APPLIED PHYSICS 2

2nd Semester | Diploma / Polytechnic

Unit – 5: Electromagnetism

Detailed Study Notes with Formulas, Examples & Diagrams

Unit – 5: Electromagnetism

Electromagnetism is the branch of physics that studies the relationship between electricity and magnetism. Whenever electric current flows through a conductor, a magnetic field is produced around it, and conversely, a changing magnetic field can produce electric current. This unit covers the fundamental laws, forces, and devices based on these principles, all of which are essential for understanding modern electrical and electronic systems.

1. Magnetic Field

1.1 Definition

A magnetic field is a region of space around a magnet, a current-carrying conductor, or a moving charge where magnetic forces are experienced. It is a vector quantity — it has both magnitude and direction.

- Symbol: B
- It is also called magnetic flux density.
- Direction: Represented by field lines that go from North pole to South pole outside the magnet.

1.2 Origin of Magnetic Field

Magnetic fields are produced by:

- Moving electric charges (current-carrying conductors)
- Permanent magnets (due to spin of electrons inside atoms)
- Changing electric fields (as stated by Maxwell's equations)

In simple terms, wherever there is electric current, there is a surrounding magnetic field.

1.3 Units of Magnetic Field

- SI Unit: Tesla (T)
- CGS Unit: Gauss (G) — 1 Tesla = 10,000 Gauss
- Magnetic flux (Φ) = B × A; Unit of flux: Weber (Wb)

2. Lorentz Force

When a charged particle moves through a magnetic field, it experiences a force called the Lorentz Force (magnetic part). If both electric and magnetic fields are present, the total force is:

$$F = q(E + v \times B)$$

For the magnetic component alone (when $E = 0$):

Formula

- $F = qvB \sin\theta$
- F = force on the charge (Newtons)
- q = charge of the particle (Coulombs)
- v = velocity of the particle (m/s)
- B = magnetic field strength (Tesla)
- θ = angle between velocity and magnetic field

Key Points

- Force is maximum when $\theta = 90°$ (velocity perpendicular to B): $F = qvB$
- Force is zero when $\theta = 0°$ or $180°$ (velocity parallel to B)
- Direction is given by Fleming's Left Hand Rule for positive charges
- The force is always perpendicular to both v and B — so it does NO work on the charge

Real-life example: This principle is used in cyclotrons, mass spectrometers, and in cathode ray tubes (CRTs) of old televisions.

Example: An electron (charge = 1.6×10^{-19} C) moves with velocity 2×10^{6} m/s at right angles to a magnetic field of 0.5 T. Find the force on it.

Solution: $F = qvB \sin\theta = 1.6 \times 10^{-19} \times 2 \times 10^{6} \times 0.5 \times \sin 90° = 1.6 \times 10^{-13}$ N

3. Biot–Savart Law

Statement

The Biot–Savart Law gives the magnetic field dB produced by a small element (dl) of a current-carrying conductor at a point P located at distance r from the element. The law states:

$$dB = (\mu_0 / 4\pi) \times (I\, dl \sin\theta) / r^2$$

- μ_0 = Permeability of free space = $4\pi \times 10^{-7}$ T·m/A
- I = Current in the conductor (A)
- dl = Small element length (m)
- r = Distance from element to point P (m)
- θ = Angle between dl and the line joining element to point P

3.1 Application – Magnetic Field Due to Straight Conductor

For an infinitely long straight current-carrying conductor, the magnetic field at a perpendicular distance 'r' from it is:

$$B = \mu_0 I / (2\pi r)$$

- The field forms concentric circular loops around the wire.
- Direction: Use the Right Hand Thumb Rule — Thumb points in the direction of current, fingers curl in the direction of the magnetic field.
- Field strength decreases as distance r increases.

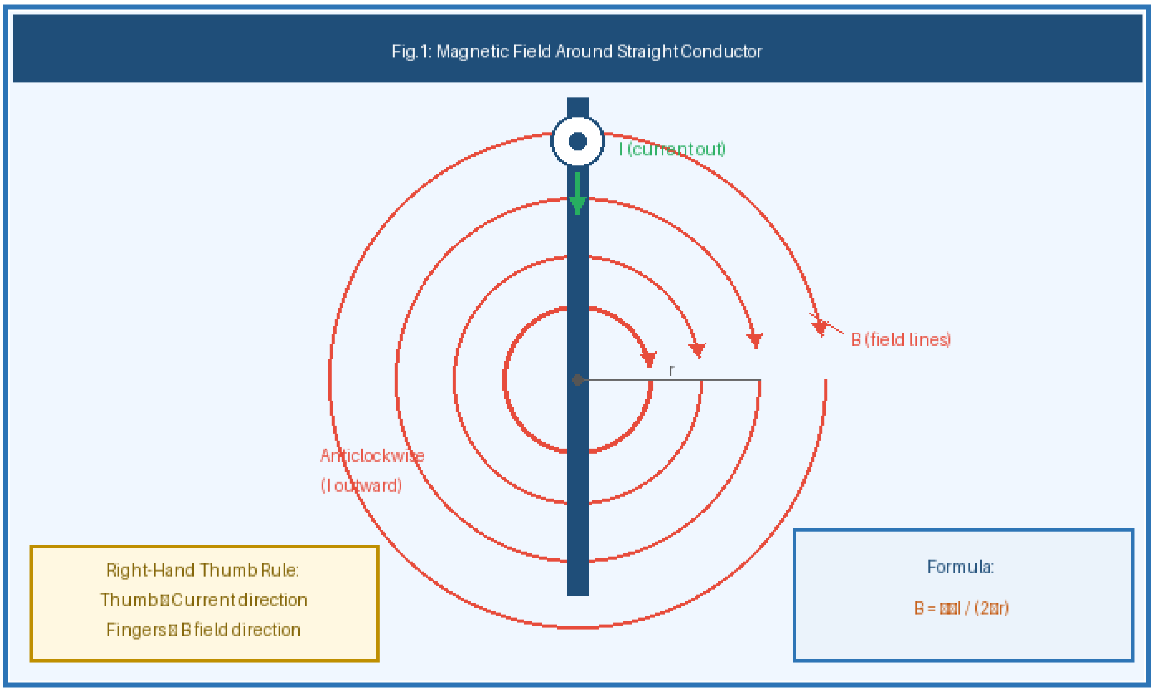


Fig.1: Magnetic Field Around Straight Conductor

3.2 Application – Magnetic Field at the Centre of a Circular Loop

For a circular current loop of radius R carrying current I, the magnetic field at the centre is:

$$B = \mu_0 I \ / \ (2R)$$

- Direction: Perpendicular to the plane of the loop (use right-hand rule for the loop)
- For N turns: $B = \mu_0 \, NI / (2R)$

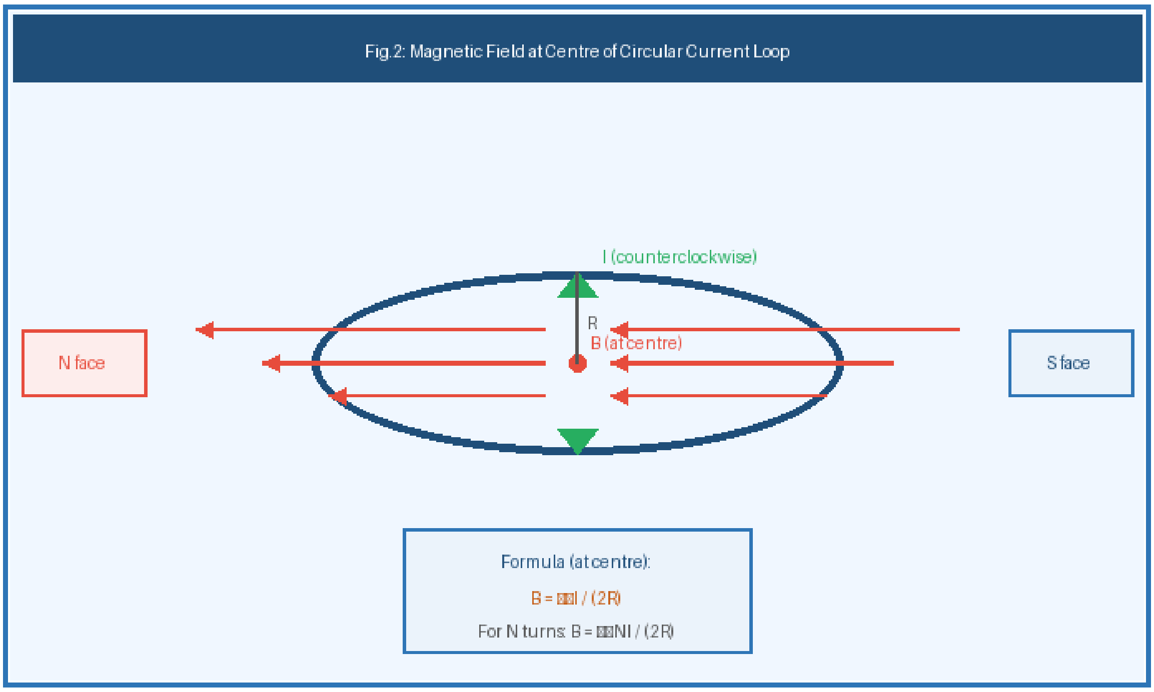


Fig.2: Magnetic Field at Centre of Circular Current Loop

4. Magnetic Dipole

A magnetic dipole is a system that has two magnetic poles (North and South) separated by a small distance, similar to an electric dipole. Examples include:

- A bar magnet
- A small current-carrying loop
- An atom with a net magnetic moment (due to electron spin)

The magnetic dipole moment (m) is defined as: m = NIA, where N = number of turns, I = current, A = area of the loop. It represents the strength and orientation of the magnetic dipole. The unit is A·m².

5. Force on a Current-Carrying Conductor in a Magnetic Field

When a conductor carrying current is placed in an external magnetic field, it experiences a mechanical force. This is the principle behind electric motors. The force is given by:

$$F = BIL \sin\theta$$

- F = Force on the conductor (N)
- B = Magnetic field strength (T)
- I = Current through the conductor (A)
- L = Length of conductor in the field (m)
- θ = Angle between conductor and magnetic field direction
- Maximum force when θ = 90°: F = BIL
- Zero force when θ = 0° (conductor parallel to field)

Direction of force: Use Fleming's Left Hand Rule — First finger (B), Middle finger (I), Thumb (Force/Motion).

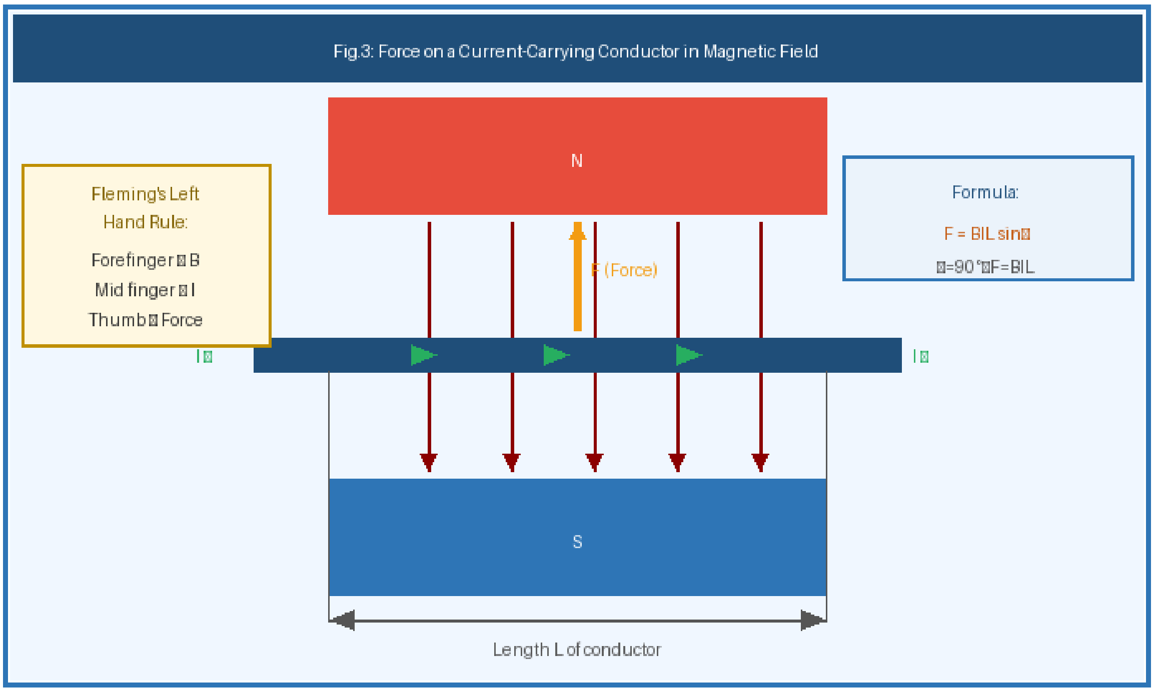


Fig.3: Force on a Current-Carrying Conductor in Magnetic Field

Example: A conductor of length 0.5 m carries 4 A current and is placed perpendicular to a magnetic field of 0.3 T. Find the force.

Solution: F = BIL sinθ = 0.3 × 4 × 0.5 × sin90° = 0.6 N

6. Torque on a Rectangular Coil in a Magnetic Field

When a rectangular coil carrying current is placed in a uniform magnetic field, the two sides of the coil (those parallel to the axis of rotation) experience forces in opposite directions. These two equal and opposite forces form a couple, producing a torque (turning effect) on the coil.

$$\tau = NBIA \sin\theta$$

- τ = Torque on the coil (N·m)
- N = Number of turns in the coil
- B = Magnetic field strength (T)
- I = Current in the coil (A)
- A = Area of the coil (m²)
- θ = Angle between the plane of coil and magnetic field
- Maximum torque: when $\theta = 90°$ (coil plane parallel to B) → $\tau = NBIA$
- Zero torque: when $\theta = 0°$ (coil plane perpendicular to B)

This principle is the basis of working of the moving coil galvanometer and all DC motors.

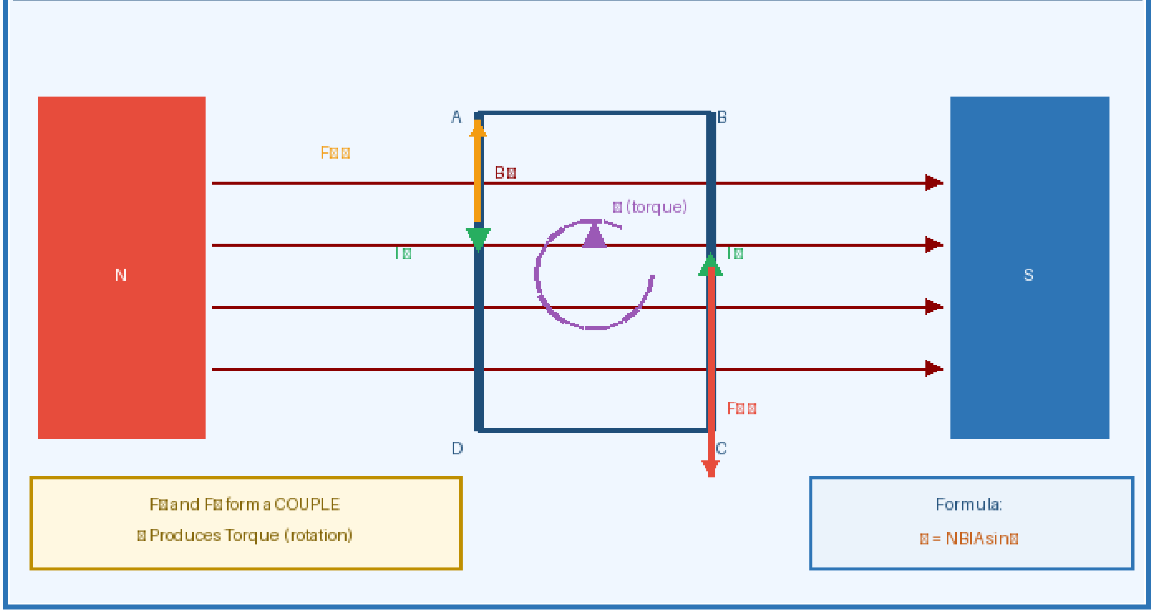


Fig.4: Torque on a Rectangular Coil in Magnetic Field

7. Electromagnetic Induction

Concept

Electromagnetic induction is the phenomenon of producing an electromotive force (EMF) and hence electric current in a conductor by changing the magnetic flux linked with it. This was discovered by Michael Faraday in 1831. It is the foundational principle of generators, transformers, and inductors.

Magnetic flux (Φ) through a surface is defined as: $\Phi = B \times A \times \cos\theta$, where θ is the angle between B and the normal to the surface. Unit: Weber (Wb).

7.1 Faraday's Laws of Electromagnetic Induction

Faraday proposed two laws to explain electromagnetic induction:

- First Law: Whenever there is a change in the magnetic flux linked with a coil or conductor, an EMF is induced in it. The induced EMF exists as long as the flux is changing.
- Second Law: The magnitude of the induced EMF is directly proportional to the rate of change of magnetic flux. Mathematically:

$$\text{EMF } (\varepsilon) = -N \times (d\Phi/dt)$$

- The negative sign represents Lenz's Law — the induced current always opposes the change in flux that caused it.
- N = Number of turns in the coil
- $d\Phi/dt$ = Rate of change of magnetic flux

Real-life examples: AC generators, transformers, induction cookers, wireless charging pads all work on the principle of electromagnetic induction.

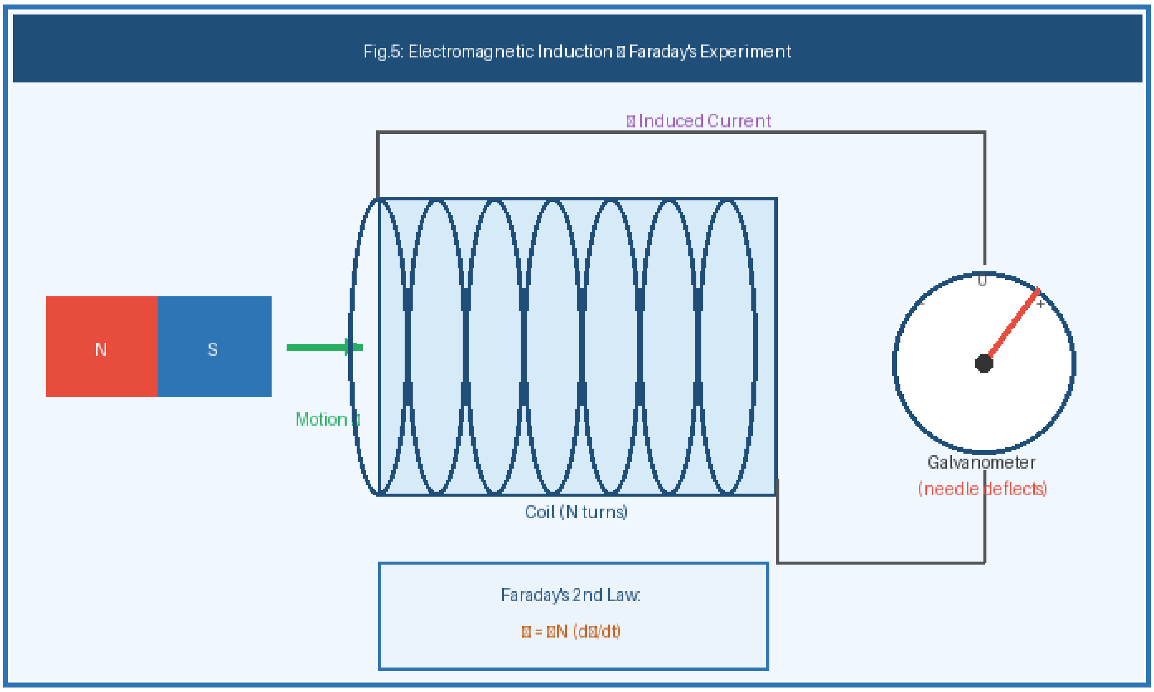


Fig.5: Electromagnetic Induction – Faraday's Experiment

8. Moving Coil Galvanometer

Principle

A moving coil galvanometer works on the principle that when a current-carrying coil is placed in a magnetic field, it experiences a torque. This torque causes the coil to rotate, and the deflection is proportional to the current flowing through it.

Construction

A moving coil galvanometer consists of the following main parts:

- Coil: A rectangular coil of fine insulated copper wire wound on a light aluminium frame, suspended between the poles of a strong permanent magnet.
- Permanent Magnet: A horse-shoe (U-shaped) magnet with concave cylindrical poles to produce a radial magnetic field.

- Soft Iron Core: A cylindrical soft iron core placed inside the coil to concentrate the magnetic field and make it radial and uniform.
- Suspension Wire: A flat phosphor-bronze strip that supports the coil and also carries current into it. It provides a restoring torque.
- Pointer and Scale: A light pointer attached to the coil moves over a calibrated scale.

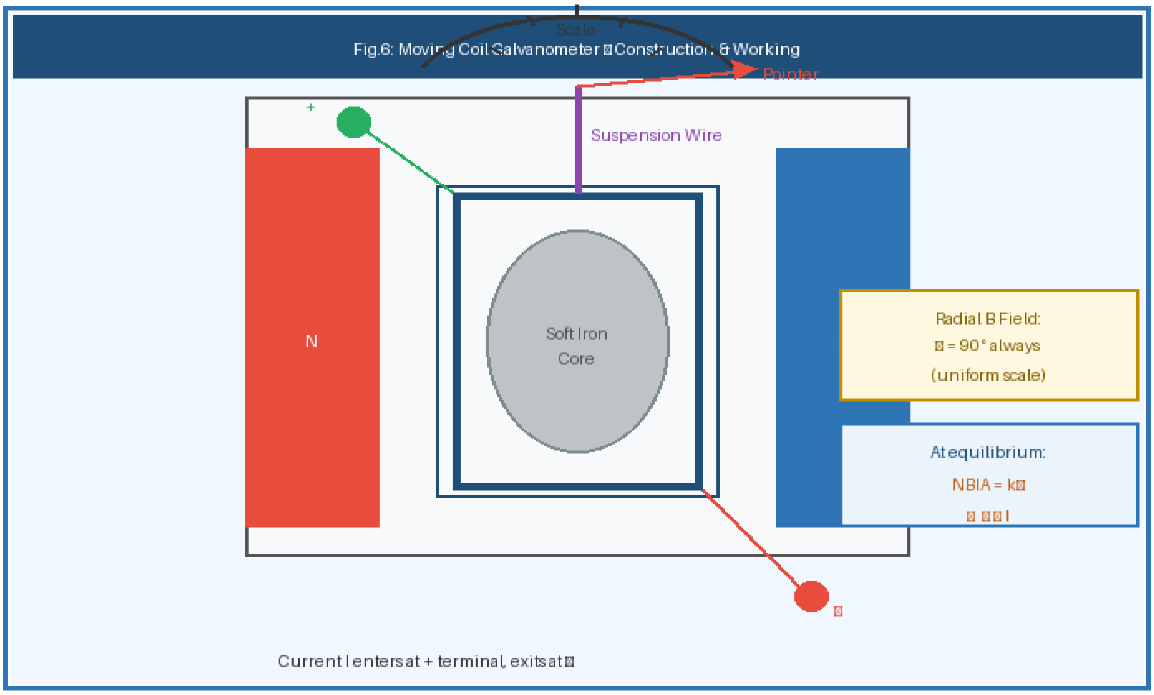
Working

When current I passes through the coil, a torque τ = NBIA acts on it and rotates the coil. The suspension wire twists and produces a restoring torque τ' = kθ (where k is the torsion constant and θ is the angle of deflection). At equilibrium, τ = τ':

$$NBIA = k\theta \quad \rightarrow \quad I = (k / NBA) \times \theta$$

Since k, N, B, and A are constants, deflection θ is directly proportional to current I. The galvanometer is a very sensitive instrument and can detect very small currents (in micro-amperes).

- Sensitivity: A galvanometer is more sensitive if it shows large deflection for small current.
- Full-Scale Deflection Current (Ig): The minimum current that produces maximum deflection.



9. Conversion of Galvanometer

9.1 Conversion into Ammeter

An ammeter is used to measure large currents in a circuit. It is connected in series and must have very low resistance. A galvanometer is converted to an ammeter by connecting a low resistance wire called a shunt (S) in parallel with the galvanometer coil.

The shunt value is calculated so that the excess current (I – Ig) flows through S, while only Ig flows through the galvanometer. The formula is:

$$S = (Ig \times G) / (I - Ig)$$

- S = Shunt resistance (Ω)

- G = Galvanometer resistance (Ω)
- I = Total current to be measured (A)
- Ig = Full-scale deflection current of galvanometer (A)
- The shunt has very low resistance (milli-ohms range)

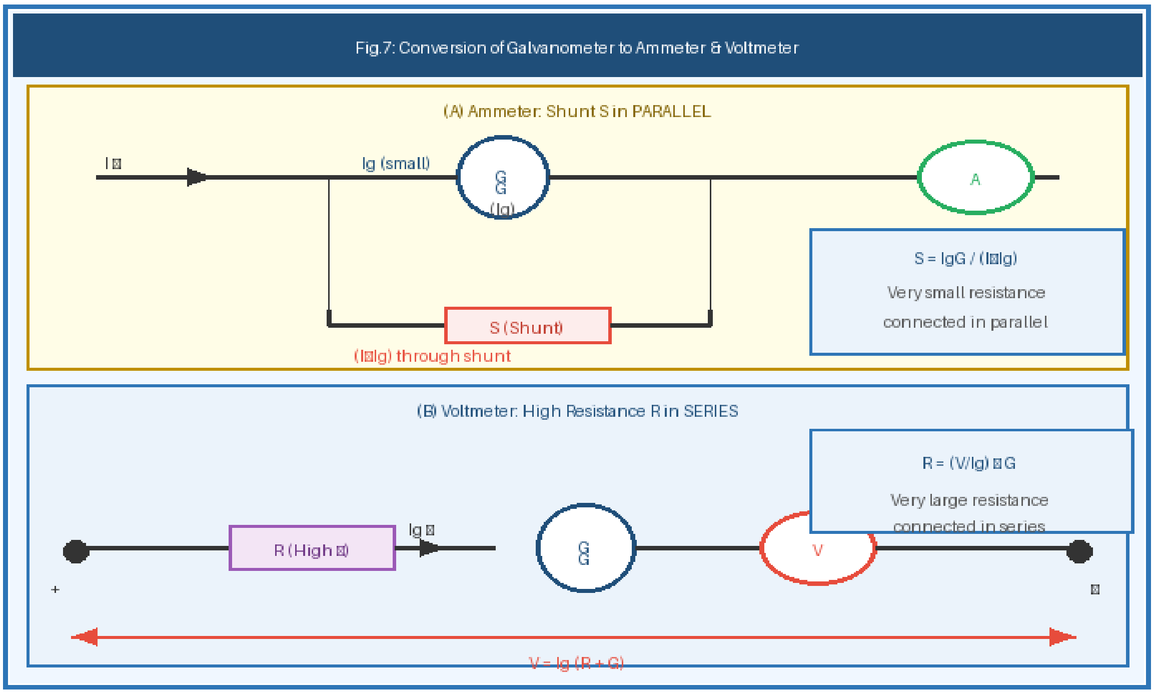


Fig.7: Conversion of Galvanometer to Ammeter & Voltmeter

9.2 Conversion into Voltmeter

A voltmeter is used to measure potential difference (voltage) across circuit elements. It is connected in parallel and must have very high resistance. A galvanometer is converted to a voltmeter by connecting a high resistance R in series with the galvanometer.

$$R = (V / Ig) - G$$

- R = High series resistance (Ω)
- V = Voltage to be measured (V)
- Ig = Full-scale deflection current (A)
- G = Galvanometer resistance (Ω)
- R is very large (kΩ to MΩ range) to limit current through the voltmeter

Example: A galvanometer has G = 50 Ω and Ig = 2 mA. Calculate (a) Shunt to convert it to 5 A ammeter, (b) Series resistance to convert it to 10 V voltmeter.

(a) S = (Ig × G) / (I – Ig) = (0.002 × 50) / (5 – 0.002) = 0.1 / 4.998 ≈ 0.02 Ω

(b) R = (V / Ig) – G = (10 / 0.002) – 50 = 5000 – 50 = 4950 Ω

10. Magnetic Materials

All materials respond to an applied magnetic field, but their responses differ greatly. Based on this response, materials are classified into three categories: Diamagnetic, Paramagnetic, and Ferromagnetic.

10.1 Diamagnetic Materials

These materials are weakly repelled by a magnetic field and tend to move from stronger to weaker parts of the field. The magnetic effect in these materials is very weak.

- Cause: Orbital magnetic moments of electrons cancel out; no net magnetic moment per atom
- In an external field, they are weakly magnetized opposite to the field
- Relative permeability: μr slightly less than 1
- Susceptibility: Small and negative ($\chi < 0$)
- Examples: Bismuth (Bi), Copper (Cu), Gold (Au), Water, Silver
- Application: Used in magnetic levitation and superconductors

10.2 Paramagnetic Materials

These materials are weakly attracted by a magnetic field and move from weaker to stronger regions of the field. They have permanent atomic magnetic moments, but in random directions.

- Cause: Atoms have net unpaired electrons → permanent magnetic dipole moments, but randomly oriented
- When an external field is applied, dipoles partially align with the field → weak magnetization
- Relative permeability: μr slightly greater than 1
- Susceptibility: Small and positive ($\chi > 0$)
- Magnetism is lost when the external field is removed (no permanent magnetism)
- Examples: Aluminium (Al), Platinum (Pt), Manganese (Mn), Oxygen gas, Chromium

10.3 Ferromagnetic Materials

These materials are strongly attracted by a magnetic field and can be permanently magnetized. They are the most important class for practical applications and form the basis of all magnetic storage and electromagnetic devices.

- Cause: Due to quantum mechanical exchange interaction, groups of atoms form 'magnetic domains' — small regions (about 10^{-6} m) where all atomic moments are aligned in the same direction
- In an unmagnetized sample, domains are randomly oriented → no net magnetism
- When an external field is applied, domains aligned with the field grow and others shrink → strong magnetism
- Above the Curie Temperature (Tc), ferromagnetic materials become paramagnetic
- Relative permeability: $\mu r >> 1$ (can be thousands to lakhs)
- Susceptibility: Large and positive ($\chi >> 0$)
- Show hysteresis — retain some magnetism after the external field is removed
- Examples: Iron (Fe), Nickel (Ni), Cobalt (Co), Steel
- Applications: Permanent magnets, transformer cores, magnetic hard drives, electromagnets

Comparison of Magnetic Materials

Property	Diamagnetic / Paramagnetic / Ferromagnetic
Attraction by field	Weakly repelled / Weakly attracted / Strongly attracted

Susceptibility (χ)	Negative / Small positive / Large positive
Relative permeability	$\mu_r < 1$ / μ_r slightly > 1 / $\mu_r >> 1$
Permanent Magnet	No / No / Yes
Examples	Cu, Bi / Al, Pt / Fe, Ni, Co

Key Formulas Summary

Quantity	Formula
Lorentz Force	$F = qvB \sin\theta$
Force on Conductor	$F = BIL \sin\theta$
Biot-Savart (Straight Wire)	$B = \mu_0 I / (2\pi r)$
Biot-Savart (Circular Loop)	$B = \mu_0 I / (2R)$ [centre]
Torque on Coil	$\tau = NBIA \sin\theta$
Faraday's EMF	$\varepsilon = -N \times (d\Phi/dt)$
Galvanometer Equation	$I = (k/NBA) \times \theta$
Shunt (Ammeter)	$S = I_g G / (I - I_g)$
Series R (Voltmeter)	$R = (V/I_g) - G$
Magnetic Flux	$\Phi = BA \cos\theta$ (Wb)
Magnetic Dipole Moment	$m = NIA$ ($A \cdot m^2$)

★ IMPORTANT FOR EXAM

- State and explain Biot-Savart Law with its application to straight conductor and circular loop
- Derive expression for torque on rectangular coil in magnetic field
- Explain the construction and working of a moving coil galvanometer with diagram
- How is a galvanometer converted into an ammeter? (with formula and diagram)
- How is a galvanometer converted into a voltmeter? (with formula and diagram)
- State Faraday's laws of electromagnetic induction
- Distinguish between diamagnetic, paramagnetic, and ferromagnetic materials
- What is Lorentz force? Explain with formula and examples
- Numerical problems on Lorentz force, force on conductor, shunt and voltmeter conversion

□ Common Viva Questions

- What is the SI unit of magnetic field? — Tesla (T)
- What is the direction of magnetic force on a charge moving parallel to the field? — Zero force
- State the right-hand thumb rule for a current-carrying wire.
- What is the difference between a galvanometer and an ammeter?
- Why is a shunt of very low resistance used to convert galvanometer to ammeter?
- Why is a large resistance connected in series to make a voltmeter?
- What is meant by 'Curie Temperature' in ferromagnetic materials?
- What are magnetic domains? Where do they exist?
- What happens to the torque on the coil when it is perpendicular to B?
- What is Lenz's Law? How is it related to conservation of energy?
- Give two real-life examples of electromagnetic induction.
- What is the full form of EMF, and is it actually a force?

□ Quick Revision Points

- Magnetic field (B) exists around current-carrying conductors and magnets. Unit: Tesla
- Lorentz force: $F = qvB \sin\theta$ — always perpendicular to velocity (no work done)
- Biot-Savart law gives magnetic field due to a current element
- Straight conductor: $B = \mu_0 I/(2\pi r)$; Circular loop centre: $B = \mu_0 I/(2R)$
- Force on conductor: $F = BIL \sin\theta$; direction by Fleming's Left Hand Rule
- Torque on coil: $\tau = NBIA \sin\theta$ — maximum when coil is parallel to B
- Faraday's EMF: $\varepsilon = -N(d\Phi/dt)$; negative sign = Lenz's Law
- Galvanometer works on torque principle; deflection ∝ current
- Ammeter: low resistance shunt in parallel; Voltmeter: high resistance in series
- Diamagnetic repelled; Paramagnetic weakly attracted; Ferromagnetic strongly attracted
- Ferromagnetic materials have 'magnetic domains'

— End of Unit 5: Electromagnetism —