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Chapter 6 : Electromagnetic Induction (Notes)

by - Tomar Sir

Notes

GSEB and CBSE Board Exam preparation subjective notes · Class 12 Physics · NCERT Chapter 6

Q.1 Describe Faraday's experiments on electromagnetic induction. (3 Marks)

What conclusion did they lead to?

Electromagnetic induction: The phenomenon in which an electric current is generated by varying magnetic fields. It was discovered by Michael Faraday (England) and Joseph Henry (USA) around 1830.

Experiment 6.1 (magnet and coil): A coil C_1 is connected to a galvanometer G (Fig. 6.1).

- When the N-pole of a bar magnet is pushed towards the coil, G deflects; the deflection lasts only while the magnet moves.
- When the magnet is held stationary, there is **no deflection**.
- When the magnet is pulled away, G deflects in the **opposite** direction.
- Using the S-pole reverses the deflections; faster motion gives a larger deflection.
- Moving the coil instead of the magnet gives the same effects.

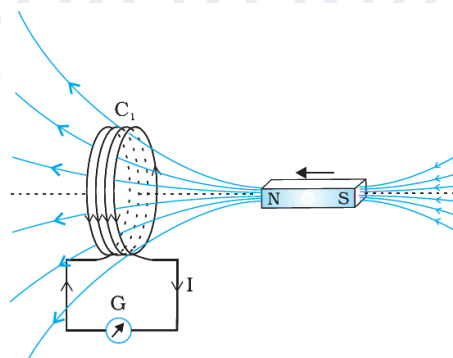


Fig. 6.1: When the bar magnet is pushed towards the coil, the pointer in the galvanometer G deflects

Conclusion: It is the **relative motion** between the magnet and the coil that induces an electric current in the coil.

Experiment 6.2 (two coils): The magnet is replaced by a second coil C_2 carrying a steady current (Fig. 6.2). Moving C_2 towards or away from C_1 induces a current in C_1 .

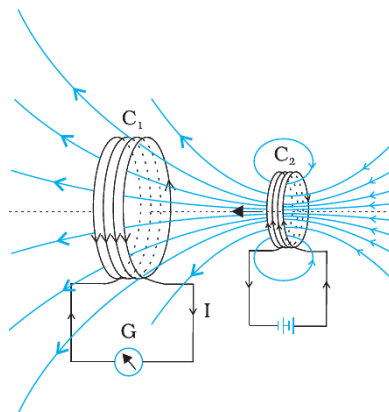


Fig. 6.2: Current is induced in coil C_1 due to motion of the current-carrying coil C_2

Experiment 6.3 (no motion): Two stationary coils: C_1 with a galvanometer and C_2 with a battery and tapping key K (Fig. 6.3). G shows a **momentary** deflection when K is pressed and an opposite one when K is released; no deflection while K is held pressed. Inserting an **iron rod** along the axis increases the deflection dramatically.

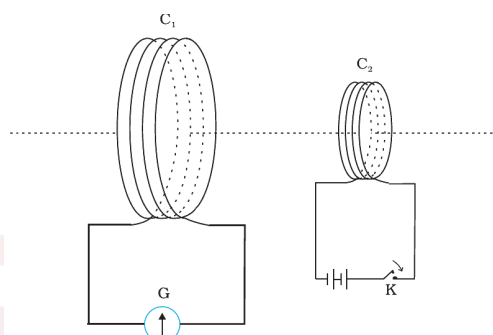


Fig. 6.3: Experimental set-up for Experiment 6.3

Overall conclusion: An emf is induced in a coil whenever the **magnetic flux through it changes** with time. Relative motion is not an absolute requirement.

Q.2 Define magnetic flux. Give its SI unit.

(2 Marks)

Magnetic flux through a plane area A in a uniform magnetic field B (Fig. 6.4):

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

where θ is the angle between $\vec{B}$ and the area vector $\vec{A}$ (normal to the surface).

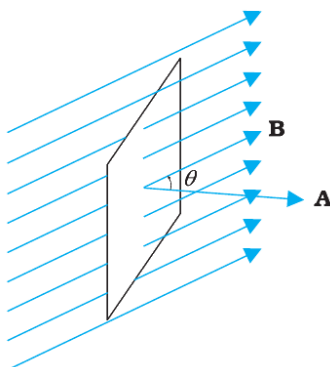


Fig. 6.4: A plane of surface area A placed in a uniform magnetic field B

For a curved surface or non-uniform field (Fig. 6.5):

$$\Phi_B = \vec{B}_1 \cdot d\vec{A}_1 + \vec{B}_2 \cdot d\vec{A}_2 + \dots = \sum_{\text{all}} \vec{B}_i \cdot d\vec{A}_i$$

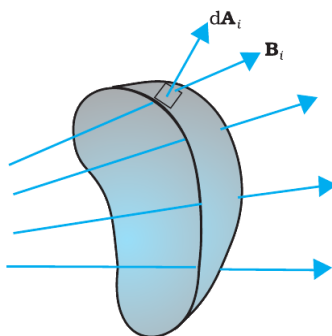


Fig. 6.5: Magnetic field B_i at the i^{th} area element; dA_i is its area vector

SI unit: weber (Wb) = T m². **Dimensions:** $[ML^2 T^{-2} A^{-1}]$. Magnetic flux is a **scalar**.

Key Examination Points for Full Marks:

- Flux is maximum (BA) when the plane is perpendicular to B ($\theta = 0^\circ$), and zero when the plane is parallel to B ($\theta = 90^\circ$).
- The flux can be changed by changing B , A or θ .

Q.3 State Faraday's law of electromagnetic induction. Write the expression for induced emf. (2 Marks)

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.

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

For a closely wound coil of N turns (the same flux change in each turn):

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

The **negative sign** indicates the direction of ε (and hence of the current) — Lenz's law.

If the circuit is closed with resistance R , the induced current is $I = \varepsilon / R$, and the **induced charge** is

$$q = \frac{N\Delta\Phi}{R}$$

which is independent of the time taken.

Key Examination Points for Full Marks:

- The emf can be increased by increasing N , or by changing the flux faster.
- Example 6.2:** Square loop of side 10 cm, $R = 0.5 \Omega$, in the E-W plane; $B = 0.10$ T in the NE direction ($\theta = 45^\circ$) falls to zero in 0.70 s: $\Phi = \frac{10^{-3}}{\sqrt{2}}$ Wb, $\varepsilon = 1.0$ mV, $I = 2$ mA.
- Example 6.3:** Coil ($r = 10$ cm, $N = 500$, $R = 2 \Omega$) turned through 180° in 0.25 s in $B_H = 3 \times 10^{-5}$ T: $\varepsilon = 3.8 \times 10^{-3}$ V, $I = 1.9 \times 10^{-3}$ A (estimated values).

Q.4 State Lenz's law. Show that it is consistent with the law of conservation of energy. (3 Marks)

Lenz's law (1834): The polarity of the induced emf is such that it tends to produce a current which opposes the change in magnetic flux that produced it.

This is the meaning of the negative sign in $\varepsilon = - d\Phi_B / dt$.

Explanation with Experiment 6.1 (Fig. 6.6):

- As the **N-pole approaches** the coil, the flux increases. The induced current flows **anticlockwise** (seen from the magnet's side), so the face of the coil towards the magnet becomes a **N-pole** — it **repels** the approaching magnet.
- As the **N-pole is withdrawn**, the flux decreases. The induced current flows **clockwise**, the near face becomes a **S-pole** and it **attracts** the receding magnet.

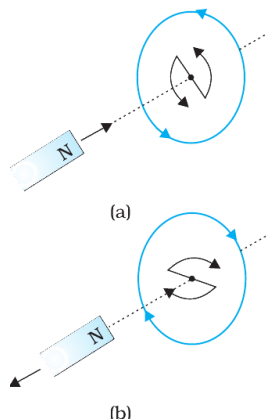


Fig. 6.6: Illustration of Lenz's law

Lenz's law and conservation of energy: Suppose the induced current were in the opposite direction (Fig. 6.6(a)). Then a S-pole would face the approaching N-pole, attracting the magnet with ever-increasing acceleration. A gentle push would make its kinetic energy grow continuously without any energy being spent — a **perpetual-motion machine**, which violates conservation of energy. Hence this cannot happen.

In the correct case, the magnet is repelled, so a person must **do work** to move it. This mechanical energy is converted into electrical energy and finally dissipated as **Joule heat** by the induced current.

Key Examination Points for Full Marks:

- For an **open circuit**, an emf is still induced across the open ends; its polarity is found using Lenz's law.
- Example 6.4:** Loops moving into a field (into page): flux increases — current opposes (bcdab for the rectangle); moving out: flux decreases — current tries to maintain it. No current when a loop is completely inside or completely outside the field.

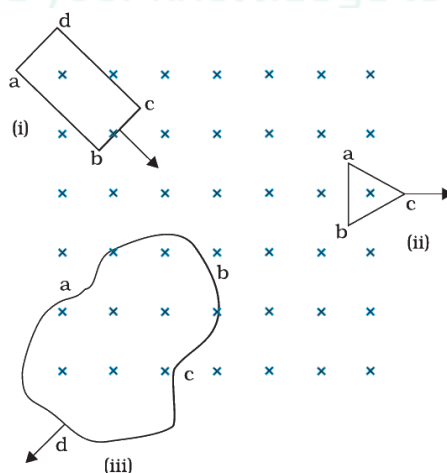


Fig. 6.7: Planar loops moving into or out of a magnetic field directed into the page (Example 6.4)

Q.5 Derive the expression for motional emf. Also explain it using the Lorentz force. (3 Marks)

Using Faraday's law: A rectangular conductor PQRS has a movable arm PQ of length l , moved to the left with constant velocity v in a uniform field B perpendicular to the plane (Fig. 6.10). If $RQ = x$, the flux enclosed is

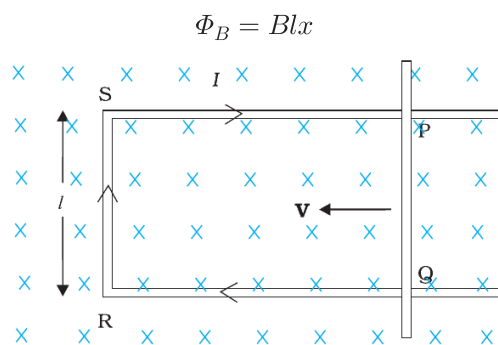


Fig. 6.10: The arm PQ is moved to the left, decreasing the area of the rectangular loop. This induces a current I

$$\varepsilon = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}(Blx) = -Bl\frac{dx}{dt} = Blv$$

(since $dx/dt = -v$). Thus

$$\varepsilon = Blv$$

This is called the **motional emf** — produced by moving a conductor in a field rather than by changing the field.

Using the Lorentz force: A charge q in the rod moves with speed v in field B , so it feels a force qvB along the rod (towards Q). Work done in moving it from P to Q:

$$W = qvBl \Rightarrow \varepsilon = \frac{W}{q} = Blv$$

Key Examination Points for Full Marks:

- For a **stationary** conductor in a time-varying field, the force on charges is $q\vec{E}$ alone ($v = 0$). So a **time-varying magnetic field must generate an electric field**. Electric fields due to changing B differ from those of static charges.
- If v , B and l are not mutually perpendicular, $\varepsilon = (\vec{v} \times \vec{B}) \cdot \vec{l}$.

Q.6 Derive the emf induced between the centre and the rim when a metal rod rotates in a magnetic field. (2 Marks)

A metallic rod of length R rotates with angular velocity ω about one end O (at the centre of a circular metal ring), in a uniform field B parallel to the axis (Fig. 6.11).

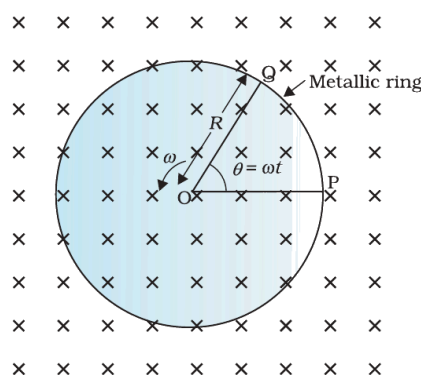


Fig. 6.11: A metal rod OQ rotating in a uniform magnetic field (Example 6.6)

Method I: An element dr at distance r moves with speed $v = \omega r$, so it has emf $d\varepsilon = Bv dr$:

$$\varepsilon = \int_0^R B\omega r dr = \frac{B\omega R^2}{2}$$

Method II: Imagine a closed loop OPQ. The area of sector OPQ is $\frac{1}{2}R^2\theta$:

$$\varepsilon = B \frac{d}{dt} \left(\frac{1}{2} R^2 \theta \right) = \frac{1}{2} B R^2 \frac{d\theta}{dt} = \frac{B \omega R^2}{2}$$

$$\varepsilon = \frac{1}{2} B \omega R^2 = B \pi \nu R^2$$

Key Examination Points for Full Marks:

- **Example 6.6:** $l = 1 \text{ m}$, $\nu = 50 \text{ rev/s}$, $B = 1 \text{ T}$: $\varepsilon = \frac{1}{2} \times 1 \times 2\pi \times 50 \times 1^2 = 157 \text{ V}$.
- **Example 6.7:** A wheel with 10 spokes, each 0.5 m, at 120 rev/min in $H_E = 0.4 \text{ G}$:
 $\varepsilon = \frac{1}{2} \times 4\pi \times 0.4 \times 10^{-4} \times (0.5)^2 = 6.28 \times 10^{-5} \text{ V}$. **The number of spokes does not matter** — the spokes are in parallel.

Q.7 What is inductance? Define mutual inductance and derive it for two long co-axial solenoids. (3 Marks)

Inductance: For a coil, the flux linkage $N\Phi_B$ is proportional to the current: $N\Phi_B \propto I$. The constant of proportionality is the **inductance**. It depends only on the geometry of the coil and the material (permeability) — like capacitance.

Unit: henry (H). **Dimensions:** $[ML^2 T^{-2} A^{-2}]$. It is a scalar.

Mutual inductance: Consider two long co-axial solenoids of length l (Fig. 6.12): inner S_1 (radius r_1 , n_1 turns per unit length) and outer S_2 (radius r_2 , n_2 turns per unit length).

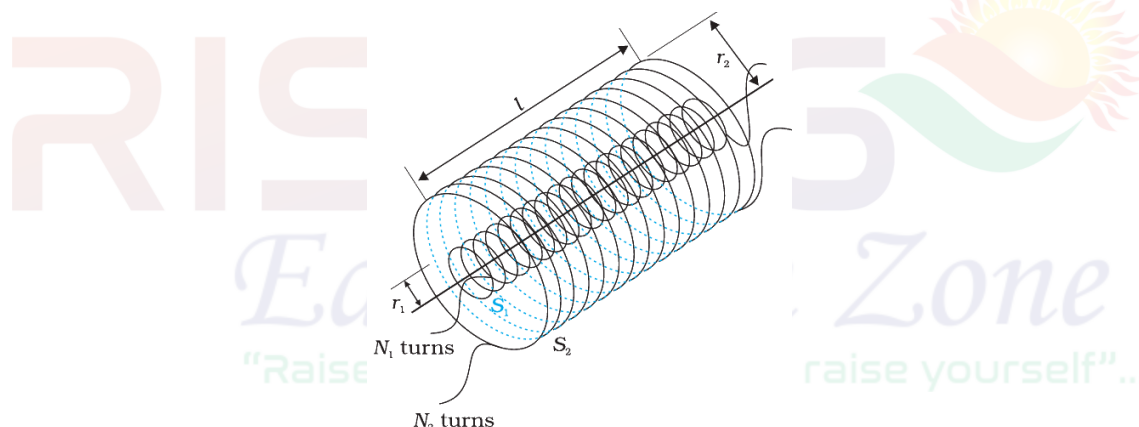


Fig. 6.12: Two long co-axial solenoids of the same length l

A current I_2 in S_2 produces a field $\mu_0 n_2 I_2$. Flux linkage with S_1 :

$$N_1 \Phi_1 = M_{12} I_2, \quad N_1 \Phi_1 = (n_1 l) (\pi r_1^2) (\mu_0 n_2 I_2)$$

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

M_{12} is the **mutual inductance** of S_1 with respect to S_2 (coefficient of mutual induction). In the reverse case, a current I_1 in S_1 produces flux (confined inside S_1) through S_2 :

$$N_2 \Phi_2 = (n_2 l) (\pi r_1^2) (\mu_0 n_1 I_1) \Rightarrow M_{21} = \mu_0 n_1 n_2 \pi r_1^2 l$$

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

With a medium of relative permeability μ_r : $M = \mu_r \mu_0 n_1 n_2 \pi r_1^2 l$.

Induced emf: $\varepsilon_1 = -M \frac{dI_2}{dt}$ — a varying current in one coil induces an emf in the neighbouring coil.

Key Examination Points for Full Marks:

- M depends on the **separation and relative orientation** of the coils, the number of turns, the area and the medium.

- **Example 6.8:** Two co-axial concentric coils ($r_1 \ll r_2$): $M = \frac{\mu_0 \pi r_1^2}{2r_2}$.

Q.8 Define self-inductance. Derive the self-inductance of a long solenoid. (3 Marks)

Self-induction: An emf is induced in a coil due to a change of flux caused by varying the current through the same coil. The flux linkage is proportional to the current:

$$N\Phi_B = LI$$

L is the **self-inductance** (coefficient of self-induction). The induced emf is

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

The self-induced emf always **opposes any change** (increase or decrease) of current — it is also called the **back emf**.

Long solenoid: Area A , length l , n turns per unit length. The field is $B = \mu_0 nI$. Total flux linkage:

$$N\Phi_B = (nl) (\mu_0 nI) (A) = \mu_0 n^2 AlI$$

$$L = \frac{N\Phi_B}{I} = \mu_0 n^2 Al$$

With a core of relative permeability μ_r (e.g. soft iron):

$$L = \mu_r \mu_0 n^2 Al$$

Key Examination Points for Full Marks:

- In terms of total turns N : $L = \frac{\mu_0 N^2 A}{l}$, so $L \propto N^2$.
- L depends on geometry and permeability, not on the current.
- For two nearby coils: $\varepsilon_1 = -L_1 \frac{dI_1}{dt} - M_{12} \frac{dI_2}{dt}$.

Q.9 Show that the energy stored in an inductor is $\frac{1}{2}LI^2$. Express the magnetic energy density. (3 Marks)

Self-inductance plays the role of inertia — it is the electromagnetic analogue of mass. Work must be done against the back emf to establish a current, and it is stored as **magnetic potential energy**.

Rate of work done at current I : $\frac{dW}{dt} = |\varepsilon|I = LI \frac{dI}{dt}$ (ignoring resistive losses).

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

This resembles $\frac{1}{2}mv^2$ — L is **electrical inertia**; it opposes the growth and decay of current.

Energy in terms of B (Example 6.9): For a solenoid, $B = \mu_0 nI$ and $L = \mu_0 n^2 Al$:

$$U_B = \frac{1}{2}LI^2 = \frac{1}{2}(\mu_0 n^2 Al) \left(\frac{B}{\mu_0 n}\right)^2 = \frac{1}{2\mu_0} B^2 Al$$

Energy density (per unit volume, $V = Al$):

$$u_B = \frac{B^2}{2\mu_0}$$

Compare the electric energy density $u_E = \frac{1}{2}\varepsilon_0 E^2$. In both cases, energy density is proportional to the **square of the field**; these results are general.

Key Examination Points for Full Marks:

- Dimensions of $B^2/2\mu_0$ are those of pressure: $[M L^{-1} T^{-2}]$.
- The energy is stored in the magnetic field, not in the wire.

Q.10 Explain the principle, construction and working of an AC generator. Derive the expression for induced emf. (3 Marks)

Principle: Electromagnetic induction — when a coil rotates in a magnetic field, the angle between its area vector and the field changes, so the **flux through it changes** and an emf is induced. It converts **mechanical energy into electrical energy**. (Credited to Nicola Tesla.)

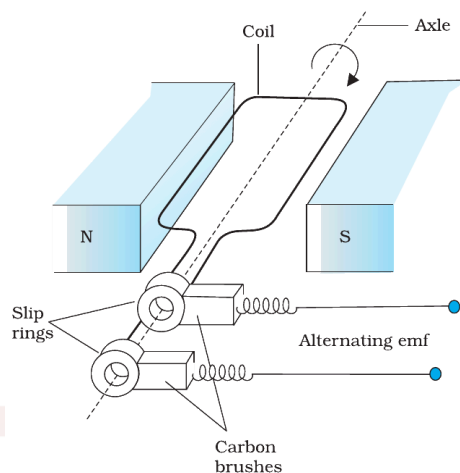


Fig. 6.13: AC generator

Construction: A coil (**armature**) is mounted on a rotor shaft, with the axis of rotation perpendicular to the magnetic field. Its ends are connected to an external circuit through **slip rings** and **carbon brushes**.

Working and emf: The coil of N turns and area A rotates with constant angular speed ω . If $\theta = 0$ at $t = 0$, then $\theta = \omega t$, and

$$\begin{aligned}\Phi_B &= BA \cos \theta = BA \cos \omega t \\ \varepsilon &= -N \frac{d\Phi_B}{dt} = -NBA \frac{d}{dt} (\cos \omega t) \\ \varepsilon &= NBA\omega \sin \omega t = \varepsilon_0 \sin \omega t\end{aligned}$$

where $\varepsilon_0 = NBA\omega$ is the **maximum (peak) emf**, reached when $\sin \omega t = \pm 1$ — i.e. $\theta = 90^\circ$ or 270° , when the plane of the coil is **parallel** to the field and the flux changes fastest. With $\omega = 2\pi\nu$: $\varepsilon = \varepsilon_0 \sin 2\pi\nu t$.

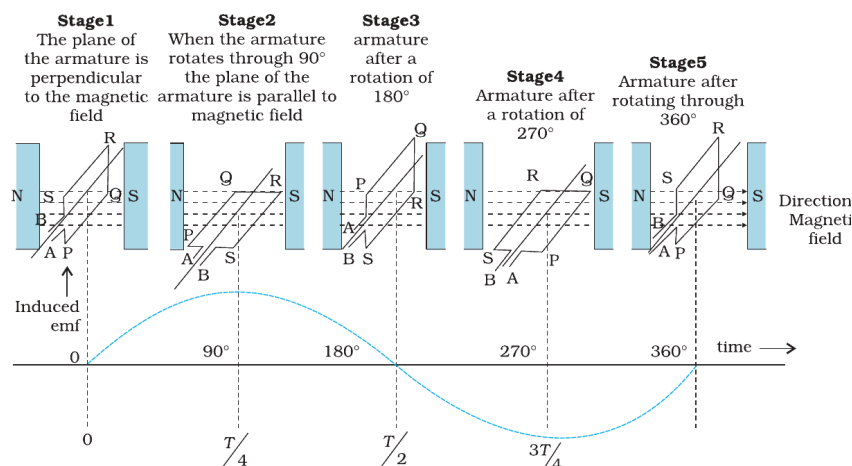


Fig. 6.14: An alternating emf is generated by a loop of wire rotating in a magnetic field

The polarity of the emf changes periodically, so the current is called **alternating current (ac)**.

Key Examination Points for Full Marks:

- The emf is zero when the plane of the coil is perpendicular to B (maximum flux) and maximum when parallel to B (zero flux).
- Types: hydro-electric, thermal and nuclear power generators. In most generators the coils are stationary and the **electromagnets rotate**. The frequency is 50 Hz in India (60 Hz in the USA).
- Example 6.10:** $N = 100$, $A = 0.10 \text{ m}^2$, $\nu = 0.5 \text{ Hz}$, $B = 0.01 \text{ T}$: $\varepsilon_0 = NBA (2\pi\nu) = 0.314 \text{ V}$.

Formula Sheet — Electromagnetic Induction

Quantity	Formula	SI Unit
Magnetic flux	$\Phi_B = \vec{B} \cdot \vec{A} = BA \cos \theta$	Wb
Faraday's law	$\varepsilon = -N \frac{d\Phi_B}{dt}$	V
Induced current	$I = \frac{\varepsilon}{R} = -\frac{N d\Phi}{R dt}$	A
Induced charge	$q = \frac{N \Delta\Phi}{R}$	C
Motional emf	$\varepsilon = Blv$	V
Rotating rod	$\varepsilon = \frac{1}{2} B \omega l^2$	V
Self-induced emf	$\varepsilon = -L \frac{dI}{dt}$; $N\Phi = LI$	V
Mutual emf	$\varepsilon_1 = -M \frac{dI_2}{dt}$; $N_1\Phi_1 = MI_2$	V
L of solenoid	$L = \mu_r \mu_0 n^2 Al = \frac{\mu_0 \mu_r N^2 A}{l}$	H
M of co-axial solenoids	$M = \mu_0 n_1 n_2 \pi r_1^2 l$	H
M of concentric coils ($r_1 \ll r_2$)	$M = \frac{\mu_0 \pi r_1^2}{2r_2}$	H
Energy in inductor	$U = \frac{1}{2} LI^2$	J
Magnetic energy density	$u_B = \frac{B^2}{2\mu_0}$	J m^{-3}
AC generator	$\varepsilon = NBA\omega \sin \omega t$; $\varepsilon_0 = NBA\omega$	V

Units of L: $\text{H} = \text{Wb A}^{-1} = \text{V s A}^{-1} = \Omega \text{ s}$.

Dimensions: flux $[\text{M L}^2 \text{T}^{-2} \text{A}^{-1}]$; emf $[\text{M L}^2 \text{T}^{-3} \text{A}^{-1}]$; L and M $[\text{M L}^2 \text{T}^{-2} \text{A}^{-2}]$; L/R has dimensions of time.

NEET / JEE Quick Points and Tricks

- No change in flux → no induced emf**, however strong the field. A loop completely inside a uniform field, moving or not, has zero emf.
- Induced charge** $q = N\Delta\Phi/R$ does not depend on how fast the flux changes. It equals the area under the I–t graph; $\Delta\Phi = R \times (\text{area under I–t graph})$.
- Lenz's law shortcut:** an approaching pole sees the **same** pole on the coil face (repulsion); a receding pole sees the **opposite** pole (attraction). A magnet falling through a coil or copper tube falls with acceleration **less than g**.

4. **Motional emf** uses the length perpendicular to v (effective length). A semicircular or bent wire of chord length d moving perpendicular to B gives $\varepsilon = Bvd$.
5. **Rotating rod** about one end: $\frac{1}{2}B\omega l^2$. About its centre: zero between the ends. A wheel with spokes: the number of spokes does not matter (parallel).
6. **Fleming's right-hand rule** gives the direction of the induced current: thumb $\rightarrow$ motion, forefinger $\rightarrow$ field, middle finger $\rightarrow$ current.
7. $L \propto N^2$ for the same geometry. Rewinding the same wire into more turns changes L .
8. **Combinations (no mutual coupling)**: series $L = L_1 + L_2$; parallel $\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2}$ — same rules as resistors.
9. **Coupled coils**: $M = k\sqrt{L_1 L_2}$ ($k \leq 1$); maximum $M = \sqrt{L_1 L_2}$.
10. **Square loop (side L) — field at centre** $= \frac{2\sqrt{2}\mu_0 I}{\pi L}$; mutual inductance with a small co-centric loop of area a : $M = \frac{2\sqrt{2}\mu_0 a}{\pi L}$.
11. **Iron core in a solenoid in series with a bulb on ac**: L increases $\rightarrow$ reactance increases $\rightarrow$ bulb becomes dimmer.
12. **Generator emf** is maximum when the coil plane is **parallel** to B ; flux is maximum when the plane is **perpendicular** to B (90° phase difference).
13. **Eddy currents** (induced in bulk conductors) cause heating losses; reduced by laminating the core. Used in electromagnetic damping, induction furnaces and braking of trains.
14. **Energy density** $B^2/2\mu_0$ has the same dimensions as pressure: $[M L^{-1} T^{-2}]$.

