FREE NOTES · NCERT + JEE/NEET LEVEL

Electromagnetic Induction

Magnetic flux, Faraday's and Lenz's laws, motional EMF, eddy currents, self and mutual inductance, energy in an inductor and the AC generator. With diagrams and solved numericals.

01 Faraday's experiments
02 Magnetic flux
03 Faraday's law
04 Lenz's law
05 Motional EMF
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01 Faraday's experiments

Oersted showed that current creates a magnetic field. Faraday asked the reverse: can a magnetic field create a current? Yes, but only when the field is **changing**.

- Move a magnet toward or away from a coil: the galvanometer deflects. Not when the magnet is still.
- The faster the magnet moves, the larger the deflection.
- Switch the current in one coil on or off: a current appears in a nearby coil (only at that moment).

The current produced by a changing field is the **induced current**, and the EMF is the **induced EMF**.

02 Magnetic flux

$$\Phi = B \cdot A = B\,A\cos\theta$$

θ = angle between B and the area vector (normal to the surface). Unit weber (Wb) = T·m². A scalar. N turns: total flux NΦ.

Flux can change in three ways: **change B**, **change the area**, or **change the angle** (rotate the coil).

03 Faraday's law

STATEMENT

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

Induced EMF = rate of change of flux. Average: $\varepsilon = -N\Delta\Phi/\Delta t$. The minus sign is Lenz's law.

Induced current $I = \varepsilon/R$

Induced charge $Q = N\Delta\Phi/R$

The charge depends only on the total change in flux, not on how fast it changed.

04 Lenz's law

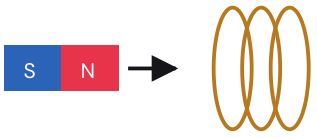
STATEMENT

The induced current flows in a direction that **opposes the change** that produced it.

- Bring a magnet's N pole toward a coil ⇒ the near face of the coil becomes N (repels).
- Move the N pole away ⇒ the near face becomes S (attracts, to resist).

ENERGY CONSERVATION

If the induced current supported the change, energy would be created for free, which is impossible. Lenz's law follows from energy conservation: the work done pushing the magnet becomes the electrical energy.



N face (repels)

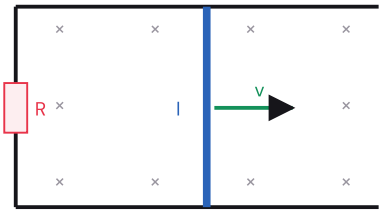
The coil becomes N to oppose an approaching N

05 Motional EMF

A rod of length l moves with velocity v perpendicular to B. The Lorentz force on its charges produces an EMF.

$$\varepsilon = B\,l\,v$$

With a closed circuit (resistance R): I = Blv/R, and an opposing force $F = B^2l^2v/R$ acts on the rod. Power to keep it moving at constant $v = B^2l^2v^2/R$ = heat (I^2R).



A rod sliding on rails, B into the page

06 Rotating rod & disc

Rod (length l) rotating about one end at ω, B ⊥: $\varepsilon = \frac{1}{2}\,B\,\omega\,l^2$

Disc (radius R): between centre and rim $\varepsilon = \frac{1}{2}\,B\,\omega\,R^2$

Each part of the rod moves at a different speed; use the average speed ωl/2.

07 Eddy currents

In a bulk piece of metal, changing flux creates swirling loops of current inside: **eddy currents**. They produce heat and oppose motion.

USES

- Electromagnetic brakes in trains.
- Damping that makes a galvanometer needle settle quickly.
- Induction furnaces, induction cooktops.
- Speedometers.

LOSSES AND PREVENTION

Energy loss and heating in transformer/motor cores. Prevention: build the core from thin **laminated** (insulated) sheets so the current paths are broken up.

08 Self inductance

When a coil's own current changes, its own flux changes ⇒ an EMF in itself that opposes the change (back EMF). It is the "inertia" of current.

$$N\Phi = L\,I$$

$$\varepsilon = -\,L\,dI/dt$$

Long solenoid: $L = \mu_0\, n^2\, A\, l = \mu_0 N^2 A/l$

Unit henry (H). An iron core (μ_r) multiplies L by μ_r.

ENERGY STORED IN AN INDUCTOR

$$U = \tfrac{1}{2}\,L\,I^2$$

Stored in the magnetic field. Energy density = $B^2/(2\mu_0)$. Like $\tfrac{1}{2}mv^2$ for a mass: L ↔ m, I ↔ v.

Opening a switch tries to drop the current to 0 suddenly ⇒ a very large back EMF ⇒ a **spark**.

09 Mutual inductance

A changing current in one coil induces an EMF in a nearby coil.

$$N_2\Phi_2 = M\,I_1,\ \varepsilon_2 = -\,M\,dI_1/dt$$

Two coaxial solenoids: $M = \mu_0\, n_1\, n_2\, A\, l$

$$M = k\,\sqrt{(L_1 L_2)},\ 0 \le k \le 1 \text{ (coupling)}$$

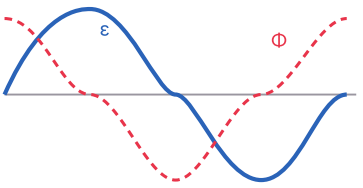
$M_{12} = M_{21}$. Coils close together on the same axis ⇒ larger M. Transformers work on this.

10 AC generator

Rotate a coil (N turns, area A) in a magnetic field at ω. The angle θ = ωt changes ⇒ flux $NBA\cos\omega t$ changes ⇒ EMF.

$$\varepsilon = N\,B\,A\,\omega\sin\omega t = \varepsilon_0\sin\omega t$$

Peak EMF ε_0 = NBAω. When the coil's plane is parallel to B (flux 0), the EMF is **maximum**. When perpendicular (flux maximum), EMF is 0.



Flux maximum ⇒ EMF 0, and vice versa (π/2 apart)

Mechanical energy (turbine, water, steam) → electrical energy. In India f = 50 Hz.

11 JEE Extra + Tricks

JEE LEVEL

- Motional emf: rod $\varepsilon = Bvl$; rod rotating about one end $\varepsilon = \frac{1}{2}B\omega l^2$; disc $\frac{1}{2}B\omega R^2$.
- Self-inductance of solenoid $L = \mu_0 n^2 Al$; energy $\frac{1}{2}LI^2$; energy density $B^2/2\mu_0$.
- LR circuit: growth $I = I_0(1 - e^{-t/\tau})$, decay $I = I_0 e^{-t/\tau}$, $\tau = L/R$. At $t = 0$ inductor acts as open circuit; at steady state as a plain wire.
- Mutual inductance of coaxial solenoids $M = \mu_0 n_1 n_2 Al$; $M \le \sqrt{(L_1 L_2)}$.
- Lenz's law is conservation of energy: induced current opposes the change (magnet falling through a copper tube falls slowly).

12 Solved numericals

Q1. The flux in a 100-turn coil changes from 0.05 Wb to 0.01 Wb in 0.2 s. EMF?
$\varepsilon = 100 \times 0.04/0.2 = 20$ V. **Ans: 20 V**

Q2. A 50 cm rod moves at 4 m/s ⊥ to a 0.5 T field. EMF? Current if R = 2 Ω?
$\varepsilon = 0.5 \times 0.5 \times 4 = 1$ V. $I = 0.5$ A. **Ans: 1 V, 0.5 A**

Q3. A 1 m rod rotates about one end at 10 rad/s in a 0.2 T field. EMF?
$\varepsilon = \frac{1}{2} \times 0.2 \times 10 \times 1 = 1$ V. **Ans: 1 V**

Q4. A coil with L = 0.2 H: current falls from 5 A to 0 in 0.1 s. Induced EMF?
$\varepsilon = L\,\Delta I/\Delta t = 0.2 \times 50 = 10$ V. **Ans: 10 V**

Q5. A 2 H inductor carries 3 A. Stored energy?
$U = \frac{1}{2} \times 2 \times 9 = 9$ J. **Ans: 9 J**

Q6. Generator: 100 turns, A = 0.1 m², B = 0.01 T, 50 Hz. Peak EMF?
$\omega = 100\pi$. $\varepsilon_0 = 100 \times 0.01 \times 0.1 \times 100\pi = 10\pi \approx 31.4$ V. **Ans: ≈ 31.4 V**

13 Common mistakes

- Assuming an EMF with constant flux. Only **changing** flux induces EMF.
- Getting Lenz's direction backwards: the induced current **opposes** the change.
- Writing "maximum flux gives maximum EMF" for a generator (it's the opposite).
- Using Blv for a rotating rod (½Bωl² is correct).
- Mixing n (per metre) and N (total) in the formula for L.

14 Formula sheet

Flux	$\Phi = BA\cos\theta$
Faraday	$\varepsilon = -N\,d\Phi/dt$
Induced charge	$Q = N\Delta\Phi/R$
Motional EMF	$\varepsilon = Blv$
Rotating rod	$\varepsilon = \frac{1}{2}B\omega l^2$
Self inductance	$\varepsilon = -L\,dI/dt,\ L = \mu_0 n^2 Al$
Mutual inductance	$\varepsilon = -M\,dI/dt,\ M = \mu_0 n_1 n_2 Al$
Energy	$U = \frac{1}{2}LI^2,\ u = B^2/2\mu_0$
AC generator	$\varepsilon = NBA\omega\sin\omega t$

15 Practice questions

1. A solenoid's number of turns is doubled (same length). L?
2. A generator's speed is doubled. Peak EMF?
3. A magnet is pushed into a coil quickly or slowly: difference in induced charge?
4. Why is a transformer core laminated?

ANSWERS

1) 4 times ($L \propto N^2$) · 2) Doubles · 3) No difference ($Q = N\Delta\Phi/R$) · 4) To reduce eddy current losses

16 Quick revision: 5 minutes before the exam

LAWS

- $\varepsilon = -N\, d\Phi/dt$.
- Lenz: opposes the change (energy conservation).
- $Q = N\Delta\Phi/R$ (independent of speed).

MOTIONAL

- Rod: Blv.
- Rotating rod/disc: $\frac{1}{2}B\omega l^2$.
- Eddy currents: reduced by laminated cores.

INDUCTANCE

- $\varepsilon = -L\, dI/dt$; $L = \mu_o n^2 Al$.
- $U = \frac{1}{2}LI^2$.
- $M = k\sqrt{(L_1 L_2)}$.

GENERATOR

- $\varepsilon_o = NBA\omega$.
- Maximum flux ⇒ EMF 0.

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