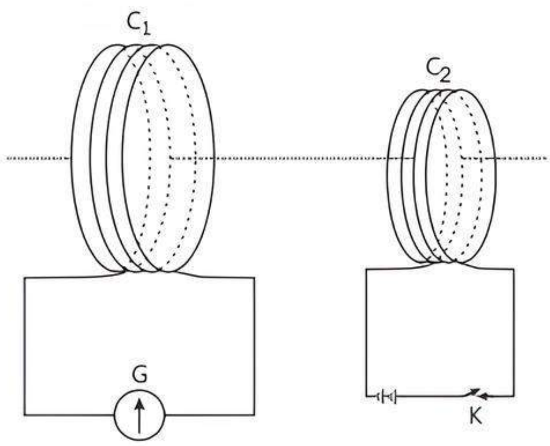
When the bar magnet is pushed towards the coil, the pointer in the galvanometer G deflects.

Experiment 2: It shows that the relative motion between the coils that induces the electric current.



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

Experiment 3: In this experiment, Faraday showed that, relative motion showed in experiment 1 and 2 is not an absolute requirement.



Experimental set-up for experiment 3

It is observed that the galvanometer shows a momentary deflection when the tapping key K is pressed. The pointer in the galvanometer returns to zero immediately. If the key is held pressed continuously, there is no deflection in the galvanometer. When the key is released, a momentary deflection is observed again, but the opposite direction. It is also observed that the deflection increase dramatically when an iron rod is inserted into the coils along their axis.

- **Lenz's Law:** The production of emf induced through a coil opposes the change in magnetic flux responsible for its production.

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

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

- **Motional E.M.F. of a Coil in Uniform Magnetic Field**

$$e = -Blv$$

- **Inductance:** 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. The flux linkage of a closely wound coil of N turns is directly proportional to the current:

i.e., $N\phi \propto I$

The constant of proportionality in this relation is called inductance. Inductance is a scalar quantity and its SI unit is Henry (H).

Inductance is classified into two types as : self inductance and mutual inductance.

- **Self Inductance:** The phenomenon of production of induced emf in a coil, when a current passes through it, undergoes a change.

$$L = \frac{-\varepsilon}{dI/dt}$$

where, L = coefficient of self induction or self inductance.

SI unit of L is henry.

- **Inductance of a long solenoid**

$\because$ $L = \frac{N\phi}{I}$

$\therefore$ $L = \frac{\mu_0 N^2 A l I}{I} = \mu_0 n^2 A l$

- **Mutual Inductance:** The phenomenon of inducing e.m.f. by changing the magnetic flux in nearby coil,

$$\phi_S \propto I_p$$

or $\phi_S = M I_p$

where, M = mutual inductance or coefficient of mutual inductance

SI unit of M is henry.

- **Mutual Inductance of Two Long Co-axial Solenoid**

$$M = \frac{\mu_0 n_1 n_2 A}{l}$$

where, l = length of solenoid

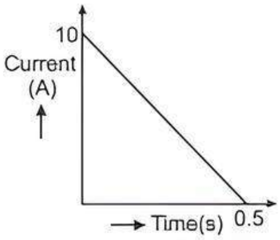
- **Energy Stored in an Inductor:** When an electric current is flowing in an inductor, there is an energy stored in the magnetic field.

$$U = \frac{1}{2}LI^2$$

Practice Exercise

Multiple Choice Questions

Q 1. In a coil of resistance 100 Ω a current is induced by changing the magnetic flux through it. The variation of current with time is as shown in the figure. The magnitude of change in flux through coil is: *(CBSE SQP 2022-23)*



a. 200 Wb b. 275 Wb
c. 225 Wb d. 250 Wb

Q 2. A constant current is flowing through a solenoid. An iron rod is inserted in the solenoid along its axis. Which of the following quantities will not increase? *(CBSE 2021 Term-1)*

a. The magnetic field at the centre
b. The magnetic flux linked with the solenoid
c. The rate of heating
d. The self-inductance of the solenoid

Q 3. A square shaped coil of side 10 cm, having 100 turns is placed perpendicular to a magnetic field which is increasing at 1 T/s. The induced emf in the coil is: *(CBSE 2023)*

a. 0.1 V b. 0.5 V
c. 0.75 V d. 1.0 V

Q 4. A square of side L meters lies in the X-Y plane in a region, where the magnetic field is given by $\vec{B} = B_0(2\hat{i} + 3\hat{j} + 4\hat{k})$T, where B_0 is constant. The magnitude of flux passing through the square is: *(NCERT EXEMPLAR)*

a. $2B_0L$ Wb
b. $2B_0L^2$ Wb
c. $4B_0L^2$ Wb
d. $\sqrt{29}B_0L^2$ Wb

Q 5. A loop, made of straight edges has six corners at A (0, 0, 0), B(L, 0, 0), C(L, L, 0), D(0, L, 0), E (0, L, L) and F(0, 0, L). A magnetic field $\vec{B} = B_0(\hat{i} + \hat{k})$T is present in the region. The flux passing through the loop $ABCDEFA$ (in that order) is: *(NCERT EXEMPLAR)*

a. B_0L^2Wb b. $2B_0L^2$ Wb
c. $\sqrt{2}B_0L^2$ Wb d. $4B_0L^2$ Wb

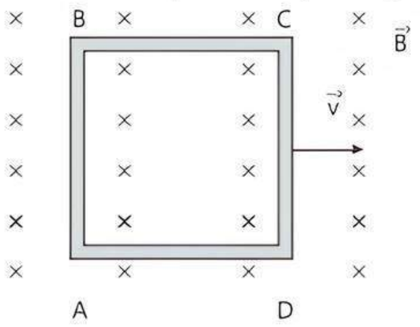
Q 6. Which of the following option(s) is true?

a. Moving electric charges produce magnetic fields.
b. The phenomenon of generating current of emf by changing magnetic fields is called electromagnetic induction.
c. Generators. transformers etc. works on the principle of electromagnetic induction.
d. All of the above

Q 7. **Due to relative motion of a magnet with respect to a coil, an emf is induced in the coil, identify the principle involved:**

a. Ampere's circuital law b. Faraday's law
c. Gauss law d. Biot-Savart's law

Q 8. **A conducting square loop of side 'L' and resistance 'R' moves in its plane with the uniform velocity 'v' perpendicular to one of its sides. A magnetic induction 'B' constant in time and space pointing perpendicular and into the plane of the loop exits everywhere as shown in the figure. The current induced in the loop is:** *(CBSE SQP 2021 Term-1)*



a. BLv/R clockwise b. BLv/R anti-clockwise
c. $2BLv/R$ anti-clockwise d. zero

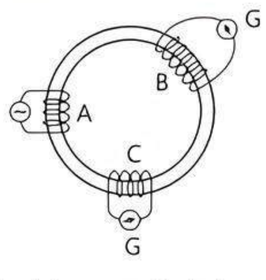
Q 9. **The magnetic flux linked with the coil (in Weber) is given by the equation:** *[CBSE SQP 2021 Term-1]*

$$(\phi = 5t^2 + 3t + 16)$$

The induced emf in the coil at time, t = 4 will be:

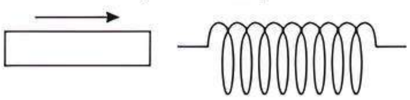
a. –27 V b. –43 V
c. –108 V d. 210 V

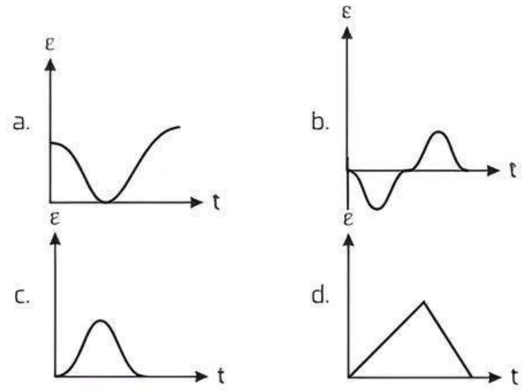
Q 10. **A, B and C are the three coils of conductor having different number of turns, wound around a soft iron ring as shown in the figure. Ends of coils B and C are connected to the galvanometers. The observation that can be made when ends of coil A are connected to an AC source is:**



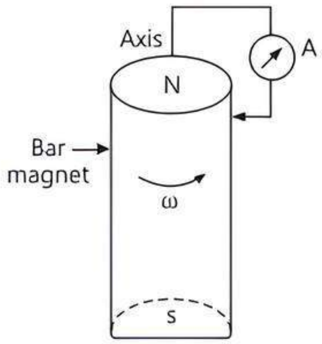
a. same electric current is induced in B and C
b. no electric current is induced in B and C
c. induced electric current is more in B than in C
d. induced electric current is less in B than in C

Q 11. **The variation of induced emf ε with time t in a coil if a short bar magnet is moved along its axis with a constant velocity is best represented as:**



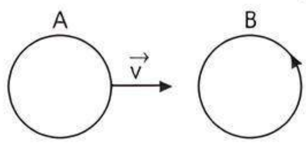


Q 12. **A cylindrical bar magnet is rotated about its axis as shown in figure. A wire is connected from the axis and is made to touch the cylindrical surface through a contact. Then:** *(NCERT EXEMPLAR)*



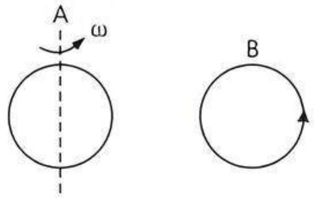
a. a direct current flows in through the ammeter A
b. no current flows through the ammeter A.
c. an alternating sinusoidal current flows through the ammeter A with a time period. $T = \frac{2\pi}{\omega}$.
d. a time varying non-sinusoidal current flows through the ammeter A.

Q 13. **There are two coils A and B as shown in the figure. A current starts flowing in B as shown, when A is moved towards B and stops when stops moving. The current in A is counter-clockwise, B is kept stationary when A moves. We can infer that:** *(NCERT EXEMPLAR)*



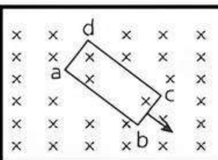
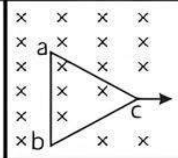
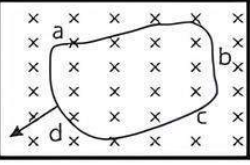
a. there is a constant current in the clockwise direction of A.
b. there is a varying current in A.
c. there is no current in A.
d. there is a constant current in the counter-clockwise direction in A.

Q 14. **Same as problem 13 except the coil A is made to rotate about a vertical axis. No current flows in B if A is at rest. The current in coil A, when the current in B (at $t = 0$) is counter-clockwise and the coil A is as shown at this instant, $t = 0$, is:** *(NCERT EXEMPLAR)*



a. constant current clockwise
b. varying current clockwise
c. varying current counter-clockwise
d. constant current counter-clockwise

Q 15. Match the Column I with Column II and mark the correct option from the codes given below:

Column I (Planar loops of different shapes)	Column II (Direction of induced current)
(A) 	(p) *b a c b*
(B) 	(q) *c d a b c*
(C) 	(r) *b c d a b*

	A	B	C		A	B	C
a.	p	q	r	b.	r	q	p
c.	p	r	q	d.	r	p	q

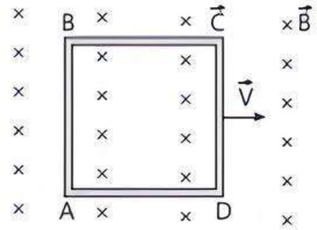
Q 16. A rectangular loop of side 6 cm and 2 cm with a small cut is moving out of a region of uniform magnetic field of magnitude 0.4 T directed normal to the loop. The voltage developed across the cut if velocity of loop is 2 cm s^{-1} in a direction normal to the longer side is:

a. 3.8×10^{-4} V b. 4.8×10^{-4} V
c. 2.2×10^{-2} V d. 3.2×10^{-2} V

Q 17. A wheel with 20 metallic spokes each of length 0.5 m long is rotated with a speed of 120 revolution per minute in a plane normal to the horizontal component of earth magnetic field at a place. If magnetic field is 0.4×10^{-4} T at the place, then induced emf between the axle and the rim of the wheel is:

a. 6.28×10^{-5} V b. 3.14×10^{-5} V
c. 1.256×10^{-5} V d. 1.57×10^{-5} V

Q 18. A conductor square loop of side *L* and resistance *R* moves in its plane with a uniform velocity *v* perpendicular to one of its sides. A magnetic induction *B* constant in time and space, pointing perpendicular and into the plane of the loop exists everywhere. The current induced in the loop is:



a. $\frac{Blv}{R}$ clockwise b. $\frac{Blv}{R}$ anti-clockwise
c. $\frac{2Blv}{R}$ anti-clockwise d. zero

Q 19. A rectangular, a square, a circular and an elliptical loop, all in the (*x*-*y*) plane, are moving out of a uniform magnetic field with a constant velocity $\vec{v} = v\hat{i}$. The magnetic field is directed along the negative *Z*-axis direction. The induced emf, during the passage of these loops, out of the field region, will not remain constant for: *(CBSE SQP 2022-23)*

a. any of the four loops
b. the circular and elliptical loops
c. the rectangular, circular and elliptical loops
d. only the elliptical loops

Q 20. The self inductance *L* of a solenoid of length *l* and area of cross-section *A*, with a fixed number of turns *N* increases as: *(NCERT EXEMPLAR)*

a. *l* and *A* increases
b. *l* decreases and *A* increases
c. *l* increases and *A* decreases
d. Both *l* and *A* decreases

Q 21. The self inductance of a long solenoid cannot be increased by:

a. increasing its area of cross-section
b. decreasing its length
c. increasing the current through it
d. increasing the number of turns in it

Q 22. When the current changes from +2 A to −2 A in 0.05 s, an emf of 8 V as induced in a coil. The coefficient of self-induction of the coil is:

a. 0.2 H b. 0.4 H c. 0.8 H d. 0.1 H

Q 23. A circular loop of radius 0.3cm lies parallel to much bigger circular of radius 20 cm. The centre of the small loop is on the axis of the bigger loop. The distance between their centres is 15 cm. If a current of 2.0 A flows through the smaller loop, then the flux linked with the bigger loop is:

(CBSE SQP 2021 Term-1)

a. 3.3×10^{-11} weber b. 6×10^{-11} weber
c. 6.6×10^{-9} weber d. 9.1×10^{-11} weber

Q 24. If both the number of turns and core length of an inductor is doubled keeping other factors constant, then its self-inductance will be:

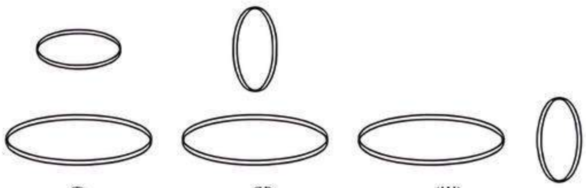
(CBSE SQP 2021 Term-1)

a. unaffected b. doubled
c. halved d. quadrupled

Q 25. **The coefficient of mutual inductance of two coils depends on:**

a. medium between the coils
b. distance between the two coils
c. orientation of the two coils
d. All of the above

Q 26. **Two circular coils can be arranged if any of three situations as shown in the figure. Their mutual inductance will be:**



(i) (ii) (iii)

a. maximum in situation (i)
b. maximum in situation (ii)
c. maximum in situation (iii)
d. same in all situations

Q 27. **A short solenoid of radius a, number of turns per unit length n_1 and length L is kept coaxially inside a very long solenoid of radius b, number of turns per unit length n_2. What is the mutual inductances of the system?**

a. $\mu_0 \pi b^2 n_1 n_2 L$
b. $\mu_0 a^2 n_1 n_2 L^2$
c. $\mu_0 \pi a^2 n_1 n_2 L$
d. $\mu_0 \pi b^2 n_1 n_2 L^2$

Q 28. **If numbers of turns in primary and secondary coils is increased to two times each, the mutual inductances:**

a. becomes 4 times
b. becomes 2 times
c. becomes $\frac{1}{4}$ times
d. remain unchanged

Q 29. **Two coils A and B having turns 300 and 600 respectively are placed near each other. On passing a current of 3A in A, the flux linked with A is 1.2×10^{-4} Wb and with B it is 9×10^{-5} Wb. The mutual induction of the system is:**

a. 2.4×10^{-4} H
b. 0.4×10^{-5} H
c. 8×10^{-5} H
d. 2×10^{-5} H

Q 30. **In mutual induction:**

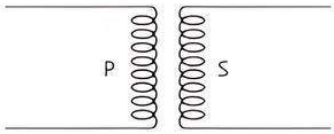
A. **When current in one coil increases, induced current in neighbouring coil flows in the opposite direction.**

B. **When current in one coil decreases, induced current in neighbouring coil flows in the opposite direction.**

Choose the correct answer:

a. A is true but B is false
b. A and B are false
c. A and B are true
d. A is false but B is true

Q 31. **The value of coefficient of mutual induction for the arrangement of two coils shown in the figure will be:**



a. zero
b. maximum
c. positive
d. negative

Assertion & Reason Type Questions

Directions (Q.Nos. 32-38): *In the following questions a statement of Assertion (A) is followed by a statement of Reason (R). Mark the correct choice as:*

a. Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).
b. Both Assertion (A) and (R) are true but Reason (R) is not the correct explanation of Assertion (A).
c. Assertion (A) is true but Reason (R) is false.
d. Both Assertion (A) and Reason (R) are false.

Q 32. **Assertion (A): Changing magnetic flux can produced induced emf.**

Reason (R): Faraday established induced emf experimentally.

Q 33. **Assertion (A): Induced emf depends on number of turns and area of the coil.**

Reason (R): Induced emf increases with increases in number of turns of coil.

Q 34. **Assertion (A): An induced emf is generated when magnet is withdrawn from the solenoid.**

Reason (R): The relative motion between magnet and solenoid induces emf.

Q 35. **Assertion (A): The quantity L/R possesses dimensions of time.**

Reason (R): To reduce the rate of increase of current through a solenoid should increase the time constant (L/R).

Q 36. **Assertion (A): Inductance coils are made of copper.**

Reason (R): Induced current is more in wire having less resistance.

Q 37. **Assertion (A): When number of turns in a coil doubled, coefficient of self inductance of the coil becomes four times.**

Reason (R): Coefficient of self inductance is proportional to the square of number of turns.

Q 38. **Assertion (A): When two coils are wound on each other, the mutual induction between the coils is maximum.**

Reason (R): Mutual induction does not depend on the orientation of the coils.

Fill in the Blanks Type Questions

Q 39. Magnetic flux linked with any surface is equal to the total number of................ passing through it.

Q 40. A closed loop moves normal to the constant electric field between the plates of a large capacitor, hence .... is induced in the loop.

Q 41. The emf ε induced in a conductor of length l moving with velocity v in a direction perpendicular to magnetic field B is ....

Q 42. The number of turns of a solenoid are doubled without changing its length and area of cross-section. The self-inductance of the solenoid will become .... times. *(CBSE 2020)*

Q 43. Self-inductance of a long solenoid (A, N, L) with magnetic core material and relative permeability μ_r is .... (where A = Area of each turn, N = No. of turns, L = Length)

Q 44. SI unit of mutual inductance is ....

Answers

1. (d) 250 Wb

Here, $R = 100\ \Omega$

As $q = \oint I dt$ = area of current-time graph

$$q = \frac{1}{2} \times 10 \times 0.5 = 2.5$$

From $q = \frac{\Delta\phi}{R}$,

$$\Delta\phi = q \times R = 2.5 \times 100$$
$$= 250 \text{ Wb}$$

2. (c) The rate of heating

3. (d) 1.0 V

Number of turns $N = 100$

Side of square loop = 10 cm = 0.1 m

and rate of change of magnetic field, $\frac{dB}{dt} = 1\ \text{Ts}^{-1}$

$\therefore$ Induced emf $= \frac{d}{dt}(NBA)$

$$= NA\frac{dB}{dt} = 100 \times 0.1 \times 0.1 \times 1 = 1 \text{ V}$$

4. (c) $4B_0L^2$Wb

Here, $\vec{B} = B_0(2\hat{i} + 3\hat{j} + 4\hat{k})$T

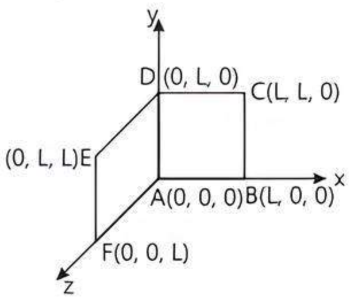
Area of the square = $L^2\hat{k}\text{m}^2$

$\therefore$ Flux passing through the square,

$$\phi = \vec{B} \cdot \vec{A} = B_0(2\hat{i} + 3\hat{j} + 4\hat{k}) \cdot L^2\hat{k} = 4B_0L^2\text{Wb}$$

5. (b) $2B_0L^2$ Wb

Here, $\vec{B} = B_0(\hat{i} + \hat{k})$T



Area vector of $ABCD = L^2\hat{k}$

Area vector $DEFA = L^2\hat{i}$

Total area vector, $\vec{A} = L^2(\hat{i} + \hat{k})$

Total magnetic flux, $\phi = \vec{B} \cdot \vec{A}$

$$= B_0(\hat{i} + \hat{k}).L^2(\hat{i} + \hat{k}) = B_0L^2(1+1) = 2B_0L^2 \text{ Wb}$$

6. (d) All of the above.

7. (b) Faraday's law

8. (d) zero

Induced current, $I = \frac{|e|}{R} = \frac{\left|\frac{d\phi}{dt}\right|}{R}$

But there is no change of flux with time, as B, A and θ all remain constant with time *i.e.*, $\frac{d\phi}{dt} = 0$

$\therefore$ No current is induced.

9. (b) – 43 V

Flux, $\phi = 5t^2 + 3t + 16$

$$\text{emf } |e| = -\frac{-d\phi}{dt} = -\frac{d}{dt}(5t^2 + 3t + 16) = -(10t + 3)$$

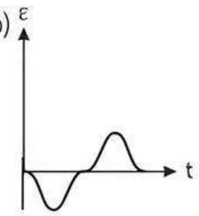
$$|e|_{t=4} = -[10(4) + 3] = -43\text{V}$$

$\therefore$ $e = -43$ V

10. (c) Induced electric current is more in B than in C.

When the end of coil A is connected to an AC source, the induced electric current will be more in B than in C as the number of turns in the coil is more in B than in C.

11. (b)



The polarity of emf will be opposite in the two cases while the magnet enters the coil and while the magnet leaves the coil. Only in option (b), polarity is changing.

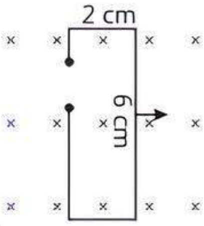
12. (b) no current flows through the ammeter A.
As there is no change in magnetic flux associated with the circuit, no current is induced in the circuit. The ammeter A shows no deflection.

13. (d) there is a constant current in the counter-clockwise direction in A.
Coil A be carrying a constant current in counter-clockwise direction. Because of that, when A moves towards B, current induced in B is counter-clockwise direction as per Lenz's law. The current in B would stops when A stops moving.

14. (a) constant current clockwise

15. (d) A-r, B-p, C-q

16. (b) 4.8×10^{-4} V



Here, $l = 6\text{ cm} = 6 \times 10^{-2}$ m

$B = 0.4$T

$v = 2 \times 10^{-2}\ \text{ms}^{-1}$

Voltage developed is

$$\varepsilon = Blv$$
$$= 0.4 \times 6 \times 10^{-2} \times 2 \times 10^{-2}$$
$$= 4.8 \times 10^{-4}\text{V}$$

17. (a) 6.28×10^{-5} V

Here, $\quad v = \dfrac{120}{60} = 2$ rps

$$\text{Induced emf} = \left(\frac{1}{2}\right)\omega BR^2 = \frac{1}{2} \times 2\pi v BR^2$$
$$= 3.14 \times 2 \times 0.4 \times 10^{-4} \times (0.5)^2$$
$$= 0.628 \times 10^{-4} = 6.28 \times 10^{-5}\text{V}$$

18. (d) zero
No flux change is taking place because magnetic field is uniform everywhere.
As there is no change in flux, induced emf is zero and therefore no current induced.

19. (b) the circular and elliptical loops
In a rectangular and a square loop, the magnetic flux change is constant over some constant period of time whereas in circular and elliptical loop, the magnetic flux change is not constant over some constant period of time. Since, the area coming out of the circular and elliptical loop is not uniform throughout the magnetic field, so the induced emf will also not be constant through them.

20. (b) l decreases and A increases

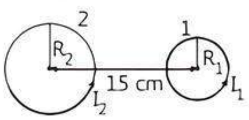
21. (c) increasing the current through it

22. (d) 0.1 H

$$\text{Induced emf, } e = -L\frac{dI}{dt} = \frac{-L(I_2 - I_1)}{t} = -L\frac{(-2-2)}{0.05}$$

$$8 = L\frac{(4)}{0.05} \Rightarrow L = \frac{8 \times 0.05}{4} = 0.1\text{H}$$

23. (d) 9.1×10^{-11} Weber
Let flux linked with smaller loop is ϕ_1 and with bigger loop is ϕ_2.



Given, $\quad R_2 = 0.2$ m

$R_1 = 0.003$ m

$X = 15\text{ cm} = 0.15$ m

Now, flux $\quad \phi_1 = B_2 A_1$

$$= \frac{\mu_0}{4\pi}\left[\frac{2\pi R_2^2 I_2}{(R_2^2 + x^2)^{3/2}}\right]\pi R_1^2$$

$$\text{Mutual inductance, } M = \frac{\phi_1}{I_2} = \frac{\mu_0}{4\pi}\frac{2\pi R_2^2 \pi R_1^2}{(R_2^2 + x^2)^{3/2}}$$

Now $\phi_2 = MI_1$

$$= \frac{\mu_0}{4\pi}\frac{2\pi R_2^2 \pi R_1^2}{(R_2^2 + x^2)^{3/2}} I_1$$

$$= \frac{10^{-7} \times 2 \times 3.14 \times (0.2)^2 \times 3.14 \times (0.003)^2}{((0.2)^2 + (0.15)^2)^{3/2}} \times 2.0$$

$$= 9.1 \times 10^{-11}\ \text{Weber}$$

24. (b) doubled
Self-inductance,

$$L = \mu_0 \frac{N^2}{l} A$$

$$L' = \mu_0 \frac{(2N)^2}{2l} A$$

$$= 2\mu_0 \frac{N^2}{l} A = 2L$$

$\therefore \quad L' = 2L$

25. (d) All of the above

26. (a) maximum in situation (i)

27. (c) $\mu_0 \pi a^2 n_1 n_2 L$

28. (a) becomes 4 times

$$m \propto n_1 n_2$$

$\therefore$ m becomes 4 times

29. (c) 8×10^{-5} H
Flux linked,

$$\phi_1 = \mu_0 N_1^2 I\left(\frac{A}{L}\right) \quad ...(1)$$

$$\text{Mutual inductance, } M = \mu_0 N_1 N_2 I\left(\frac{A}{L}\right) \quad ...(2)$$

[Assuming both coil have same A and L]

On dividing eq. (2) by eq. (1), we have

$$\frac{M}{\phi_1} = \frac{N_2}{N_1}$$

$$\Rightarrow \quad M = \frac{N_2 \phi}{N_1 I} = \frac{600}{300} \times \frac{1.2 \times 10^{-4}}{3} = 8 \times 10^{-5}\text{ H}$$

30. (a) A is true but B is false

31. (a) Zero

TiP

The mutual inductance between two coils depends upon the manner, in which two coils are placed relative to each other.

32. (b) emf induces, when there is change in magnetic flux. The magnitude of induced emf depends upon the rate at which the magnetic flux changes. When magnetic flux is steady or constant, no emf is induced. Faraday did experiment in which, there is relative motion between the coil and magnet, the flux linked with the coil changes and emf induces.

33. (b) According to Faraday's law, the induced emf (ε) is given by $\varepsilon = \frac{-d(N\phi)}{dt} = -\frac{d(NBA)}{dt} = -NA\frac{dB}{dt}$. Thus, induced emf depends on the rate of change of magnetic flux, number of turns of coil and area of the coil. If any of these factor increases (or decreases), then induced e.m.f. also increases (or decreases).

34. (a) According to Faraday's law of electromagnetic induction, induced emf will be generated in the solenoid because of the relative motion between magnet and solenoid.

35. (b) The relation of induced emf is $e = \frac{LdI}{dt}$ and current I is given by $I = \frac{e}{R} = \frac{1}{R}\cdot\frac{LdI}{dt} \Rightarrow \frac{dI}{dt} = I\frac{R}{L} = \frac{I}{L/R}$ in order to decrease the rate of increase of current through solenoid. We have to increase the time constant $\frac{L}{R}$.

36. (a) The inductance coils made of copper will have very small ohmic resistance. Due to change in magnetic flux, a large induced current will be produced in such an inductance, which will offer appreciable opposition to the flow of current.

37. (a) The coefficient of self inductance of the coil is given by

$$L = \frac{\mu_0 N^2 A}{l}$$

where N is number of turns l is length of the coil and A is area of coil, so $L \propto N^2$.

38. (c) The manner in which the two coils are oriented, determines the coefficient of coupling between them.

$$M = K^2.L_1L_2$$

When the two coils are wound on each other, the coefficient of coupling is maximum and hence mutual inductance between the coil is maximum.

39. magnetic lines of force

40. current

41. $\varepsilon = vBl$

42. Four

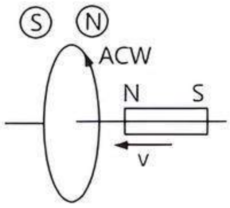
43. $\mu_0\mu_r N^2 A/L$

44. henry

Case Study Based Questions

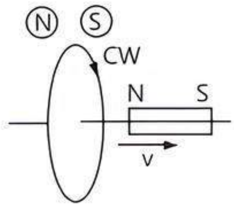
Case Study 1

Lenz's law states that the direction of induced current in a circuit is such that it opposes the change which produces it. Thus, if the magnetic flux linked with a closed circuit increases, the induced current flows in such a direction that a magnetic flux is created in the opposite direction of the original magnetic flux. If the magnetic flux linked with the closed circuit decreases, the induced current flows in such a direction so as to create a magnetic flux in the direction of the original flux.



(Rest)

(Coil face behaves as North pole to oppose the motion of magnet)



(Rest)

(Coil face behaves as South pole to oppose the motion of magnet)

Read the given passage carefully and give the answer of the following questions:

Q 1. Which of the following statement is correct?

a. The induced emf is not in the direction opposing the change in magnetic flux so as to oppose the cause which produces it.

b. The relative motion between the coil and magnet produces change in magnetic flux.

c. emf is induced only if the magnet is moved towards coil.

d. emf is induced only if the coil is moved towards magnet.

Q 2. The polarity of induced emf is given by:

a. Ampere's circuital law

b. Biot-Savart law

c. Lenz's law

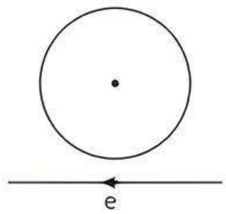
d. Fleming's right hand rule

Q 3. Lenz's law is a consequence of the law of conservation of:

a. charge b. mass

c. momentum d. energy

Q 4. 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

Q 5. Two identical circular coils A and B are kept in a horizontal tube side by side without touching each other. If the current in the coil A increases with time, in response, the coil B:

a. is attracted by A

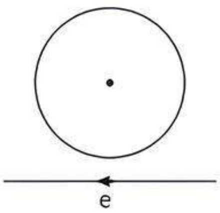
b. remains stationary

c. is repelled

d. rotates

Answers

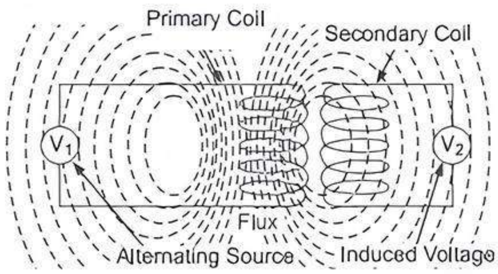
1. (b) The relative motion between the coil and magnet produces change in magnetic flux.
   The relative motion between the coil and the magnet produces change in the magnetic flux in the coil. The induced emf is always in such a direction that it opposes the change in the flux.
2. (c) Lenz's law 3. (d) energy
4. (a) variable
   When an electron is moving from right to left, the flux linked with loop (which is going into the surface) will first increase and then decrease as the electron passes by. So the induced current I in the loop will be first clockwise and will change direction (*i.e.*, will become anti-clockwise) as the electron passes by.



5. (c) is repelled
   When current in coil A increases with time, there will be a change of flux in coil B which will induce a current in B. Now, according to Lenz's law, the direction of induced current in B will be opposite to the direction of current in A. Thus, they will repel each other.

Case Study 2

Mutual inductance between the two coils is defined as the property of the coil due to which it opposes the change of current in the other coil, or you can say in the neighbouring coil. When the current in the neighbouring coil changes, the flux sets up in the coil and because of this, changing flux emf is induced in the coil called mutually induced emf and the phenomenon is known as mutual inductance.



The value of mutual inductance (M) depends upon the following factors:

1. Number of turns in the secondary or neighbouring coil,
2. Cross-sectional area,
3. Closeness of the two coils.

When on a magnetic core, two or more than two coils are wound, the coils are said to be mutually coupled. The current, when passed in any of the coils wound around the magnetic core, produces flux which links all the coils together and also the one in which current is passed. Hence, there will be both self-induced emf and mutual induced emf in each of the coils.

The best example of the mutual inductance is the transformer, which works on the principle of Faraday's law of electromagnetic induction.

Faraday's law of electromagnetic induction states that, "the magnitude of voltage is directly proportional to the rate of change of flux."

Read the given passage carefully and give the answer of the following questions:

Q 1. The phenomenon due to which there is an induced current in one coil due to current in a neighbouring coil is:

a. electromagnetism b. susceptance
c. mutual inductance d. steady current

Q 2. Mutual inductance between two magnetically coupled coils depends on:

a. permeability of the core material
b. number of the turns of the coils
c. cross-sectional area of their common core
d. All of the above

Q 3. Which of the following is a unit of inductance?

a. Ohm b. Henry
c. Ampere d. Weber/meter

Q 4. Which of the following circuit elements will oppose the change in circuit current?

a. Capacitance b. Inductance
c. Resistance d. All of these

Q 5. If in an iron cored coil, the iron core is removed so as to make the air cored coil, the inductance of the coil will be:

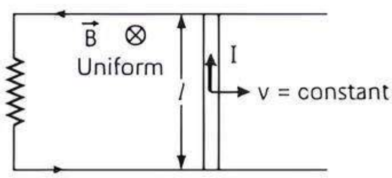
a. more b. less
c. the same d. None of these

Answers

1. (c) mutual inductance
   Mutual Inductance between the two coils is defined as the property of the coil due to which it opposes the change of current in the other coil, or you can say in the neighbouring coil.
2. (d) All of the above
   All of the factors given in the options are responsible for mutual induction.
3. (b) Henry
4. (b) Inductance
5. (b) less
   The inductance of air cored coil is less than that of iron cored coil.

Case Study 3

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



produced due to the magnetic Lorentz force acting on the free electrons of the conductor. For a circuit shown in figure, if a conductor of length l moves with velocity v in a magnetic field B perpendicular to both its length and the direction of the magnetic field, then all the induced parameters are possible in the circuit.

Read the given passage carefully and give the answer of the following questions:

Q 1. Direction of current induced in a wire moving in a magnetic field is found by which rule?

Q 2. 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. What is the current in the rod?

Q 3. A 0.1 m long conductor carrying a current of 50 A is held perpendicular to a magnetic field of 1.25 mT. What will be the required mechanical power to move the conductor with a speed of 1 ms^{-1} is?

Q 4. A bicycle generator creates 1.5 V at 15 km/hr. What is the emf generated at 10 km/hr?

Q 5. What is the dimensional formula for emf ε in MKS system?

Answers

1. Direction of current induced in a wire moving in a magnetic field is found by using Fleming's right hand rule.

2. Induced emf $\varepsilon = Blv$

   Current in the rod, $I = \frac{\varepsilon}{R} = \frac{Blv}{R}$

3. Here, $l = 0.1$ m, $v = 1$ m s^{-1}

   $I = 50$ A, $B = 1.25$ mT $= 1.25 \times 10^{-3}$ T

   The induced emf is $\varepsilon = Blv$

   The mechanical power is

   $P = \varepsilon I = BlvI = 1.25 \times 10^{-3} \times 0.1 \times 1 \times 50$

   $= 6.25 \times 10^{-3}$ W $= 6.25$ mW

4. emf induced, $\varepsilon = Blv$

   Here, $\vec{B}$, $\vec{l}$ and $\vec{v}$ are mutually perpendicular

   For given B and l, $\varepsilon \propto v$.

   $\therefore \quad \frac{\varepsilon_1}{\varepsilon_2} = \frac{v_1}{v_2}$

   Here, $\varepsilon_1 = 1.5$V, $v_1 = 15$ km/hr $= 15 \times \frac{5}{18}$ ms^{-1}

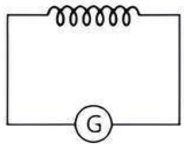
   $v_2 = 10$ km/hr $= 10 \times \frac{5}{18}$ m s^{-1}, $\varepsilon_2 = ?$

   $$\frac{1.5}{\varepsilon_2} = \frac{15 \times \frac{5}{18}}{10 \times \frac{5}{18}} = \frac{3}{2} \quad \Rightarrow \quad \varepsilon_2 = 1\text{ V}$$

5. $\varepsilon = \frac{[W]}{q} = \frac{[ML^2T^{-2}]}{[AT]} = [ML^2T^{-3}A^{-1}]$

Case Study 4

When a current I flows through a coil, flux linked with it is $\phi = LI$, where L is a constant known as self inductance of the coil. Any change in current sets up an induced emf in the coil. Thus, self inductance of a coil is the induced emf set up in the coil when the current passing through it changes at the unit rate. It is a measure of the opposition to the growth or the decay of current flowing through the coil. Also, value of self inductance depends on the number of turns in the solenoid, its area of cross-section and the relative permeability of its core material.



Read the given passage carefully and give the answer of the following questions:

Q 1. A current of 2.5 A flows through a coil of inductance 5 H. What is the magnetic flux linked with the coil?

Q 2. The inductance L of a solenoid depends upon which factor?

Q 3. What is the unit of self-inductance?

Q 4. What will be the induced emf in a coil of 10 henry inductance in which current varies from 9 A to 4 A in 0.2 second?

Answers

1. Here, $I = 2.5$ A, $L = 5$ H

   Magnetic flux linked with the coil is

   $\phi_B = LI = (5\text{H})\,(2.5\text{A}) = 12.5\text{Wb}$

2. The inductance of a solenoid is

   $L = \mu_0 n^2 Al$

   where, A is the area of cross-section of the solenoid, l its length and n is the number of turns per unit length.

   As, $A = \pi R^2$, where R is the radius of the solenoid.

   $$L = \mu_0 n^2 \pi R^2 l$$

   Thus, inductance of a solenoid depends on area of solenoid, length of solenoid, number of turns and radius of solenoid.

3. The magnitude of induced emf is

   $$|\varepsilon| = L\frac{dI}{dt} \Rightarrow L = \frac{|\varepsilon|\,dt}{dI}$$

   $\therefore$ Unit of self inductance,

   $$L = \frac{\text{volt} \times \text{second}}{\text{ampere}} = \text{ohm-second}$$

4. Here, $L = 10$ henry, $I_1 = 9$ A, $I_2 = 4$A

   and $\Delta t = 0.2$ second

   Then induced emf

   $$\varepsilon_1 = -L\frac{dI}{dt} = -L\frac{(I_2 - I_1)}{\Delta t}$$

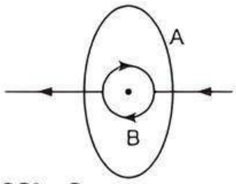
   $$= \frac{-10 \times (4-9)}{0.2} = \frac{50}{0.2} = 250\text{ V}$$

Very Short Answer Type Questions

Q 1. A long straight current carrying wire passes normally through the centre of circular loop. If the current through the wire increases, will there be an induced emf in the loop? Justify. *(CBSE 2019)*

Ans. The flux created by straight current wire is depicted in the figure. So, induced emf (e) $\propto$ rate of change of magnetic flux (ϕ_B) and

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



Here, $B \perp A \Rightarrow \phi_B = BA \cos 90° = 0$

So, induced emf = 0. Hence, a change in current of wire will not create any emf in the loop.

TiP

Magnetic field is perpendicular to area i.e., $B \perp A$.

Q 2. State Faraday's laws of electromagnetic induction. *[CBSE 2017, 16, 15]*

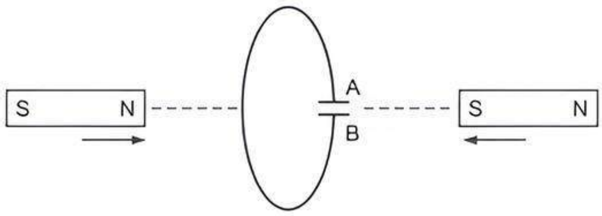
Ans. Faraday's laws of electromagnetic induction:

(i) Whenever there is change in magnetic flux linked with a circuit, an emf is induced in the circuit. The induced emf lasts so long as the change in magnetic flux continues.

(ii) The magnitude of induced emf in a circuit is equal to time rate of change of magnetic flux linked with the circuit.

i.e., $$\varepsilon = -N\frac{d\phi}{dt} = -N\frac{\phi_2 - \phi_1}{t}$$

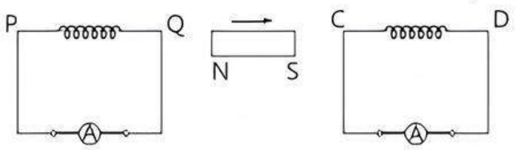
Q 3. Predict the polarity of the capacitor in the situation described below:



(CBSE 2017)

Ans. Plate A of the capacitor will develop positive polarity w.r.t. B as induced current will be in clockwise direction.

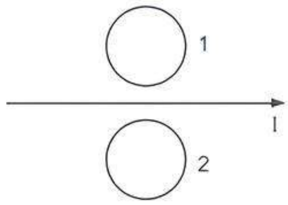
Q 4. A bar magnet is moved in the direction indicated by the arrow between two coils PQ and CD. Predict the direction of the induced current in each coil. *(CBSE 2017)*



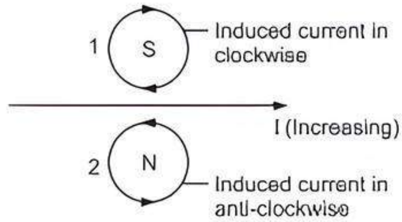
Ans. From the figure, it is clear that north pole of the magnet is moving away from coil PQ, so the direction of current at end Q will flow in such a way that it will oppose the movement of north pole, so it has to act as south pole. Hence, the direction of current will be anti-clockwise.

Again, the south pole is approaching towards coil CD, so end C of the coil will act as south pole (to oppose the approaching of south pole). Hence, the direction of current will be clockwise.

Q 5. What is the direction of induced currents in metal rings 1 and 2 when current I in the wire is increasing steadily?



Ans.



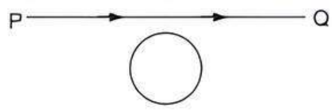
TR!CK

Use Lenz's law.

Q 6. A conducting loop is held above a current carrying wire 'PQ' as shown in the figure. Depict the direction of the current induced in the loop when the current in the wire 'PQ' is constantly increasing.

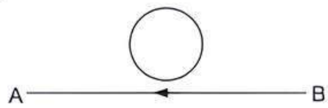
Ans. Clockwise.

Q 7. A conducting loop is held below a current carrying wire 'PQ' as shown in the figure. Predict the direction of the induced current in the loop when the current in the wire 'PQ' is constantly increasing.



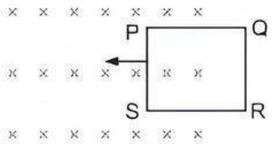
Ans. Anti-clockwise.

Q 8. The electric current flowing in a wire in the direction from B to A is decreasing. Find out the direction of the induced current in the metallic loop kept above the wire as shown in figure.



Ans. Clockwise.

Q 9. The closed loop (*PQRS*) of wire is moved into a uniform magnetic field at right angles to the plane of the paper as shown in figure. Predict the direction of the induced current in the loop.



Ans. Anti-clockwise.

TR!CK

Use Lenz's law.

Q 10. The number of turns and length of the solenoid are both doubled, keeping area of cross-section of the solenoid same. What will be the self inductance of the coil?

Sol. As we know,

$$L = \frac{\mu_0 N^2 A}{l}$$

Now, let us assume the new inductance is L', so

$$N' = 2N \text{ and } l' = 2l$$

$$\therefore \quad L' = \frac{\mu_0 (2N)^2 A}{2l} = \frac{4\mu_0 N^2 A}{2l}$$

$$= \frac{2\mu_0 N^2 A}{l} = 2L$$

Q 11. Define mutual inductance of a coil. Write its SI unit.

[CBSE 2019, 15]

Ans. Mutual inductance of two coils may be defined as the total magnetic flux linked with one coil, when unit current flows through the other coil.

Its SI unit is henry (H).

Short Answer Type-I Questions

Q 1. What is motional electromotive force (motional emf)?

A rod of length *l* is moved horizontally with a uniform velocity '*v*' in a direction perpendicular to its length through a region in which a uniform magnetic field is acting vertically downward. Derive an expression for the emf induced across the ends of the rod.

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

Expression for motional emf:

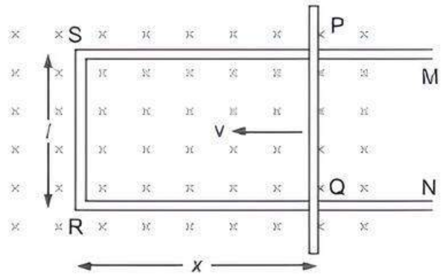
Magnetic flux enclosed by loop *PQRS*

$$\phi = \vec{B}\,\vec{A} = Blx$$

Since x is variable w.r.t. time, the rate of change of magnetic flux will induce an emf given by

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

$$\Rightarrow \quad \varepsilon = -\frac{d}{dt}(Blx) = Bl\left(-\frac{dx}{dt}\right)$$



$$\Rightarrow \quad \varepsilon = Blv$$

where, $v = -\dfrac{dx}{dt}$, because velocity v is in opposite direction.

COMMON ERR!R

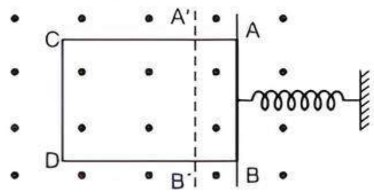
Students often get confused with negative sign at the end.

$$\therefore \quad v = \frac{-dx}{dt}.$$

Its just a indication of the direction.

Q 2. A rectangular frame of wire is placed in a uniform magnetic field directed outwards, normal to the paper. *AB* is connected to a spring which is stretched to *A′B′* and then released at time $t = 0$. Explain qualitatively how induced electromotive force in the coil would vary with time. (Neglect damping of oscillations of spring)

(CBSE 2018)



Ans. According to figure, when wire *AB* is moved towards left at *A′B′*, then spring is stretched and provide a restoring force on wire, which starts moving towards right side, *i.e.* wire *AB* performs simple harmonic motion. In this case, magnetic flux linked with wire continuously changes, therefore an induced emf is produced across wire *AB* which continuously decreases with time and finally becomes zero.

Q 3. A square loop of side 10cm and resistance 0.5Ω is placed vertically in the east-west plane. A uniform magnetic field of 0.10 T is set up across the plane in the north-east direction. The magnetic field is decreased to zero in 0.70s at a steady rate. Determine the magnitudes of induced emf and current during this time-interval.

Ans. The angle θ made by the area vector of the coil with the magnetic field is 45°. Hence, the initial magnetic flux is

$$\phi = BA\cos\theta$$

$$= 0.1 \times 10^{-2} \times \cos 45° = \frac{0.1 \times 10^{-2}}{\sqrt{2}} = \frac{10^{-3}}{\sqrt{2}}\text{ Wb}$$

Final flux, $\phi_{min} = 0$

The change in flux is brought about in 0.70 s. So, the magnitude of the induced emf is given by

$$\varepsilon = \frac{|\Delta\phi_B|}{\Delta t} = \frac{|\phi - 0|}{\Delta t} = \frac{10^{-3}}{\sqrt{2} \times 0.7} = 1.0 \text{ mV}$$

And the magnitude of the current is

$$I = \frac{\varepsilon}{R} = \frac{10^{-3} \text{ V}}{0.5\Omega} = 2 \text{ mA}$$

Q 4. A 2 m long solenoid with diameter 2 cm and 2000 turns has a secondary coil of 1000 turns would closely near its mid-point. What will be the mutual inductance between the two coils?

Sol. Here, $l = 2$ m, diameter $= 2$ cm

$\therefore$ Radius, $r = \frac{2}{2} = 1 \text{ cm} = 1 \times 10^{-2}$ m

$N_1 = 2000$, $N_2 = 1000$

Area $= \pi r^2 = \pi \times (1 \times 10^{-2})^2 = 3.14 \times 10^{-4} \text{m}^2$

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

$$= \frac{4\pi \times 10^{-7} \times 2000 \times 1000 \times 3.14 \times 10^{-4}}{2}$$

$= 3.9 \times 10^{-4}$ H

Short Answer Type-II Questions

Q 1. (i) Derive an expression for the induced emf developed when a coil of N turns and area of cross-section A is rotated at a constant angular speed ω in a uniform magnetic field B.

(ii) A wheel with 100 metallic spokes each 0.5m long is rotated with a speed of 120 rev/min in a plane normal to the horizontal component of the Earth's magnetic field. If the resultant magnetic field at that place is 4×10^{-4} T and the angle of dip at the place is 30°, find the emf induced between the axle and the rim of the wheel. *(CBSE 2019)*

Ans. (i) When a coil of area of cross-section A having N number of turns is rotating with angular velocity ω in uniform magnetic field B, then magnetic flux linked with coil,

$$\phi = BA \cos\theta$$

$$\phi = BA \cos\omega t \qquad [\because \theta = \omega t]$$

Induced emf (ε) in the coil,

$$\varepsilon = -N\frac{d\phi}{dt} = -N\frac{d}{dt}BA\cos\omega t$$

$$= NBA\,\omega \sin\omega t$$

$$\varepsilon = \varepsilon_0 \sin\omega t \qquad [\text{where, } \varepsilon_0 = NBA\omega]$$

(ii) Given, number of spokes = 100, length, $l = 0.5$ m, $\omega = 120$ rev/min,

$B_E = 4 \times 10^{-4}$ T and $\theta = 30°$

$$E = \frac{1}{2}B_H l^2\omega = \frac{1}{2}B_e \cos\theta . l^2\omega \qquad [\because B_H = B_e \cos\theta]$$

$$= \frac{1}{2} \times 4 \times 10^{-4} \times \frac{\sqrt{3}}{2} \times (0.5)^2 \times 2\pi \times \frac{120}{60}$$

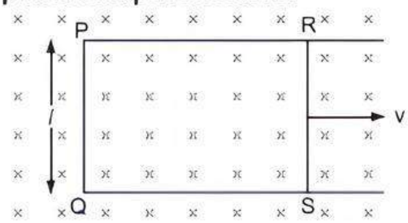
$= 5.43 \times 10^{-4}$ V

Q 2. Figure shows a rectangular conducting loop $PQSR$ in which arm RS of length 'l' is movable. The loop is kept in a uniform magnetic field 'B' directed downwards perpendicular to the plane of the loop. The arm RS is moved with a uniform speed 'v'. Deduce the expression for the:

(i) emf induced across the arm 'RS'

(ii) external force required to move the arm and

(iii) power dissipated as heat.



Ans. **(i) Induced emf**

Magnetic flux enclosed by loop $PQSR$

$$\phi = BA = Blx$$

Since x is changing with time, the rate of change of magnetic flux will induce an emf given by

$$|\varepsilon| = \frac{d\phi}{dt} = \frac{d}{dt}(Blx) = Bl\left(\frac{dx}{dt}\right)$$

$$\Rightarrow \quad |\varepsilon| = Blv$$

(ii) External force required to move the arm RS

Induced current, $I = \frac{\varepsilon}{R} = \frac{Blv}{R}$

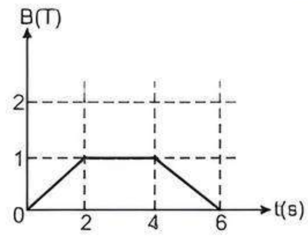
$\Rightarrow$ External force required,

$$F = BIl\sin 90° = B\left(\frac{Blv}{R}\right)l = \frac{B^2l^2v}{R}$$

(iii) Power dissipated as heat

$$p = I^2R = \left(\frac{Blv}{R}\right)^2 \times R = \frac{B^2l^2v^2}{R}$$

Q 3. The magnetic field through a circular loop of wire 12cm in radius and 8.5Ω resistance, changes with time as shown in the figure. The magnetic field is perpendicular to the plane of the loop. Calculate the current induced in the loop and plot a graph showing induced current as a function of time. *(CBSE SQP 2022-23)*



Sol. Given, radius of circular loop, $r = 12$ cm $= 0.12$ m,

Resistance, $R = 8.5\ \Omega$

We have, area of the circular loop $= \pi r^2$

$$= 3.14 \times (0.12)^2\ m^2 = 4.5 \times 10^{-2}\ m^2$$

Also, $$E = -\frac{d\phi}{dt} = -\frac{d}{dt}(BA)$$

$$= -A\frac{dB}{dt} = -A \cdot \frac{B_2 - B_1}{t_2 - t_1}$$

For $0 < t < 2$ s,

$$E_1 = -4.5 \times 10^{-2} \times \left\{\frac{1-0}{2-0}\right\}$$

$$= -2.25 \times 10^{-2}\ V$$

$$I_1 = \frac{E_1}{R} = \frac{-2.25 \times 10^{-2}}{8.5}\ A$$

$$= -2.6 \times 10^{-3}\ A = -2.6\ mA$$

For $2\ s < t < 4$ s,

$$E_2 = -4.5 \times 10^{-2} \times \left\{\frac{1-1}{4-2}\right\} = 0$$

$$\therefore \quad I_2 = \frac{E_2}{R} = 0$$

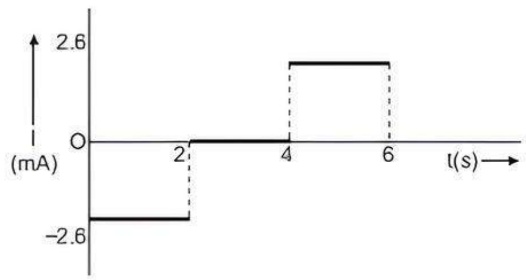
For $4\ s < t < 6$ s,

$$I_3 = -\frac{4.5 \times 10^{-2}}{8.5} \times \left\{\frac{0-1}{6-4}\right\} A = 2.6\ mA$$

So, the current induced in the loop is given in the table as:

	$0 < t < 2$ s	2 s $< t < 4$ s	4 s $< t < 6$ s
E (V)	$-$ 0.023	0	+ 0.023
I (mA)	$-$ 2.6	0	+ 2.6

Graph showing induced current as a function of time:



Q 4. Define self-inductance of a coil. Obtain the expression for the energy stored in an inductor L connected across a source of emf. *(CBSE 2017)*

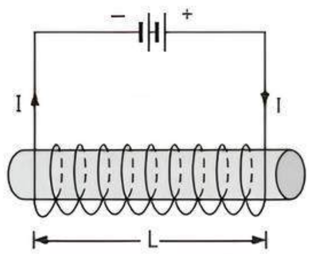
Ans. Self Inductance: Self inductance of a coil is numerically equal to the emf induced in that coil when the current in it changes at a unit rate. Alternatively, the self inductance of a coil equals the flux linked with it when a unit current flows through it.

The work done against induced emf is stored as magnetic potential energy.

The rate of work done, when a current I passing through the coil, is

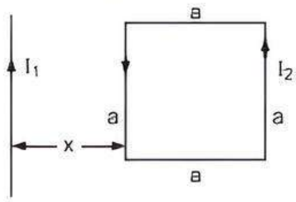
$$\frac{dW}{dt} = |\varepsilon| I = \left(L\frac{dI}{dt}\right)I$$

$$\therefore \quad W = \int dW = \int_0^I LI dI = \frac{1}{2}LI^2$$



Q 5. (i) Define mutual inductance and write its SI unit.

(ii) A square loop of side 'a' carrying a current I_2 is kept at distance x from an infinitely long straight wire carrying a current I_1 as shown in the figure. Obtain the expression for the resultant force acting on the loop.



(CBSE 2019)

Ans. (i) **Mutual Inductance:** The phenomenon according to which an opposing emf is produced in a coil *i.e.*, primary coil as a result of change in current or magnetic flux linked with a neighbouring coil *i.e.*, secondary coil is called mutual inductance.

SI unit of mutual inductance is henry (H).

(ii) Force per unit length between two parallel straight conductors is given by $F = \frac{\mu_0}{4\pi}\frac{2I_1I_2}{d}$

$\therefore$ Force on the part of the loop which is parallel to infinite straight wire and at a distance x from it.

$$F_1 = \frac{\mu_0}{2\pi}\frac{I_1I_2a}{x} \text{ (away from the infinite straight wire)} \quad ...(1)$$

Force on the part of the loop which is at a distance $(x + a)$ from it.

$$F_2 = \frac{\mu_0}{2\pi}\frac{I_1I_2a}{(x+a)} \text{ (towards the infinite straight wire)} \quad ...(2)$$

$\therefore$ Net force, $F = F_1 - F_2$

$$F = \frac{\mu_0}{2\pi}I_1I_2a\left[\frac{1}{x} - \frac{1}{x+a}\right]$$

$$\Rightarrow F = \frac{\mu_0}{2\pi}\frac{I_1I_2a^2}{x(x+a)}$$

(away from the infinite straight wire)

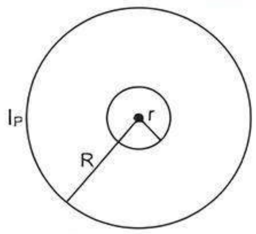
Q 6. (i) Define mutual inductance and write its SI unit.

(ii) Two circular loops, one of small radius r and other of larger radius R, such that $R >> r$, are placed coaxially with centres coinciding. Obtain the mutual inductance of the arrangement. *(CBSE SQP 2023-24)*

Ans. (i) **Mutual Inductance:** The phenomenon according to which an opposing emf is produced in a coil *i.e.*, primary coil as a result of change in current or magnetic flux linked with a neighbouring coil *i.e.*, secondary coil is called mutual inductance.

SI unit of mutual inductance is henry (H).

(ii)



Let a current I_p flow through the circular loop of radius R. The magnetic induction at the centre of the loop is

$$B_p = \frac{\mu_0 I_P}{2R}$$

As, $r << R$, the magnetic induction B_p may be considered to be constant over the entire cross-sectional area of inner loop of radius r. Hence, magnetic flux linked with the smaller loop will be

$$\phi_S = B_P A_S = \frac{\mu_0 I_P}{2R}\pi r^2$$

Also, $\phi_S = MI_P$

$$M = \frac{\phi_S}{I_P} = \frac{\mu_0 \pi r^2}{2R}$$

Q 7. What is meant by the term 'mutual inductance' of a pair of coils? Obtain an expression for the mutual inductance of two long coaxial solenoids, each of length l but having different number of turns N_1 and N_2 and radii r_1 and r_2 ($r_2 > r_1$). *(CBSE 2023)*

Ans. Mutual inductance between two coils is equal to the magnetic flux linked with one coil when a unit current is passed in the other coil.

Alternatively, $e = -\frac{MdI}{dt}$

Mutual inductance is equal to the induced emf set up in one coil when the rate of change of current flowing through the other coil is unity.

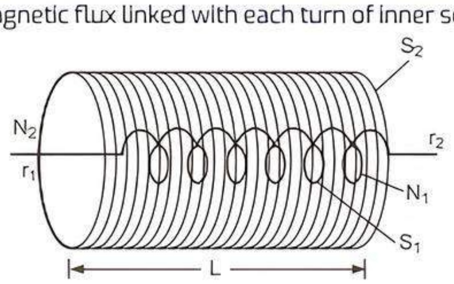
Expression for mutual inductance of two long coaxial solenoids:

Mutual inductance between two co-axial long solenoids of same length wound one over the other:

Magnetic field at the centre of solenoid S_2,

$$B_2 = \mu_0 n_2 I_2 = \frac{\mu_0 N_2 I_2}{L}$$

Magnetic flux linked with each turn of inner solenoid S



$$\phi_1 = B_2 A_1 = \left(\frac{\mu_0 N_2 I_2}{L}\right)A_1 = \frac{\mu_0 N_2 I_2 A_1}{L}$$

Hence, mutual inductance,

$$M_{12} = \frac{N_1\phi_1}{I_2} = \frac{N_1}{I_2}\left(\frac{\mu_0 N_2 I_2 A_1}{L}\right) = \frac{\mu_0 N_1 N_2 A_1}{L}$$

$$\Rightarrow \quad M_{12} = \frac{\mu_0 (n_1 L)(n_2 L) r_1^2}{L} = \mu_0 n_1 n_2 r_1^2 L$$

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

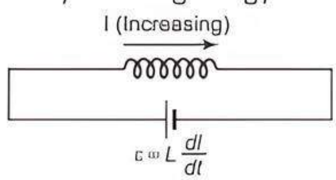
$$\Rightarrow \quad M_{12} = M_{21} = M = \mu_0 n_1 n_2 r_1^2 L$$

If a medium of relative permeability μ_r is filled in between the solenoids, then

$$M = \mu_0 \mu_r n_1 n_2 r_1^2 L$$

Q 8. Derive an expression for the magnetic energy stored in an inductor, when a current I develops in it. Hence, obtain the expression for the magnetic energy density. *(CBSE 2019)*

Ans. The energy of a capacitor is stored in the electric field between its plates. Similarly, an inductor has the capability of storing energy in its magnetic field.



An increasing current in an inductor causes an emf between its terminals.

The work done per unit time is power.

$$P = \frac{dW}{dt} = -\varepsilon I = -LI\frac{dI}{dt}$$

From $dW = -dU$ or $\frac{dW}{dt} = -\frac{dU}{dt}$, we have

$$\frac{dU}{dt} = LI\frac{dI}{dt} \quad \text{or} \quad dU = LI\,dI$$

The total energy U supplied while the current increases from zero to a final value I is

$$U = L\int_0^I IdI = \frac{1}{2}LI^2$$

$$\therefore \quad W = U = \frac{1}{2}LI^2 \quad \text{... (1)}$$

The magnetic field, $B = \frac{\mu_0 NI}{l} \Rightarrow I = \frac{Bl}{\mu_0 N}$ ...(2)

The self-inductance, $L = \frac{\mu_0 N^2 A}{l}$ ...(3)

Putting values of L and I in eq. (1)

$$\Rightarrow \quad U_m = \frac{1}{2}\times\frac{\mu_0 N^2 A}{l}\times\frac{B^2 l^2}{\mu_0^2 N^2} = \frac{B^2(Al)}{2\mu_0}$$

$$\Rightarrow \quad \frac{U_m}{Al} = \frac{1}{2}\frac{B^2}{\mu_0}$$

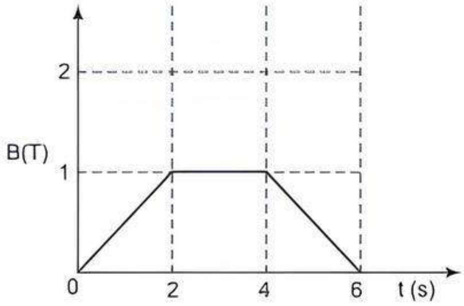
where, $\frac{U_m}{Al}$ = energy density.

$$U_m = \frac{1}{2}\frac{B^2}{\mu_0}$$

Long Answer Type Questions

Q 1. (i) State Faraday's law of electromagnetic induction.

(ii) The magnetic field through a circular loop of wire 12 cm in radius and 8.5 Ω resistance, changes with time as shown in the figure. The magnetic field is perpendicular to the plane of the loop. Calculate the induced current in the loop and plot it as a function of time.



(iii) Show that Lenz's law is a consequence of conservation of energy. *(CBSE 2017)*

Ans. (i) **Faraday's law:** The magnitude of the induced emf in a circuit is equal to the time rate of change of magnetic flux through the circuit *i.e.*,

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

(ii) Area $= \pi R^2 = \pi \times 1.44 \times 10^{-2}\ m^2$ ($\because r = 12cm = 0.12$ m)

$= 3.14 \times 1.44 \times 10^{-2}\ m^2$

$= 4.5 \times 10^{-2}\ m^2$

For $0 < t < 2$

$$\text{emf, } \varepsilon_1 = \frac{d\phi_1}{dt} = -A\frac{dB}{dt} = -4.5\times10^{-2}\times\frac{1}{2}$$

$$= -2.25 \times 10^{-2}\ V$$

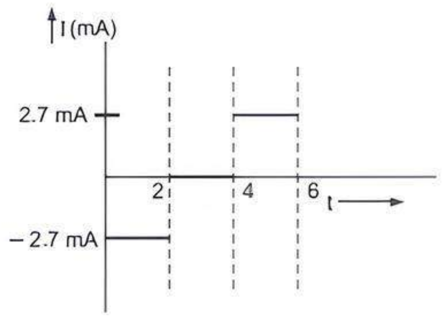
$$I_1 = -\frac{\varepsilon_1}{R} = \frac{-2.25\times10^{-2}}{8.5} = -2.7\ mA$$

For $2 < t < 4$

$$I_2 = \frac{\varepsilon_2}{R} = 0$$

For $4 < t < 6$

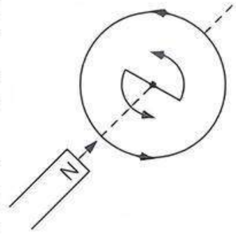
$$I_3 = -\frac{\varepsilon_3}{R} = +2.7\ mA$$



COMMON ERR(!)R

Students often fails to plot it as a function of time.

(iii) If a North pole of the bar magnet moves towards the coil the magnetic flux through the coil increases. Hence, induced current is counter clockwise (to oppose the increase in flux, by producing a North pole). In this situation, the bar magnet experiences a repulsive force, therefore work has to be done to move the magnet towards the coil. It is this work that gets converted into electrical energy.



Q 2. A metallic rod of length *l* and resistance *R* is rotated with a frequency ν, with one end hinged at the centre and the other end at the circumference of a circular metallic ring of radius *l*, about an axis passing through the centre and perpendicular to the plane of the ring. A constant and uniform magnetic field *B* parallel to the axis is present everywhere.

(i) Derive an expression for the induced emf and the current in the rod.

(ii) Due to the presence of the current in the rod and of the magnetic field, find the expression for the magnitude and direction of the force acting on this rod.

(iii) Hence, obtain an expression for the power required to rotate the rod.

Ans. (i) In one revolution

change in area, $dA = \pi l^2$

$\therefore$ Change of magnetic flux

$$d\phi = \vec{B} \cdot d\vec{A} = BdA\cos 0° = B\pi l^2$$

If period of revolution is T

(a) Induced emf, $\varepsilon = \dfrac{d\phi}{T} = \dfrac{B\pi l^2}{T} = B\pi l^2 \nu$

(b) Induced current in the rod,

$$I = \frac{\varepsilon}{R} = \frac{\pi\nu B l^2}{R}$$

(ii) Force acting on the rod, $F = IlB = \dfrac{\pi\nu B^2 l^3}{R}$

The external force required to rotate the rod opposes the Lorentz force acting on the rod/ external force acts in the direction opposite to the Lorentz force.

(iii) Power required to rotate the rod.

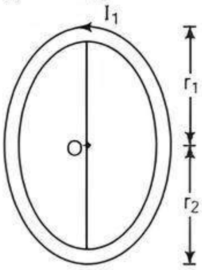
$$P = Fv = \frac{\pi\nu B^2 l^3 v}{R}$$

Q 3. (i) Explain the meaning of the term mutual inductance. Consider two concentric circular coils, one of the radius r_1 and the other of radius $r_2 (r_1 < r_2)$ placed coaxially with centres coinciding with each other. Obtain the expression for the mutual inductance of the arrangement.

(ii) **A rectangular coil of area *A*, having number of turns *N* is rotated at *f* revolutions per second in a uniform magnetic field *B*, the field being perpendicular to the coil. Prove that the maximum emf induced in the coil is $2\pi fNBA$.**

(CBSE 2016)

Ans. (i) 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.' Mutual induction is also known as mutual inductance.



According to question, let the current in big coil of radius r_2 be I_1 so, magnetic field at point *O* due to this coil will be $\mu_0 I_1/2r_2$.

Change in magnetic flux in the coil of radius r_1 is,

$$\phi = \vec{B}\vec{A} = \frac{\mu_0 I_1}{2r_2} \times \pi r_1^2$$

Mutual inductance, $M = \frac{\phi}{I_1} = \frac{\mu_0 I_1 \pi r_1^2}{2r_2 \times I_1} = \frac{\mu_0 \pi r_1^2}{2r_2}$

This is the required expression.

(ii) According to the question, if a coil of *N* turns rotates with an angular velocity of ω and angle θ is suspended in time *t*,

thus $\theta = \omega t$

$\therefore \quad \phi = BA\cos\theta = BA\cos\omega t$

As the coil rotates, the magnetic flux linked with it changes. An induced emf is set up in the coil which is given by

$$\varepsilon = \frac{-d\phi}{dt} = \frac{-d}{dt}(BA\cos\omega t) = BA\omega\sin\omega t$$

For *N* number of turns, $\varepsilon = NBA\omega\sin\omega t$

For maximum value of emf, ωt must be equal to 90°,

So, maximum emf induced is $= NBA\omega$

i.e., $\varepsilon = NBA2\pi f$ or $2\pi fNBA$ $\quad [\because \omega = 2\pi f]$

Chapter Test

Multiple Choice Questions

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

a. 0.02Wb
b. 0.06Wb
c. 0.08Wb
d. 0.01Wb

Q 2. Whenever there is a change in the magnetic flux linked with a closed circuit, an emf and a current are induced in the circuit. This statement is referred to as:

a. Lenz's law
b. Faraday's second law of electromagnetic induction
c. Faraday's first law of electromagnetic induction
d. Laplace's law

Assertion and Reason Type Questions

Directions (Q.Nos. 3-4): *In the following questions, statement of Assertion (A) is followed by a statement of Reason (R). Mark the correct choice as:*

a. Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).
b. Both Assertion (A) and Reason (R) are true but Reason (R) is not the correct explanation of Assertion (A).
c. Assertion (A) is true but Reason (R) is false.
d. Both Assertion (A) and Reason (R) are false.

Q 3. Assertion (A): The induced emf in a conducting loop of wire will be non-zero when it rotates in a uniform magnetic field.

Reason (R): The emf is induced due to change in magnetic flux.

Q 4. Assertion (A): In the phenomenon of mutual induction, self induction of each of the coils persists.

Reason (R): Self induction arises when strength of current in same coil changes. In mutual induction, current is changing in both the individual coils.

Fill in the blanks

Q 5. SI unit of magnetic flux is ....

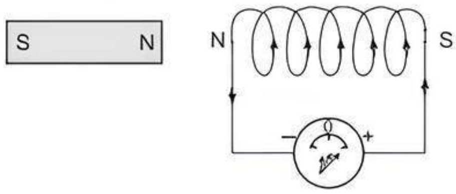
Q 6. The .... of a coil is proportional to the square of the number of turns.

Case Study Based Question

Q 7. The induced electromotive force with different polarities induces a current whose magnetic field opposes the change in magnetic flux through the loop in order to ensure that original flux is maintained through the loop when current flows in it.

To better understand Lenz's law, let us consider two cases:

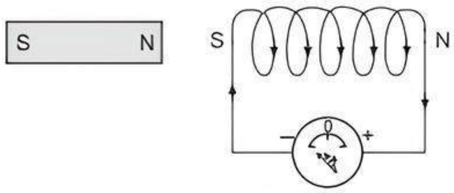
Case 1: When a magnet is moving towards the coil.



When the north pole of the magnet is approaching towards the coil, the magnetic flux linking to the coil increases. According to Faraday's law of electromagnetic induction, when there is a change in flux, an emf and hence current is induced in the coil and this current will create its own magnetic field.

Now according to Lenz's law, this magnetic field created will oppose its own or we can say opposes the increase in flux through the coil and this is possible only if approaching coil side attains north polarity, as we know similar poles repel each other. Once we know the magnetic polarity of the coil side, we can easily determine the direction of the induced current by applying right hand rule. In this case, the current flows in the anti-clockwise direction.

Case 2: When a magnet is moving away from the coil.

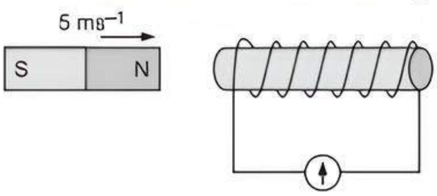


When the north pole of the magnet is moving away from the coil, the magnetic flux linking to the coil decreases. According to Faraday's law of electromagnetic induction, an emf and hence current is induced in the coil and this current will create its own magnetic field.

Now according to Lenz's law, this magnetic field created will oppose its own or we can say opposes the decrease in flux through the coil and this is possible only if approaching coil side attains south polarity, as we know dissimilar poles attract each other. Once we know the magnetic polarity of the coil side, we can easily determine the direction of the induced current by applying right hand rule. In this case, the current flows in a clockwise direction.

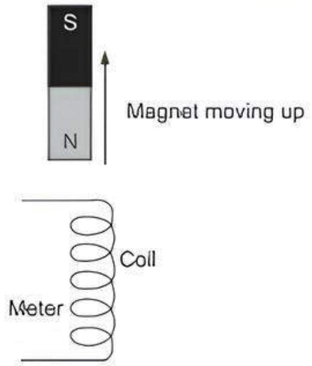
Read the given passage carefully and give the answer of the following questions:

(i) What is the direction of the induced magnetic field?



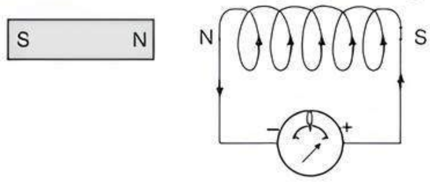
a. Left b. Right c. Up d. Down

(ii) What is the direction of the induced magnetic field?



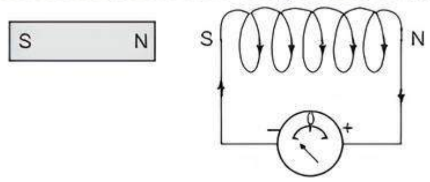
a. Left b. Right c. Up d. Down

(iii) In what direction is the magnet moving?



a. Left b. Right c. Up d. Down

(iv) In what direction is the magnet moving?



a. Left b. Right c. Up d. Down

(v) Which of the following is Not an application of Lenz's Law?

a. Transformer
b. AC Generator
c. DC Motor
d. A coil transversed by AC current

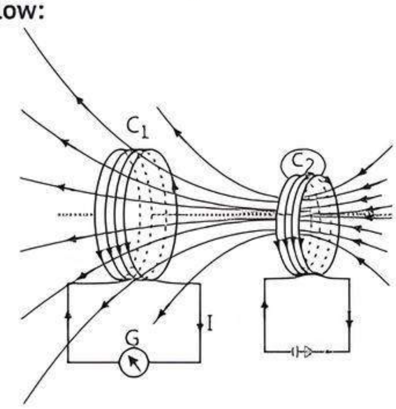
Very Short Answer Type Questions

Q 8. A straight line conductor of length 0.4 m is moved with a speed of 7 m/s perpendicular to a magnetic field of intensity 0.9 Wb/m^2. Calculate the induced emf across the conductor.

Q 9. When the number of turns of the coil is increased twice and the length is reduced by 4, what will be the self inductance of the coil?

Short Answer Type-I Questions

Q 10. Dinesh sir was demonstrating an experiment in his class with the setup as shown in the figure given below:



(i) What would he do to obtain a large deflection on the galvanometer?

(ii) How would he demonstrate the presence of an induced current in the absence of a galvanometer?

Q 11. A rectangular coil of 100 turns and size 0.1 m $\times$ 0.05 m is placed perpendicular to a magnetic field of 0.1 T. If the field drops to 0.05 T in 0.05 second, what is the magnitude of the e.m.f. induced in the coil?

Short Answer Type-II Questions

Q 12. A coil of 100 turns and resistance of 10 Ω encloses an area of $100 m^2$. It is placed at an angle of 70° with a magnetic field of 0.1 Wb/m^2. What is the magnetic flux through the coil? If magnetic flux is reduced to zero in 10^{-3}s. What emf is induced in the coil and what charge flows through it?

Q 13. A wire in the form of a circular loop of radius 10 cm lies in a plane normal to a magnetic field of 100T. If it is pulled to take a square shape in the same plane in 0.1s. Calculate the average induced emf in the loop.

Q 14. (i) Obtain the expression for the magnetic energy stored in a solenoid in terms of magnetic field B, area A and length l of the solenoid.

(ii) How does this magnetic energy compare with the electrostatic energy stored in a capacitor?

Long Answer Type Questions

Q 15. (i) A circular loop of radius 0.3 cm lies parallel to a much bigger circular loop of radius 20cm. The centre of the small loop is on the axis of the bigger loop. The distance between their centres is 15cm. If a current of 2.0 A flows through the smaller loop, calculate the flux linked with bigger loop.

(ii) A long solenoid with 10 turns per cm has a small loop of area 3 cm^2 placed inside, normal to the axis of the solenoid. If the current carried by the solenoid changes steadily from 2A to 4A in 0.2s, what is the induced voltage in the loop, while the current is changing?

Q 16. (i) Define coefficient of self-induction. Obtain an expression for self-inductance of a long solenoid of length l, area of cross-section A having N turns.

(ii) Calculate the self-inductance of a coil using the following data obtained when an AC source of frequency $\left(\frac{200}{\pi}\right)$ Hz and a DC source is applied across the coil. *(CBSE 2023)*

AC Source		
S. No.	V (Volts)	I (A)
1.	3.0	0.5
2.	6.0	1.0
3.	9.0	1.5

DC Source		
S. No.	V (Volts)	I (A)
1.	4.0	1.0
2.	6.0	1.5
3.	8.0	2.0