

$$R_1 = \rho_1 \frac{L_1}{A_1} \quad \text{here } A_1 = L^2$$

$$1.08 \times 10^{-4} = 5 \times 10^{-8} \frac{0.5}{L^2}$$

$$L^2 = 5 \times 10^{-8} \frac{0.5}{1.08 \times 10^{-4}}$$

$$L^2 = 2.31 \times 10^{-4} \text{ m}^2$$

$$L = 1.52 \times 10^{-2} \text{ m}$$

$$L = 1.52 \text{ cm}$$

- 9.7 The copper winding of an electric fan has a resistance of 50Ω at 30°C . After running for some time, the resistance becomes 52Ω . How much is the increase in temperature of the winding? [For copper $\alpha = 0.0039 \text{ K}^{-1}$]

Given

$$\text{Resistance of copper winding} = R_1 = 50 \Omega$$

$$\text{Temperature} = t_1 = 30^\circ\text{C}$$

$$\text{Resistance of copper winding} = R_2 = 52 \Omega$$

$$\text{Thermal coefficient of resistance of copper} = \alpha = 0.0039 \text{ K}^{-1}$$

$$\text{Increase in temperature} = t_2 - t_1 = \Delta t = ?$$

Solution

$$\alpha = \frac{R_2 - R_1}{R_1(t_2 - t_1)}$$

$$t_2 - t_1 = \frac{R_2 - R_1}{R_1 \alpha}$$

$$\Delta t = \frac{52 - 50}{50(0.0039)} = 10.2^\circ\text{C}$$

- 9.8 During an experiment, a copper wire of 50 m long and $150 \mu\text{m}$ thick is hung vertically. Then a current of 1 A is passed across its ends for 50 s . Find the resistance of the wire and the heat dissipated during this process. [Resistivity of copper is $1.69 \times 10^{-8} \Omega\text{m}$.]

Given

$$\text{Length of copper wire} = 50 \text{ m}$$

$$\text{Thickness of wire} = D = 150 \mu\text{m} = 150 \times 10^{-6} \text{ m}$$

$$\text{Area of cross section of copper rod} = A$$

$$= \pi \left(\frac{D}{2}\right)^2 = 3.14 \left(\frac{150 \times 10^{-6}}{2}\right)^2$$

$$A = 1.76 \times 10^{-6} \text{ m}^2$$

$$\text{Current} = I = 1 \text{ A}$$

$$\text{Time} = 50 \text{ s}$$

$$\text{Resistance of wire} = R = ?$$

$$\text{Heat dissipated} = H = ?$$

Solution

$$R = \rho \frac{L}{A}$$

$$R = 1.69 \times 10^{-8} \frac{50}{1.76 \times 10^{-6}} = 47.8 \Omega$$

Now

$$H = I^2 R t$$

$$H = 1 \times 47.8 \times 50 = 2390 \text{ J}$$

- 9.9 The emf of a battery is 12 V . It is connected to a 3.6Ω resistor. If the internal resistance of the battery is 0.2Ω , what will be the terminal voltage across the battery?

Given

$$\text{Emf of battery} = \epsilon = 12 \text{ V}$$

$$\text{External resistance} = R = 3.6 \Omega$$

$$\text{Internal resistance of battery} = r = 0.2 \Omega$$

$$\text{Terminal voltage} = V = ?$$

Solution

$$I = \frac{\epsilon}{R + r}$$

$$I = \frac{12}{3.6 + 0.2} = \frac{12}{3.8} = 3.16$$

Now

$$V = \epsilon - Ir$$

$$V = 12 - 3.16 \times 0.2 = 11.4 \text{ V}$$

CHAPTER

10

ELECTROMAGNETISM

STUDENT LEARNING OBJECTIVES

After studying this chapter, you will be able to:

- State that a force can act on a current-carrying conductor when it is placed in a magnetic field.
- Use the equation $F = BIl \sin \theta$, along with Fleming's left-hand rule, to solve problems.
- Define magnetic flux as the product of magnetic flux density and the cross-sectional area perpendicular to the direction of magnetic flux density.
- Use the equation $\phi = BA$ to solve problems.
- Understand the concept of magnetic flux linkage.
- Define magnetic flux density as the force acting per unit current per unit length on a wire placed at right angles to the magnetic field.
- Use the equation $F = qvB \sin \theta$ to solve problems.
- Describe how a charged particle moves in a uniform magnetic field when it is perpendicular to the particle's motion.
- Explain how electric and magnetic fields are used in velocity selection.
- Explain experiments that demonstrate Faraday's and Lenz's laws, including how a changing magnetic flux induces an emf in a circuit, how the induced emf opposes the change that produces it, and the factors affecting the magnitude of the induced emf.
- Use Faraday's and Lenz's laws of electromagnetic induction to solve problems.
- Describe how ferrofluids work, which involves temporary soft magnetic materials suspended in liquids that react to magnet poles and have applications in electronics.
- Explain how seismometers use electromagnetic induction to detect earthquakes.

This chapter explores how electricity and magnetism are connected and how they affect our world and technology.

This chapter explores the fascinating world of electromagnetism, which is the study of how electric charges and magnetic fields interact. This field is vital for understanding various natural phenomena and modern technologies like phones, computers, and medical devices.

Introduction to Electromagnetism

We have already learned that a magnetic field is produced around a current-carrying conductor. Additionally, a changing magnetic field can create a current in a conductor placed within it. Electromagnetism is a crucial area of physics that investigates how electric charges and magnetic fields interact. In 1820, Hans Christian Oersted discovered that electricity and magnetism are correlated.

Fig. 10.1

The direction of magnetic field produced by a current

For Your Information

- Q:** Who first discovered the correlation between electricity and magnetism, and what is the origin of magnetism?
- Ans:** In 1820, Hans Christian Oersted found that electricity and magnetism are correlated. Magnetism began with lodestone, a natural mineral discovered in ancient Turkey. Lodestone, or magnetite (Fe_3O_4), can attract metals like iron and steel and aligns with the Earth's magnetic poles, leading to the invention of the compass.

10.1 FORCE ON A CURRENT-CARRYING CONDUCTOR IN A UNIFORM MAGNETIC FIELD

Q. What happens when a current-carrying conductor is placed in a magnetic field?

Ans

When a conductor that carries an electric current is placed in a magnetic field, it experiences a force.

Cause of force

Just like two magnets push or pull each other through their magnetic fields, a current-carrying conductor feels a force because its own magnetic field interacts with the external magnetic field.

Direction of the force

The magnetic field created by the current in the conductor and the external magnetic field either strengthen each other on one side of the conductor or oppose each other on the other side. This makes the conductor move towards the side where the combined magnetic field is weaker. The force is always perpendicular to both the conductor and the magnetic field.

FLEMING'S LEFT-HAND RULE

Fleming's Left-Hand Rule helps to find the direction of the force on a current-carrying conductor in a magnetic field.

To apply the rule: We position our left hand so that our first finger points in the direction of the magnetic field, our second finger points in the direction of the current, and our thumb will then point in the direction of the force.

FLEMING'S RIGHT HAND RULE:

Can the Right-Hand Rule also determine the direction of force?

Yes, we can also use a right-hand rule:

To apply the rule: We curl fingers of our right hand from the direction of the current to the direction of the magnetic field (through the smaller angle), and our stretched thumb will indicate the direction of the force.

Factors effecting the force

The magnitude of the force (F) acting on the conductor is directly proportional to:

1. The current (I) in the conductor.
2. The length (L) of the conductor.
3. The strength of the external magnetic field (B), also known as magnetic induction.

Formula for the force on a current-carrying conductor

The force (F) on a conductor of length L , carrying current I , and placed perpendicular to a magnetic field of strength B , is given by:

$$F = BIL \quad (\text{Equation 10.1})$$

If the conductor is placed at an angle θ with respect to the magnetic field, we use the component of L perpendicular to B , which is $L \sin\theta$.

So, the formula becomes:

$$F = BIL \sin\theta \quad (\text{Equation 10.2})$$

In vector form, this is:

$$\vec{F} = I(\vec{L} \times \vec{B}) \quad (\text{Equation 10.3})$$

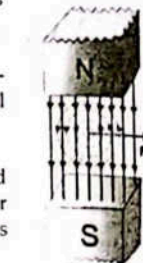


Fig 10.2

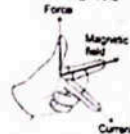


Fig 10.3

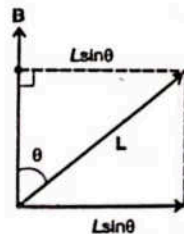


Fig. 10.4

Interesting Information



The Earth's magnetic field is approximately that of a dipole, like that of the fictitious bar magnet, where the south magnetic pole is towards the geographic north pole and the north magnetic pole is towards the geographic south pole.

Maximum and Minimum Force:

When is the force maximum and when is it zero?

- The force is maximum (BIL) when the conductor is perpendicular to the field (i.e., $\theta = 90^\circ$, since $\sin 90^\circ = 1$).
- The force is zero when the conductor is parallel to the field (i.e., $\theta = 0^\circ$, since $\sin 0^\circ = 0$).

Q. What is magnetic strength (magnetic induction) and its unit?

Ans

MAGNETIC INDUCTION

Magnetic strength (B) is numerically equal to the force exerted on a conductor of length one meter carrying one ampere current, when placed perpendicular to the magnetic field.

From $F = BIL$, we get $B = F/(IL)$.

The SI unit of B is tesla (T).

$$1 \text{ T} = 1 \text{ N A}^{-1} \text{ m}^{-1}$$

Magnetic induction is a vector quantity, and its direction is the same as that of the magnetic field.

TESLA:

A magnetic induction is said to be one tesla if it exerts a force of one Newton on one meter length of the conductor placed at right angles to the field when a current of one ampere passes through the conductor.

$$\text{i. e. } 1 \text{ T} = 1 \text{ N A}^{-1} \text{ m}^{-1}$$

Other Unit Of Magnetic Induction:

The magnetic induction is also expressed in smaller unit Gauss (G) that is related with tesla as;

$$10^4 \text{ G} = 1 \text{ T}$$

$$\text{or } 1 \text{ G} = 10^{-4} \text{ T}$$

Q. Explain the principle of extension of right hand rule? SWL 2021 LHR 2021

Ans

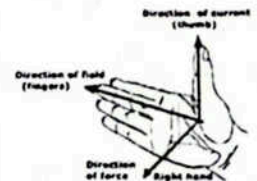
EXTENSION OF RIGHT HAND RULE: (PALM RULE)

According to this rule, the right hand is extended so that if the current ' I '

flowing in conductor is along thumb, the external magnetic field \vec{B} along fingers. Then force will be along the normal to palm of right hand.

INTERESTING INFORMATION: EARTH'S MAGNETIC FIELD

The Earth's magnetic field is like that of a bar magnet. The south magnetic pole of this "fictitious" bar magnet is near the Earth's geographic North Pole, and the north magnetic pole is near the geographic South Pole.



MULTIPLE CHOICE QUESTIONS

A current-carrying conductor is placed in a uniform magnetic field. The force on the conductor is maximum when the conductor is:

- (a) Parallel to the magnetic field.
- (b) Perpendicular to the magnetic field.
- (c) At an angle of 45° to the magnetic field.
- (d) Moving with the magnetic field.

Answer: (b) Perpendicular to the magnetic field.

Explanation: The formula for the force is $F = BIL \sin\theta$. The force is maximum when $\sin\theta = 1$, which occurs when $\theta = 90^\circ$ (perpendicular).

Fleming's Left-Hand Rule is used to determine the direction of:

- (a) Magnetic field around a current-carrying wire.
- (b) Current induced in a conductor.
- (c) Force on a current-carrying conductor in a magnetic field.
- (d) Magnetic flux.

Answer: (c) Force on a current-carrying conductor in a magnetic field

Explanation: Fleming's Left-Hand Rule specifically relates the directions of the magnetic field, current, and the resulting force on a conductor.

The SI unit of magnetic induction (magnetic field strength) is:

- (a) Weber (Wb) (b) Tesla (T) (c) Ampere (A) (d) Newton (N)

Answer: (b) Tesla (T)

Explanation: Tesla (T) is the SI unit for magnetic field strength or magnetic flux density. It is equivalent to $\text{N A}^{-1} \text{m}^{-1}$.

If a current-carrying conductor is placed parallel to a uniform magnetic field, the force acting on it will be:

- (a) Maximum (b) Half of maximum (c) Zero (d) Variable

Answer: (c) Zero

Explanation: When the conductor is parallel to the field, $\theta=0^\circ$, and $\sin 0^\circ=0$. Thus, $F=BIL\sin 0^\circ=0$.

The force on a current-carrying conductor in a magnetic field is always perpendicular to:

- (a) Only the magnetic field. (b) Only the direction of current. (c) Both the conductor and the magnetic field. (d) The plane containing the conductor and the magnetic field.

Answer: (c) Both the conductor and the magnetic field.

Explanation: The force F is given by the cross product $I(\mathbf{L} \times \mathbf{B})$, meaning it is perpendicular to both the length vector (direction of current) and the magnetic field vector.

SLO BASED SHORT QUESTIONS & ANSWERS

State Fleming's Left-Hand Rule.

Ans: Position your left hand such that the first finger points in the direction of the magnetic field, the second finger points in the direction of current, and then your thumb will indicate the direction of the force.

What factors influence the magnitude of the force on a current-carrying conductor in a magnetic field?

Ans: The magnitude of the force is directly proportional to the current (I) in the conductor, the length (L) of the conductor, the strength of the magnetic field (B), and the sine of the angle ($\sin \theta$) between the conductor and the magnetic field. $F = BIL \sin \theta$

Define 1 Tesla (T) in terms of force, current, and length.

Ans: 1 Tesla (T) is defined as the magnetic field strength (or magnetic induction) that exerts a force of 1 Newton on a conductor of 1 meter length carrying 1 Ampere current, when placed perpendicular to the magnetic field.

When is the force on a current-carrying conductor in a magnetic field zero?

Ans: The force on a current-carrying conductor in a magnetic field is zero when the conductor is placed parallel to the direction of the magnetic field ($\theta = 0^\circ$).

Describe how the magnetic field produced by a current-carrying wire interacts with an external uniform magnetic field to produce a force on the wire.

Ans: The magnetic field produced by the current-carrying wire reinforces the external magnetic field on one side of the wire and opposes it on the other side. This creates a region of stronger field and a region of weaker field, causing the wire to be pushed from the stronger field region towards the weaker field region.

10.2 MAGNETIC FLUX AND FLUX DENSITY

Q. How is the strength of a magnetic field represented?

Ans:

The strength of a magnetic field (B) can be shown by lines of force, similar to how electric fields are represented.

MAGNETIC FLUX (Φ_B)?

Magnetic flux through an area (A) is the number of magnetic lines of force passing through that area.

If Surface is Perpendicular to Magnetic Field

If B represents the number of lines per unit area passing through a surface perpendicular to the field, then the total flux (Φ_B) through area A perpendicular to the field will be:

$$\Phi_B = B \cdot A \quad (\text{Equation 10.4})$$

This means $\Phi_B = BA$.

If Surface is not Perpendicular to Magnetic field

If the normal to the surface makes an angle θ with the magnetic field B , then we will have to use the component of B along the vector area A , which is $B \cos \theta$.

The magnetic flux is then:

$$\Phi_B = BA \cos \theta \quad (\text{Equation 10.5})$$

MAGNETIC FLUX IN TERMS OF VECTORS

Since both \vec{B} and \vec{A} are vectors, magnetic flux can be defined as the dot product of \vec{B} and \vec{A} :

$$\Phi_B = \vec{B} \cdot \vec{A} \quad (\text{Equation 10.6})$$

This shows that Φ_B is a scalar quantity (it only has magnitude, no direction). Here, \vec{A} is a vector whose magnitude is the area, and its direction is along the normal (perpendicular) to the surface. θ is the angle between the directions of vectors \vec{B} and \vec{A} .

When is magnetic flux maximum and when is it zero?

- **Maximum Flux:** When the magnetic field is directed along the normal to the area ($\theta=0^\circ$), $\cos 0^\circ=1$, and the flux is maximum, equal to BA .
- **Zero Flux:** When the magnetic field is parallel to the plane of the area ($\theta=90^\circ$), $\cos 90^\circ=0$, and the flux through the area is zero.

How is magnetic flux calculated for a curved surface?

MAGNETIC FLUX FOR A CURVED SURFACE:

For a curved surface in a uniform magnetic field, the surface is divided into many small elements, each assumed to be flat. The total flux is found by adding up the contributions from all these small elements using Equation.

$$\Phi_B = \sum \vec{B} \cdot \Delta \vec{A}$$

What is the unit of magnetic flux and magnetic flux density?

- The unit of magnetic flux (Φ_B) is N m A^{-1} , which is called weber (Wb).
- Magnetic induction (B) is defined as flux per unit area of a surface perpendicular to B , so it is also called magnetic flux density.
- Its unit is Wb m^{-2} . Therefore, magnetic induction/magnetic field strength is measured in Wb m^{-2} or $\text{N A}^{-1} \text{m}^{-1}$ (tesla).

FLUX DENSITY:

The magnetic flux per unit area placed at right angle to the field is called flux density.

Consider a surface of vector area \vec{A} placed perpendicular to the magnetic field \vec{B} . Thus magnetic flux through the surface is;

$$\Phi_B = \vec{B} \cdot \vec{A} = BA \cos 0^\circ$$

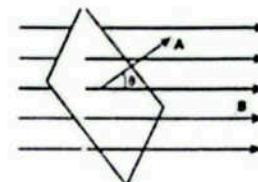


Fig. 10.5

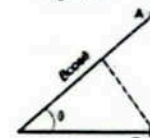
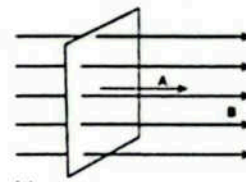
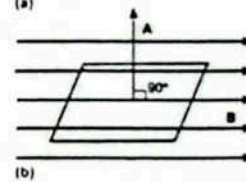


Fig. 10.6



(a)



(b)

Fig. 10.7

$$\Phi_B = BA$$

Or

$$B = \frac{\Phi_B}{A}$$

i.e. the magnetic induction B is the flux per unit area of a surface perpendicular to \vec{B} , hence it is also called as flux density.

MULTIPLE CHOICE QUESTIONS

- Magnetic flux is defined as:
 - The strength of the magnetic field.
 - The number of magnetic lines of force passing through a given area.
 - The force exerted on a unit current.
 - The density of magnetic lines.
- Answer: (b) The number of magnetic lines of force passing through a given area.
- Explanation: Magnetic flux (Φ_B) is a measure of the total number of magnetic field lines passing through a specific surface area.
- The SI unit of magnetic flux is:
 - Tesla (T)
 - Weber (Wb)
 - Henry (H)
 - Ampere (A)
- Answer: (b) Weber (Wb) Explanation: The Weber (Wb) is the SI unit for magnetic flux, equivalent to $T \cdot m^2$ or $N \cdot m \cdot A^{-1}$.
- Magnetic flux through a surface is maximum when the normal to the surface is:
 - Parallel to the magnetic field.
 - Perpendicular to the magnetic field.
 - At an angle of 45° to the magnetic field.
 - In the direction of current.
- Answer: (a) Parallel to the magnetic field.
- Explanation: The formula is $\Phi_B = BA \cos \theta$. Flux is maximum when $\cos \theta = 1$, which means $\theta = 0^\circ$, or the normal to the area is parallel to the magnetic field.
- Magnetic flux density (B) is also known as:
 - Magnetic permeability
 - Magnetic flux linkage
 - Magnetic induction
 - Magnetic susceptibility
- Answer: (c) Magnetic induction
- Explanation: Magnetic flux density and magnetic induction are interchangeable terms for the strength of the magnetic field.
- If a surface is placed such that its plane is parallel to the magnetic field lines, the magnetic flux through it is:
 - Maximum
 - Half of maximum
 - Zero
 - Negative
- Answer: (c) Zero Explanation: If the plane of the surface is parallel to the field lines, the normal to the surface is perpendicular to the field lines ($\theta = 90^\circ$). Since $\cos 90^\circ = 0$, the flux $\Phi_B = BA \cos 90^\circ = 0$.

SLO BASED SHORT QUESTIONS & ANSWERS

- Define magnetic flux.
- Answer: Magnetic flux is the measure of the total number of magnetic field lines passing through a given area.
- How is magnetic flux density related to magnetic flux and area?
- Answer: Magnetic flux density (B) is the magnetic flux (Φ_B) per unit area (A) perpendicular to the field, expressed as $B = \Phi_B / A$.
- What is the SI unit of magnetic flux density, and what is its alternative name?
- Answer: The SI unit of magnetic flux density is Tesla (T). Its alternative name is magnetic induction.
- Under what condition is the magnetic flux through a given surface zero?
- Answer: The magnetic flux through a given surface is zero when the plane of the surface is parallel to the magnetic field lines (or when the normal to the surface is perpendicular to the field lines).
- Is magnetic flux a scalar or vector quantity? Justify your answer.
- Answer: Magnetic flux is a scalar quantity. This is because it is defined as the dot product (scalar product) of the magnetic field vector (\vec{B}) and the area vector (\vec{A}), i.e. $\Phi_B = \vec{B} \cdot \vec{A}$.

10.3 MAGNETIC FLUX LINKAGE

MAGNETIC FLUX LINKAGE

Magnetic flux linkage is the product of the magnetic flux passing through a coil and the total number of turns in that coil. It shows how much magnetic flux is effectively connected or "linked" with the coil due to its many turns.

Formula for Magnetic Flux Linkage

$$\text{Magnetic flux linkage, } \Phi = N\Phi_B \quad (\text{Equation 10.7})$$

Where Φ_B is the magnetic flux through a single loop of area A , and N is the total number of turns in the coil.

Why is magnetic flux linkage important?

It is a crucial concept in understanding how coils and inductors work in electrical circuits. It is particularly important in Faraday's law of electromagnetic induction. It plays a key role in the design and operation of transformers, electric motors, generators, and inductors.



A magnetic strip on the ATM card contains millions of tiny magnetic domains held together by a resin binder. The machine reads the information encoded on the magnetic strip and it makes your money to your account.

ATM Card Magnetic Strip: An ATM card has a magnetic strip that contains millions of tiny magnetic domains. These domains hold encoded information. When we use the card, the ATM machine reads this information, allowing us to access our account.

MULTIPLE CHOICE QUESTIONS

- Magnetic flux linkage refers to the product of magnetic flux through a coil and the:
 - Current in the coil
 - Resistance of the coil
 - Number of turns in the coil
 - Diameter of the coil
- Answer: (c) Number of turns in the coil Explanation: Magnetic flux linkage (Φ) is defined as the product of the magnetic flux (Φ_B) through a single turn and the total number of turns (N) in the coil. $\Phi = N\Phi_B$.
- The concept of magnetic flux linkage is particularly important in understanding the operation of:
 - Resistors and capacitors
 - Inductors and transformers
 - Diodes and transistors
 - Batteries and power supplies
- Answer: (b) Inductors and transformers Explanation: Magnetic flux linkage is central to electromagnetic induction and is a key factor in the behavior and design of coils, inductors, generators, and transformers.
- If a coil has 100 turns and a magnetic flux of 0.05 Wb passes through each turn, the magnetic flux linkage is:
 - 0.05 Wb
 - 5 Wb
 - 50 Wb
 - 0.5 Wb
- Answer: (b) 5 Wb Explanation: Magnetic flux linkage = $N \times \Phi_B = 100 \times 0.05 \text{ Wb} = 5 \text{ Wb}$.
- Magnetic flux linkage measures:
 - The strength of the magnetic field at a point.
 - How much magnetic flux is effectively linked with a coil due to its multiple turns?
 - The rate of change of magnetic flux.
 - The force experienced by a single loop.
- Answer: (b) How much magnetic flux is effectively linked with a coil due to its multiple turns?
- Explanation: It quantifies the total magnetic field "threading through" all turns of a coil.
- The concept of magnetic flux linkage is directly utilized in which of Faraday's Laws?
 - Faraday's Law of Electrolysis
 - Faraday's Law of Electromagnetic Induction
 - Faraday's Law of Electrostatics
 - Faraday's Law of Photovoltaics
- Answer: (b) Faraday's Law of Electromagnetic Induction Explanation: Faraday's Law states that the induced EMF is proportional to the rate of change of magnetic flux linkage.

SLO BASED SHORT QUESTIONS & ANSWERS

- Define magnetic flux linkage.
- Answer: Magnetic flux linkage is the product of the magnetic flux passing through a single turn of a coil and the total number of turns in that coil.
- What is the mathematical relationship between magnetic flux linkage (Φ), magnetic flux (Φ_B), and the number of turns (N) in a coil?

Ans: The mathematical relationship is $\Phi = N\Phi_n$.

• Why is the concept of magnetic flux linkage important in the study of inductors?

Ans: It is important because inductors are coils of wire designed to store energy in a magnetic field, and their inductance is directly related to how much magnetic flux linkage they can generate per unit current.

• If a single loop has a magnetic flux Φ_n , how does the total flux linkage change if you increase the number of turns to $2N$ while keeping the flux per turn the same?

Ans: The total flux linkage would double to $2N\Phi_n$, as it is directly proportional to the number of turns.

• Give two examples of electrical devices where magnetic flux linkage plays a crucial role.

Ans: Magnetic flux linkage plays an important role in the design and operation of transformers, electric motors, and generators.

10.4 MOTION OF A CHARGED PARTICLE IN A MAGNETIC FIELD

Do individual charges moving through a magnetic field experience a force? Derive the relation.

Yes, experiments show that a charged particle does experience a force when it moves across a magnetic field. This is because a current is essentially the flow of electric charges.

Force on a single charged particle derivation.

Consider N charged particles, each with charge q , moving through a conductor of length L in time t .

The current (I) in the conductor is given by:

$$I = \frac{Q}{t} = \frac{Nq}{t} \quad \text{since Total Charge } = Q = Nq$$

If ' v ' is the velocity of the charged particles, and they move across the conductor of length L in time t , then $t = L/v$.

Substituting this ' t ' into the current formula:

$$I = \frac{Q}{t} = \frac{Nq}{L/v} = \frac{Nqv}{L} \quad \text{(Equation 10.8)}$$

The force (F) on this current-carrying conductor in a magnetic field B is:

$$\vec{F} = I(\vec{L} \times \vec{B}) \quad \text{(Equation 10.9)}$$

Here, \vec{L} is a vector representing the length and direction of current flow.

Substituting the expression for I :

$$\vec{F} = \frac{Nqv}{L} (\vec{L} \times \vec{B})$$

If \hat{L} is the unit vector along the direction of segment \vec{L} and \hat{V} is a unit vector along the velocity \vec{V} , then,

$$\hat{L} = \hat{V}$$

$$\frac{\vec{L}}{L} = \frac{\vec{V}}{v}$$

Thus,

$$v\vec{L} = L\vec{V}$$

$$\vec{F} = \frac{NqL}{L} (\vec{v} \times \vec{B}) \quad \text{(Equation 10.11)}$$

$$\vec{F} = (Nq) (\vec{v} \times \vec{B})$$

It is the expression of force acting on N particles. Therefore, the force on a single particle is:

Do you know?

Like electric field lines, magnetic field lines also never cross each other. However, they can attract or repel each other.

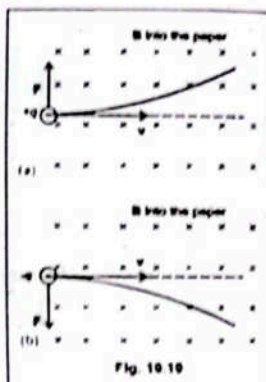


Fig. 10.10

Point to Ponder

Why does a picture become distorted when a magnetic bar is brought near to the screen of a TV, computer monitor, or oscilloscope?

(Answer): These devices use cathode ray tubes (CRTs) where electron beams create the picture. A magnetic field exerts a force on moving charged particles (electrons), causing them to deflect. When a bar magnet is brought near, its magnetic field interferes with the controlled electron beam, distorting the image.

$$\vec{F} = q(\vec{v} \times \vec{B}) \quad \text{(Equation 10.12)}$$

Magnitude of the force on a charged particle

If θ is the angle between the velocity (v) and the magnetic field (B), the magnitude of the force (F) is given by:

$$F = qvB \sin \theta \quad \text{(Equation 10.14)}$$

When is the force on a charged particle maximum and zero?

• The force is maximum (qvB) when B is perpendicular to v (i.e., $\theta = 90^\circ$).

• The force is zero when B is in the same direction as v (i.e., $\theta = 0^\circ$).

How does the direction of force affect charge particles?

• Positive Charge: A positively charged particle entering a magnetic field perpendicularly (directed into paper) from left as shown in figure will be deflected along a curved path upward.

• Negative Charge: A negatively charged particle will be deflected in the opposite direction, also along a curved path as shown in figure.

MULTIPLE CHOICE QUESTIONS

charged particle moving parallel to a uniform magnetic field will experience a magnetic force of:

- (a) Maximum magnitude (b) Half of maximum magnitude
(c) Zero (d) Variable magnitude

Answer: (c) Zero

Explanation: The force on a charged particle is $F = qvB \sin \theta$. If the particle moves parallel to the field, $\theta = 0^\circ$, $\sin 0^\circ = 0$, so $F = 0$.

The direction of the magnetic force on a positively charged particle moving in a magnetic field can be determined by:

- (a) Right-hand rule for magnetic field around a wire
(b) Fleming's Left-Hand Rule or the right-hand rule for vector product
(c) Lenz's Law (d) Faraday's Law

Answer: (b) Fleming's Left-Hand Rule or the right-hand rule for vector product

Explanation: These rules directly give the direction of the force on a moving charge.

If a charged particle enters a uniform magnetic field perpendicularly, its path will be:

- (a) A straight line (b) A parabolic path (c) A circular path (d) An elliptical path

Answer: (c) A circular path

Explanation: When the magnetic force is always perpendicular to the velocity, it acts as a centripetal force, causing the particle to move in a circle.

The magnetic force on a charged particle is directly proportional to:

- (a) Its charge (q), velocity (v), and magnetic field strength (B)
(b) Its mass (m) and velocity (v)
(c) Its energy and the magnetic field strength
(d) The square of its velocity and the magnetic field strength

Answer: (a) Its charge (q), velocity (v), and magnetic field strength (B)

Explanation: The formula for the magnetic force is $F = qvB \sin \theta$.

What happens to the kinetic energy of a charged particle moving in a uniform magnetic field (assuming no other forces)?

- (a) It increases (b) It decreases (c) It remains constant (d) It oscillates

Answer: (c) It remains constant

Explanation: The magnetic force is always perpendicular to the velocity of the particle, meaning it does no work on the particle ($W = Fd \cos 90^\circ = 0$). Since no work is done, the kinetic energy does not change.

SLO BASED SHORT QUESTIONS & ANSWERS

State the formula for the magnitude of the magnetic force on a charged particle moving in a magnetic field.

Ans: The magnitude of the magnetic force is $F = qvB \sin \theta$, where q is the charge, v is the velocity, B is the magnetic field strength, and θ is the angle between v and B .

Under what conditions will a charged particle moving in a magnetic field experience no force?

Ans: A charged particle moving in a magnetic field will experience no force if it is moving parallel or anti-parallel to the magnetic field lines ($\theta=0^\circ$ or $\theta=180^\circ$), or if its velocity is zero.

• **If an electron enters a uniform magnetic field perpendicularly, describe its subsequent motion.**
Ans: If an electron enters a uniform magnetic field perpendicularly, it will move in a circular path because the magnetic force will always act perpendicularly to its velocity, providing the necessary centripetal force.

• **Why can a magnetic field not change the kinetic energy of a charged particle?**
Ans: A magnetic field cannot change the kinetic energy of a charged particle because the magnetic force is always perpendicular to the particle's velocity, meaning it does no work on the particle ($W = \vec{F} \cdot \vec{d} = Fd \cos 90^\circ = 0$).

• **How does the direction of force differ for a positive vs. negative charge moving in the same direction in the same magnetic field?**

Ans: The direction of the magnetic force on a negative charge will be exactly opposite to the direction of the force on a positive charge moving with the same velocity in the same magnetic field.

10.5 VELOCITY SELECTOR

Q. What is a velocity selector? How does a velocity selector work?

Ans

VELOCITY SELECTOR

A velocity selector is a device designed to determine the velocity of a charged particle. It uses both electric and magnetic fields arranged in such a way that they cancel out each other for only a specific value of velocity, allowing particles with that particular velocity to pass through undeflected.

Velocity Selector Work

- Setup:** A velocity selector consists of a cylindrical tube placed within a uniform magnetic field (\vec{B}). Inside this tube, there's a parallel plate capacitor that generates a uniform electric field (\vec{E}). The electric field \vec{E} is oriented perpendicular to the magnetic field \vec{B} .
- Forces:** When a charged particle enters the device, the magnetic force acts in one direction (e.g., upward for a positive charge), and the electric force acts in the opposite direction (e.g., downward, in the direction of the electric field, for a positive charge).
- Balance:** If the strengths of the electric and magnetic fields are adjusted correctly, these two forces will be equal in magnitude and opposite in direction, effectively cancelling each other out.
- Undeflected Motion:** With no net force, the particle continues to move in a straight line at a constant velocity (according to Newton's first law) and exits the device.
- Selection:** Particles with velocities different from this specific value will experience a net force and will be deflected, thus not exiting the device.

Formula For The Selected Velocity

For no deflection of the particle, the magnetic force must balance the electric force:

$$\text{Magnetic force } (F_B) = Bqv$$

$$\text{Electric force } (F_E) = qE$$

$$\text{So, } Bqv = qE$$

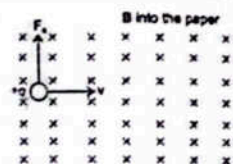


Fig. 10.11

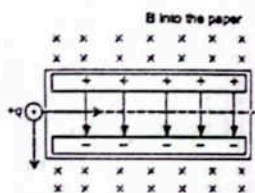


Fig. 10.12

(Point to ponder!)

A force is exerted on a moving charged particle in a magnetic field. In what direction it should move that the force is not exerted on it?

Explanation: If the charged particle moves parallel or anti-parallel to the magnetic field lines (i.e., the angle θ between its velocity vector and the magnetic field vector is 0° or 180°), then $\sin\theta$ will be zero, and thus the magnetic force $F = qvB\sin\theta$ will be zero. So, it should move along the direction of the magnetic field or exactly opposite to it.

Dividing both sides by q ,

$$v = E/B \quad (\text{Equation 10.15})$$

This is the magnitude of the velocity that will allow the particle to move undeflected through the fields.

MULTIPLE CHOICE QUESTIONS

A velocity selector uses which combination of fields to allow only particles of a specific velocity to pass undeflected?

- (a) Parallel electric and magnetic fields. (b) Perpendicular electric and magnetic fields.
 (c) Only a magnetic field. (d) Only an electric field.

Answer: (b) Perpendicular electric and magnetic fields.

Explanation: A velocity selector works by creating a region where perpendicular electric and magnetic fields exert opposing forces on a charged particle.

• For a charged particle to pass undeflected through a velocity selector, the electric force must be:

- (a) Equal to and in the same direction as the magnetic force.
 (b) Greater than the magnetic force.
 (c) Equal to and opposite in direction to the magnetic force.
 (d) Less than the magnetic force.

Answer: (c) Equal to and opposite in direction to the magnetic force.

Explanation: For no net deflection, the forces must cancel each other out, meaning they are equal in magnitude and opposite in direction.

• The selected velocity (v) in a velocity selector is determined by the ratio of:

- (a) B/E (b) E/B (c) qE/B (d) qB/E

Answer: (b) E/B

Explanation: For undeflected motion, electric force (qE) equals magnetic force (qvB), so $qE = qvB$, which simplifies to $v = E/B$.

• In a velocity selector, particles with velocities different from the selected velocity will be:

- (a) Accelerated linearly. (b) Deflected. (c) Stopped. (d) Reversed in direction.

Answer: (b) Deflected.

Explanation: If the velocity is not exactly E/B , one force (either electric or magnetic) will be stronger, causing a net force and thus a deflection.

• If a velocity selector is used for positively charged particles, and the magnetic field is directed into the page, then for undeflected motion, the electric field must be directed:

- (a) Into the page. (b) Out of the page. (c) Upward. (d) Downward

Answer: (d) Downward.

Explanation: With B into the page and v to the right, the magnetic force on a positive charge is upward (Fleming's Left-Hand Rule). To balance this, the electric force must be downward, meaning the electric field (which points in the direction of force on a positive charge) must be downward.

SLO BASED SHORT QUESTIONS & ANSWERS

• What is the purpose of a velocity selector?

Ans: A velocity selector is a device used to determine or isolate charged particles moving at a specific velocity by allowing only those particles to pass undeflected through a combination of perpendicular electric and magnetic fields.

• Describe the arrangement of electric and magnetic fields in a velocity selector.

Ans: In a velocity selector, the uniform electric field and uniform magnetic field are set up perpendicular to each other, and also perpendicular to the initial direction of motion of the charged particles.

• Derive the formula for the selected velocity ' v ' in a velocity selector.

Ans: For a particle to move undeflected the electric force ($F_e = qE$) must balance the magnetic force ($F_m = qvB$).

Setting $qE = qvB$, and canceling 'q', we get $E = vB$, thus $v = E/B$.

What happens to charged particles that enter a velocity selector with a speed greater than the selected velocity?

Ans: If their speed is greater than the selected velocity, the magnetic force (qvB) will be stronger than the electric force (qE), causing the particles to be deflected by the net magnetic force.

Can a velocity selector work for both positive and negative charged particles simultaneously? Explain.

Ans: Yes, a velocity selector works for both positive and negative charged particles simultaneously if their speeds are correct. For a given setup of perpendicular E and B fields, the direction of the electric force and magnetic force on a charge will reverse for a negative particle compared to a positive one, but they will still be opposite, allowing for cancellation at the same specific velocity $v = E/B$.

10.6 INDUCED EMF AND FARADAY'S LAW

Q. What is induced emf? What is motional emf?

Ans

INDUCED EMF

When a conductor moves through a magnetic field, an electromotive force (emf) is generated or "induced" between its ends. This induced emf is similar to the voltage produced by a battery. If the ends of the conductor are connected to form a closed circuit, this induced emf will cause a current to flow.

Motional emf

The emf induced due to the motion of a conductor across a magnetic field is specifically called motional emf.

Expression

Consider a conducting rod of length L , moving with constant velocity ' v ' to the right within a uniform magnetic field (B) directed into the page.

Force on Charges: As the rod moves, the free charges (electrons or positive charge carriers) within it also move with the same velocity ' v ' in the magnetic field B . Each charge ' q ' experiences a magnetic force given by

$\vec{F} = q(\vec{v} \times \vec{B})$. Since ' v ' is perpendicular to ' B ' ($\theta = 90^\circ$ and

$\sin 90^\circ = 1$), the magnitude of the force is

$$F = qvB \quad (\text{Equation 10.16})$$

Charge Redistribution: Using the right-hand rule, this force pushes charges from one end of the rod to the other (e.g., from 'a' to 'b'). This causes a buildup of positive charge at one end and a deficiency (negative charge) at the other, similar to the terminals of a battery.

Electric Field Formation: This separation of charge creates an electrostatic field E directed from the higher potential end to the lower potential end (e.g., from 'b' to 'a'). This electric field exerts an electric force ($F_e = qE$) on the charges, opposing the magnetic force.

$$F_e = qE$$

Equilibrium: The system quickly reaches an equilibrium where the magnetic force and the electric force on the charges are balanced:

$$F = F_e$$

$$qE = qvB$$

This means $E = vB$ (Equation 10.17).

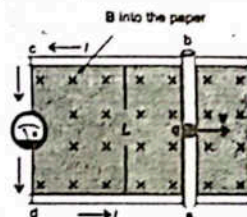


Fig. 10.13

For your information



Faraday's homopolar generator with which he was able to produce a continuous induced current.

Motional EMF: The induced emf (ϵ) is equal to the potential difference (ΔV) between the two ends of the moving conductor in this equilibrium state. Since the electric field E is the negative gradient of potential ($E = -\Delta V/L$), then $\Delta V = EL$. Substituting $E = vB$, $\Delta V = (vB)L$. So, the motional emf is:

$$\epsilon = vBL \quad (\text{Equation 10.18})$$

If the angle between velocity and magnetic field is not 90° degrees

If the angle between ' v ' and ' B ' is θ , then the magnitude of the motional emf is

$$\epsilon = vBL \sin \theta \quad (\text{Equation 10.19})$$

Q. Describe Faraday's Law of Electromagnetic Induction?

Ans

FARADAY'S LAW OF ELECTROMAGNETIC INDUCTION

Faraday's Law describes induced emfs in terms of magnetic flux. It states that the average emf induced in a conducting coil of N loops is equal to the negative of the rate at which the magnetic flux through the coil is changing with time.

Formula for Faraday's Law:

The change in magnetic flux ($\Delta \phi_B$) when the rod moves a distance Δx is

$$\Delta \phi_B = B(\Delta A) = B(\Delta x)L.$$

Since $\epsilon = vBL$ and Velocity of the rod $= v = \frac{\Delta x}{\Delta t}$

then $\epsilon = \left(\frac{\Delta x}{\Delta t}\right)BL = \left(\frac{\Delta x \cdot LB}{\Delta t}\right) = \frac{\Delta \phi}{\Delta t}$. Here $\Delta \phi = \Delta A \cdot B = \Delta x \cdot LB$

For a single loop:

$$\epsilon = -\frac{\Delta \phi}{\Delta t} \quad (\text{Equation 10.23})$$

For a coil with N loops:

$$\epsilon = -N\left(\frac{\Delta \phi}{\Delta t}\right) \quad (\text{Equation 10.24})$$

The minus sign indicates that the direction of the induced emf opposes the change in flux, which is in accordance with Lenz's Law. This law is generally true, even though it was derived from motional emf.

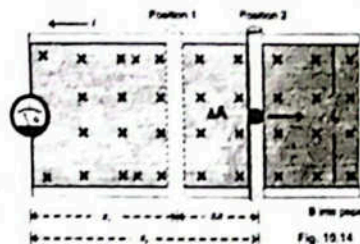
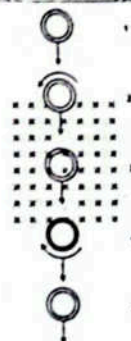


Fig. 10.14

Point to ponder!



A copper ring passes through a magnetic region where a constant magnetic field is directed into the page. What do you guess about the current in the ring at the positions 1, 2 and 4?

Position 2: Counter-clockwise current
Position 3: No current
Position 4: Clockwise current

Do we know?

Wireless charging works based on the principle of electromagnetic induction.

Wireless charging works by electromagnetic induction

- **Charging Pad (Transmitter):** An alternating current flows through a coil in the pad, creating a fluctuating magnetic field.
- **Device (Receiver):** A coil in your device picks up this changing magnetic field.
- **Electricity Generated:** This fluctuating field induces an electric current in the device's coil.
- **Charging:** This induced current is converted to DC to charge the device's battery.



Wireless charging works under the principle of electromagnetic induction.

Point to Ponder!

This heater works on the principle of electromagnetic induction. The water in the metal pot is boiling, whereas that in the glass pot is not, even though the glass top of the heater is cool to touch. The coil just beneath the top carries AC that produces a changing magnetic flux. Flux linking with pots induces emf in them. Current is generated in the metal pot that heats up the water, but no current flows through the glass pan, why?

(Answer): Metal is an electrical conductor, so the induced emf creates eddy currents within the metal pot. These eddy currents flow through the resistance of the metal, generating heat that boils the water. Glass, however, is an electrical insulator, so even if an emf is induced, it cannot drive a significant current through the glass pan to produce heat.



This heater operates on the principle of electromagnetic induction. The water in the metal pot is boiling, whereas that in the glass pot is not. Even the glass top of the heater is cool to touch. The coil just beneath the top carries AC that produces changing magnetic flux. Flux linking with pots induces emf in them. Current is generated in the metal pot that heats up the water, but no current flows through the glass pan, why?

MULTIPLE CHOICE QUESTIONS

- The emf induced in a conductor moving across a magnetic field is called:
 (a) Resistive emf (b) Motional emf (c) Electrostatic emf (d) Inductive emf

Answer: (b) Motional emf Explanation: EMF induced due to the motion of a conductor through a magnetic field is specifically termed motional EMF.

- According to Faraday's Law of Electromagnetic Induction, the induced emf in a coil is proportional to:
 (a) The magnetic flux through the coil.
 (b) The rate of change of magnetic flux through the coil.
 (c) The strength of the magnetic field. (d) The area of the coil.

Answer: (b) The rate of change of magnetic flux through the coil.

Explanation: Faraday's Law states that the magnitude of the induced EMF is directly proportional to the rate at which the magnetic flux through the circuit changes.

- The minus sign in Faraday's Law ($\epsilon = -N(\frac{\Delta\phi}{\Delta t})$) indicates:

- (a) The direction of current flow.
 (b) That induced emf always opposes the change in flux.
 (c) That energy is lost. (d) The rate of change is decreasing.

Answer: (b) That induced emf always opposes the change in flux.

Explanation: The minus sign is a mathematical representation of Lenz's Law, which states that the induced EMF and current oppose the change in magnetic flux that caused them.

- If a conducting rod of length L moves with velocity v perpendicular to a magnetic field B , the motional emf induced is:

- (a) vBL (b) vB/L (c) vL/B (d) v/BL

Answer: (a) vBL Explanation: For a conductor moving perpendicular to a uniform magnetic field, the motional EMF is given by $E = vBL$.

- Wireless charging works on the principle of:

- (a) Electrostatic induction (b) Electromagnetic induction (c) Direct current transfer (d) Conduction.

Answer: (b) Electromagnetic induction. Explanation: Wireless charging uses coils to create a changing magnetic field, which then induces a current in the receiving coil of the device, based on electromagnetic induction.

SLO BASED SHORT QUESTIONS & ANSWERS

- What is motional EMF?

Ans: Motional EMF is the electromotive force (voltage) induced across the ends of a conductor when it moves through a magnetic field, effectively acting like a temporary battery.

- State Faraday's Law of Electromagnetic Induction.

Ans: Faraday's Law states that the average emf induced in a conducting coil of N loops is equal to the negative of the rate at which the magnetic flux through the coil is changing with time ($\epsilon = -N(\frac{\Delta\phi}{\Delta t})$)

What are two factors that affect the magnitude of the induced EMF in a coil?

Ans: The magnitude of the induced EMF is affected by the rate of change of magnetic flux through the coil and the number of turns in the coil. (Also, the relative speed of the coil/conductor through the field).

Explain why a current flows in a closed loop when a conducting rod is pulled across a magnetic field.

Ans: When the rod moves, charges within it experience a magnetic force ($F = qvB$) directed along the rod, separating positive and negative charges to create a potential difference (motional EMF). If the loop is closed, this EMF drives a current.

How does the direction of induced EMF relate to the change in magnetic flux, as indicated by the minus sign in Faraday's Law?

Ans: The minus sign in Faraday's Law indicates that the direction of the induced EMF (and the resulting induced current) is always such that it opposes the change in magnetic flux that caused it, a principle known as Lenz's Law.

10.7 LENZ'S LAW AND DIRECTION OF INDUCED EMF

Q: What is Lenz's Law and how does it determine the direction of induced emf/current?

Ans

LENZ'S LAW

Lenz's Law, discovered by Heinrich Lenz in 1834, states that the direction of the induced current is always such that it opposes the change that causes the current. The minus sign in Faraday's law relates to this direction.

- Lenz's Law specifically applies to induced currents, not directly to induced emf.
- It is applied to closed conducting loops or coils. If a loop is not closed, one can imagine it closed to determine the induced current's direction, and then infer the induced emf's direction.
- Example: If a bar magnet's North Pole is moved towards a coil, the coil's face nearest the magnet will become a north pole to repel the magnet, causing the induced current to flow anticlockwise (when viewed from the magnet side). If the magnet is pulled away, the coil will create a south pole to oppose the pull.

Q: How is Lenz's Law a manifestation of the law of conservation of energy?

Ans

LENZ'S LAW AND CONSERVATION OF ENERGY

Lenz's Law is a direct consequence of the law of conservation of energy. When a conductor moves in a magnetic field and an induced current flows, it experiences a magnetic force that opposes its motion. To maintain constant velocity, an external force must be applied to counteract this opposing magnetic force. This external force provides the energy necessary for the induced current to flow.

If the induced current were in a direction that reinforced the motion, it would lead to an ever-increasing kinetic energy from nowhere, which would violate the law of conservation of energy.

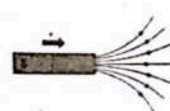
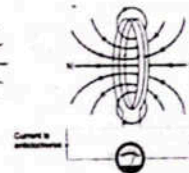
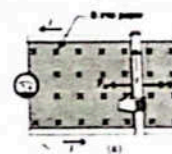


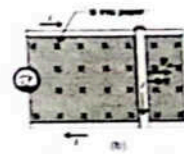
Fig. 10.15



Current's Induction



(a)



(b)

Fig. 10.16

Point to Ponder!

No. If resistance is neglected, a constant current means no change in magnetic flux. According to Faraday's Law, an induced emf (potential difference) is only produced when there is a change in magnetic flux. Without a change in flux, there is no induced emf.

Point to ponder!
By neglecting the resistance, can a constant current in a coil set up a potential difference across the coil?

MULTIPLE CHOICE QUESTIONS

- Lenz's Law states that the direction of the induced current is always such that it:
 - (a) Aids the change that causes the current.
 - (b) Opposes the change that causes the current.
 - (c) Is perpendicular to the magnetic field.
 - (d) Is parallel to the conductor's motion.
- Answer:** (b) Opposes the change that causes the current
Explanation: This is the core principle of Lenz's Law, ensuring conservation of energy.
- Lenz's Law is a manifestation of the law of:
 - (a) Conservation of charge
 - (b) Conservation of momentum
 - (c) Conservation of energy
 - (d) Conservation of mass.
- Answer:** (c) Conservation of energy
Explanation: If the induced current did not oppose the change, it would lead to a perpetual increase in kinetic energy without external work, violating energy conservation.
- If a bar magnet is pushed into a coil, according to Lenz's Law, the coil will:
 - (a) Develop a South pole towards the magnet to attract it
 - (b) Develop a North pole towards the magnet to repel it.
 - (c) Remain unmagnetized
 - (d) Develop an induced current that increases the magnet's speed
- Answer:** (b) Develop a North pole towards the magnet to repel it.
Explanation: To oppose the *pushing in* motion, the coil must create a repulsive force, which means forming a North pole facing the incoming North pole (assuming a North pole of the magnet is pushed in).
- Lenz's law is most directly applied to determine the direction of:
 - (a) Induced emf
 - (b) Induced current
 - (c) Magnetic flux
 - (d) Magnetic field strength
- Answer:** (b) Induced current
Explanation: While it affects the induced EMF, Lenz's Law specifically defines the direction of the induced *current* in a closed loop or coil, which then implies the direction of the induced EMF.
- Consider a copper ring passing through a region with a constant magnetic field directed into the page. When the ring is fully inside the field and moving uniformly, the current in the ring is:
 - (a) Clockwise
 - (b) Anticlockwise
 - (c) Continuously decreasing
 - (d) Zero
- Answer:** (d) Zero
Explanation: When the ring is fully inside a uniform magnetic field and moving, there is no *change* in magnetic flux through the loop. Since induced EMF depends on the rate of *change* of flux, the induced current will be zero.

SLO BASED SHORT QUESTIONS & ANSWERS

- State Lenz's Law.
- Ans:** Lenz's Law states that the direction of the induced current (or induced EMF) is always such that it opposes the change in magnetic flux that causes the current.
- Why Lenz's Law is considered a manifestation of the law of conservation of energy?
- Ans:** If the induced current were to aid the change in magnetic flux, it would lead to a self-accelerating system generating kinetic energy from nothing, which would violate the law of conservation of energy. Lenz's Law ensures external work is required to produce induced currents.
- If you pull a North Pole of a magnet away from a coil, what magnetic pole will be induced at the face of the coil towards the magnet, according to Lenz's Law?
- Ans:** A South Pole will be induced at the face of the coil towards the magnet. This is to attract the magnet!

- and oppose its motion away from the coil
- Does Lenz's Law apply directly to induced EMF or induced current?
- Ans:** Lenz's Law specifically applies to the direction of the induced current in a closed loop, and from that, the direction of the induced EMF can be inferred.
- When a conductor moves through a magnetic field, it experiences a magnetic force that tends to stop it. What must be done to keep the conductor moving at a constant velocity?
- Ans:** An external force, equal in magnitude and opposite in direction to the magnetic force tending to stop it, must be applied. This external force does work, which is converted into the electrical energy of the induced current.

10.8 FACTORS AFFECTING INDUCED EMF

Q. What factors affect the magnitude of the induced emf?

Ans.
FACTORS AFFECT THE MAGNITUDE OF THE INDUCED EMF

According to Faraday's law, the magnitude of the induced emf is affected by: $\varepsilon = -N \frac{\Delta\phi}{\Delta t}$

- Rate of Change of Magnetic Flux ($\Delta\phi/\Delta t$):** A faster rate of change of magnetic flux (e.g., moving a magnet quickly, or rapidly changing the field strength) results in a larger induced emf.
- Number of Turns in the Coil (N):** The induced emf is directly proportional to the number of turns in the coil. A coil with more turns will experience a greater induced emf for the same change in flux.
- Relative Speed between Coil/Conductor and Magnetic Field:** A faster relative speed between the conductor and the magnetic field lines increases the rate at which magnetic flux is cut or changes, leading to a larger induced emf.

10.9 FERROFLUIDS

Q. How can one observe the properties of ferrofluid through an experiment?

Ans.
EXPERIMENT WITH FERROFLUID

You can conduct an experiment using laser printer toner (which contains about 40% nano-scale iron oxide) and cooking oil.

- Procedure:** Pour some toner into a test tube, add cooking oil, and mix well with a stick to form the ferrofluid. Transfer this fluid to a glass bottle.
- Observation:**
 - When you shake the bottle without a magnet nearby, the fluid acts like a normal liquid.
 - When you bring a magnet near the fluid outside the bottle, the fluid jumps towards the magnet, showing it has become temporarily magnetized.
 - If you hold the magnet to the side of the bottle, the fluid will form a structure with spikes (Fig. 10.18).

Explanation: This phenomenon occurs due to the competition between magnetic forces, surface tension, and gravity. In a strong magnetic field, magnetic forces

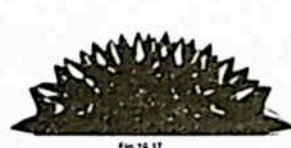


Fig. 10.17

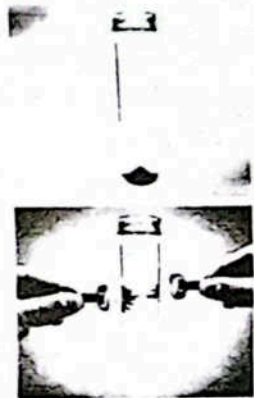


Fig. 10.18

pull the fluid upwards, forming chain-like structures that align with the magnetic field lines. These structures increase viscosity, making the fluid behave more like a solid with spikes where magnetic forces overcome other forces. When the magnet is removed, the particles demagnetize, and the ferrofluid returns to its liquid state.

How does ferrofluid behave?

- **Without a magnet:** A ferrofluid acts just like a regular liquid.
- **With a magnet nearby:** The tiny particles temporarily become magnetized, making the entire fluid behave like a magnet. They form structures within the fluid, causing it to act more like a solid.
- **Magnet removed:** When the magnet is taken away, the particles demagnetize, and the ferrofluid returns to its liquid state.

Why does ferrofluid form spikes near a magnet?

This phenomenon is a result of a competition between magnetic forces, surface tension, and gravity. In a strong magnetic field, the magnetic forces pull the fluid upwards, forming chain-like structures. Gravity and surface tension try to pull the fluid back down. These chains align along the magnetic field lines, increasing the fluid's viscosity and making it bulge in certain directions, forming "spikes." Spikes appear where the magnetic forces are strong enough to overcome the other forces.

Q: What are some practical applications of ferrofluids?

Ans

APPLICATIONS OF FERROFLUIDS

Ferrofluids have numerous applications across various fields:

- **Electronics:**
 - Used in rotary seals for computer hard drives and other rotating shaft motors to prevent contaminants from entering.
 - In loudspeakers, ferrofluids cool the voice coil by absorbing and dissipating heat, improving sound quality by dampening vibrations.
- **Medicine:**
 - Can be directed to specific areas in the body using external magnets for targeted drug delivery, reducing side effects.
 - Used as contrast agents in Magnetic Resonance Imaging (MRI).
- **Engineering and Research:**
 - Used for damping or precisely controlling the flow of liquids by manipulating the magnetic field.

For Your Information:

When was the first ferrofluid developed and for what purpose?
Ans: The first ferrofluid was developed by NASA in 1960. It was created by grinding natural magnetite and was invented to move liquids through space.

10.10 A SEISMOMETER

Q: What is a seismometer and how does it detect earthquakes using electromagnetic induction?

Ans

A SEISMOMETER

A seismometer is an instrument designed to respond to ground movements or vibrations caused by earthquakes, volcanic eruptions, and explosions. It detects earthquakes by converting ground motion into electrical signals through electromagnetic induction.

How a Seismometer Works

A seismometer converts ground motion into electrical signals using electromagnetic induction.

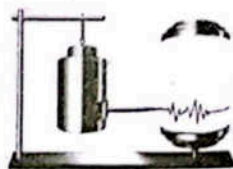


Fig. 10.18 Seismometer

1. **Components:** Typically, it includes a weight suspended by a spring. This weight is often attached to a magnet that moves inside a coil of wire (Fig 10.19)
2. **Earthquake Detection:** When an earthquake occurs, the ground and the seismometer's frame move, but the suspended weight tends to stay still due to inertia. This creates relative motion between the magnet (attached to the weight) and the coil (attached to the frame) (Fig 10.20)
3. **Induced EMF:** According to Faraday's law of electromagnetic induction, this changing magnetic flux through the coil induces an electromotive force (emf) in the coil.
4. **Induced Current:** This induced emf then generates an induced electric current.
5. **Data Recording:** The induced current is proportional to the velocity of the ground motion. These electrical signals are amplified and recorded, providing data on the amplitude, frequency, and duration of the earthquake waves.

For your information

There are two main types of seismic waves that generate earthquakes i.e., P-waves are primary waves which are longitudinal and S-waves are secondary waves which are transverse in nature.

For your information

Most earthquakes are caused by plate tectonics (displacement) and occur at a depth of 60 km. These earthquakes are categorized as shallow. Intermediate and deep intermediate can be as deep, as 280 km beneath the crust, while deep earthquakes can reach depths past 280 km.

SEISMOMETER PLACEMENT

Seismometers are typically buried under the ground at a depth of 50-1000 meters in a protective case called a vault. This vault is a cylindrical steel tank, approximately 1 meter wide and 2 meters deep, with a concrete pad at the bottom (Fig. 10.20). Solar energy charges batteries for the seismometer, and it transmits data to a computer via GPS.

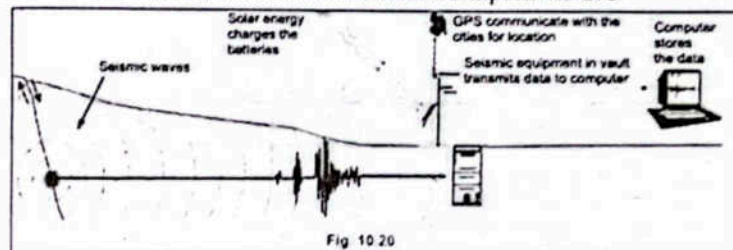


Fig. 10.20

For Your Information

Q: What causes most earthquakes and how are they categorized by depth?

Ans: Most earthquakes are caused by plate tectonics (displacement). They are categorized by depth:

- **Shallow earthquakes:** Occur at a depth of up to 60 km.
- **Intermediate earthquakes:** Can be as deep as 280 km beneath the crust.
- **Deep earthquakes:** Can reach depths past 280 km.

There are two main types of seismic waves that generate earthquakes:

- **P-waves (Primary waves):** Longitudinal in nature.
- **S-waves (Secondary waves):** Transverse in nature.

MULTIPLE CHOICE QUESTIONS

- Ferrofluids are characterized by exhibiting properties of both:
 - (a) Solids and gases
 - (b) Liquids and magnetic materials
 - (c) Conductors and insulators
 - (d) Acids and bases
- **Answer:** (b) Liquids and magnetic materials
- **Explanation:** Ferrofluids are colloidal suspensions of tiny magnetic particles in a carrier fluid, allowing them to flow like liquids but also react to magnetic fields.
- The magnetic particles in ferrofluids are typically coated with a surfactant to:
 - (a) Increase their magnetic strength.
 - (b) Prevent them from settling and clumping.
 - (c) Make them electrically conductive.
 - (d) Change their color.
- **Answer:** (b) Prevent them from settling and clumping.

Explanation: The surfactant reduces surface tension and prevents the nanoparticles from aggregating, ensuring they remain evenly dispersed.

• **How do seismometers detect earthquakes?**

- (a) By measuring static electric charges in the ground
- (b) By using sound waves to map vibrations
- (c) By converting ground motion into electrical signals via electromagnetic induction.
- (d) By detecting changes in atmospheric pressure.

Answer: (c) By converting ground motion into electrical signals via electromagnetic induction

Explanation: Seismometers typically use a suspended magnet and a coil. Ground motion causes relative motion between them, inducing an EMF and current that is proportional to the ground's velocity

• **When a magnet is brought near a ferrofluid, it forms "spikes" because:**

- (a) Magnetic forces repel the fluid.
- (b) Surface tension completely dominates gravity.
- (c) Magnetic forces overcome gravity and surface tension, aligning particles along field lines.
- (d) The fluid solidifies permanently.

Answer: (c) Magnetic forces overcome gravity and surface tension, aligning particles along field lines

Explanation: The magnetic forces pull the fluid upwards, forming chain-like structures (spikes) that align with the magnetic field lines, in competition with gravity and surface tension.

• **The induced current produced by a seismometer is directly proportional to the:**

- (a) Displacement of the ground.
- (b) Acceleration of the ground.
- (c) Velocity of the ground motion.
- (d) Amplitude of seismic waves only.

Answer: (c) Velocity of the ground motion.

Explanation: The induced EMF (and thus current) in a seismometer is proportional to the rate of change of magnetic flux, which is related to the relative velocity between the magnet and coil due to ground motion.

SLO BASED SHORT QUESTIONS & ANSWERS

• **What is a ferrofluid composed of?**

Ans: A ferrofluid is a colloidal suspension of tiny, nano-scale magnetic particles (typically iron oxide) evenly dispersed in a carrier fluid (like oil or water), coated with a surfactant to prevent clumping.

• **Describe one application of ferrofluids in electronics.**

Ans: In electronics, ferrofluids are used in rotary seals for computer hard drives and other rotating shaft motors, and also in loudspeakers to cool voice coils and dampen vibrations.

• **How does a seismometer detect ground motion from an earthquake?**

Ans: A seismometer detects ground motion by using a suspended mass (often with a magnet) and a coil. When the ground moves, the inertia of the mass causes relative motion between the magnet and the coil, inducing an EMF and current through electromagnetic induction.

• **Briefly explain why the induced current in a seismometer is proportional to the velocity of the ground motion.**

Ans: The induced EMF (and thus current) is proportional to the rate of change of magnetic flux. This change in flux is caused by the relative motion between the magnet and coil, making the induced current proportional to the velocity of the ground motion.

• **What is one medical application of ferrofluids?**

Ans: In medicine, ferrofluids can be used for targeted drug delivery to specific areas of the body (like tumors) using external magnets, or as contrast agents in Magnetic Resonance Imaging (MRI).



TEXT BOOK EXERCISE WITH SOLUTION

MULTIPLE CHOICE QUESTIONS

Tick the correct answer.

10.1 A current is flowing towards north along a power line. The direction of the magnetic field over the wire is directed towards:

- (a) north
- (b) south
- (c) east
- (d) west

Answer: (c) east (Using the right-hand grip rule, if current is North, magnetic field lines circle counter-clockwise when viewed from above, so above the wire, the field points east)

10.2 The radius of curvature of the path of a charged particle in a uniform magnetic field is directly proportional to:

- (a) the particle's charge
- (b) the particle's momentum
- (c) the particle's energy
- (d) the flux density of the field

Answer: (b) the particle's momentum. (Since $r = mv / (qB)$, r is directly proportional to mv , which is momentum).

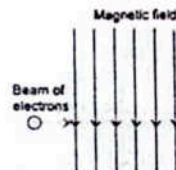
10.3 The diagram shows a beam of electrons entering a magnetic field. What is the effect of the magnetic field on the electrons?

(Assuming the magnetic field is directed into the page, and the electrons are moving to the right)

- (a) They are deflected into the plane of the diagram.
- (b) They are deflected out of the plane of the diagram.
- (c) They are deflected towards the bottom of the diagram.
- (d) They are deflected towards the top of the diagram.

Answer: (b) They are deflected out of the plane of the diagram.

(Using Fleming's left-hand rule: Field downward, current (opposite to electron flow) to the left, so force is out of paper)



10.4 The force exerted on a wire of 1 meter length carrying 1 ampere current placed at right angle to the magnetic field is called:

- (a) magnetic field intensity
- (b) magnetic flux
- (c) magnetic induction
- (d) none of these

Answer: (c) magnetic induction (This is the definition of magnetic induction, B)

10.5 The unit of flux density is:

- (a) $N A^{-1} m^{-1}$
- (b) $N A m^{-1}$
- (c) $N m A^{-2}$
- (d) $N m A$

Answer: (a) $N A^{-1} m^{-1}$ (This is the definition of Tesla, which is the unit of flux density)

10.6 A moving charged particle is surrounded by:

- (a) electric field only
- (b) magnetic field only
- (c) both electric and magnetic field
- (d) no field

Answer: (c) both electric and magnetic field (A stationary charge produces an electric field, A moving charge, which constitutes a current, produces both an electric field and a magnetic field)

10.7 Magnetic force on the charge q moving parallel to magnetic field with velocity v is:

- (a) $qvB \sin 0$
- (b) qvB
- (c) zero
- (d) ILB

Answer: (c) zero (When a charged particle moves parallel to a magnetic field, the angle $\theta = 0^\circ$, and $\sin 0 = 0$. Therefore, $F = qvB \sin 0 = 0$.)

10.8 The unit $N A^{-1} m^{-1}$ is called:

- (a) weber
- (b) tesla
- (c) coulomb
- (d) none of these

Answer: (b) tesla (This is the definition of a Tesla).

10.9 Electrons while moving perpendicularly through a uniform magnetic field are:

- (a) deflected towards north pole
- (b) deflected towards south pole
- (c) deflected along circular path
- (d) not deflected at all

Answer: (c) deflected along circular path (The magnetic force acts as a centripetal force, causing them to move in a circular or helical path)

10.10 A magnet is suspended from a spring. The magnet oscillates and moves in and out of the coil connected to a galvanometer. When the magnet oscillates, the galvanometer shows:

- (a) deflection to the left and to the right with constant amplitude
 (b) deflected on one side
 (c) no deflection
 (d) deflection to the left and right, but the amplitude steadily decreases



Answer: (d) deflection to the left and right, but the amplitude steadily decreases (This is due to induced current and Lenz's law. The induced current opposes the motion, damping the oscillation, and thus the amplitude decreases).

SHORT ANSWER QUESTIONS

- 10.1 It is said that Lenz's law specifically applies to induced currents and not directly to induce emf. Explain briefly.

Ans: Lenz's Law states that the direction of an induced current is such that it opposes the change in magnetic flux that produced it. While the induced electromotive force (EMF) is what drives the current. Induced current opposes this change due to its induced magnetic field.

- Induced Current is the Effect (and creates the opposition): For Lenz's Law to apply, there needs to be a closed circuit so that the induced EMF can actually drive an induced current.
 - Why not directly to EMF? If there's no closed circuit (e.g., an open-circuited coil), an EMF is still induced, but no current flows. Without a current, there's no opposing magnetic field, and thus no "opposition to the change in flux" in the way Lenz's Law describes.
 - Conclusion, Lenz's Law is about the consequence of the induced EMF in a closed circuit, where the resulting current acts to maintain energy conservation by opposing the cause of its own induction.
- 10.2 A square loop of wire is moving through a uniform magnetic field. The normal to the loop is oriented parallel to the magnetic field. Is an emf induced in the loop? Give a reason for your answer.

Ans: No emf will be induced in the loop.

Reason: Since the normal to the loop is parallel to uniform magnetic field so magnetic flux passing through the loop will remain constant so

$$\Delta\phi = 0$$

Hence by Faraday's Law

$$\varepsilon = -N \frac{\Delta\phi}{\Delta t} = 0$$

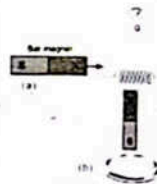
- 10.3 Does the induced emf always act to decrease the magnetic flux through a circuit?

Ans: No, the induced emf does not always act to decrease the magnetic flux. According to Lenz's law, the induced emf always opposes the cause that produces it.

- If the magnetic flux through the circuit is increasing, then induced emf acts to decrease the magnetic flux.
- If the magnetic flux through the circuit is decreasing, then induced emf acts to increase the magnetic flux.

- 10.4 When a magnet is pushed into the solenoid, as shown in the figure (a), the galvanometer indicates a small current. Why is the current produced? What will be the magnetic pole produced at the left end of the solenoid?

Ans: When a magnet is pushed into solenoid, the flux through the coil is changed. So, according to Faraday's law of electromagnetic induction an emf induced in the coil and cause of current in the galvanometer.



When we push the magnet north pole towards coil the left end will also have north pole according to Lenz's law as the induced current always opposes the cause that produces it.

- 10.5 A bar magnet falls through a fixed metal ring (Fig-b). Will the magnet fall with an acceleration of a freely falling body? Give reason.

Ans: No, the magnet will not fall with the acceleration of a freely falling body. When the bar magnet falls through the metal ring, an induced current will produce in the ring due to the change in magnetic flux. According to Lenz's law, the induced current creates a magnetic field that opposes the motion of the bar magnet. So, the bar magnet falls with an acceleration less than the acceleration due to gravity. ($a < g$)

- 10.6 Which of the two charged particles of the same mass will be deflected most in the magnetic field (a) fast moving (b) slow moving?

Ans: The force acting on a charge particle moving in a magnetic field is

$$\vec{F} = q(\vec{v} \times \vec{B}) = qvB \sin\theta$$

And the radius of curvature of charge particle in a magnetic field is

$$r = \frac{mv}{qB} \Rightarrow r \propto v$$

It shows that the r is directly proportional to the speed of moving charge. The large radius means less deflection and small radius means most deflection. So, the slow moving charge will deflect most in the magnetic field.

- 10.7 An electron and a proton are projected into a magnetic field at right angles to it with a certain velocity. Which of the particles will suffer greater deflection? Why?

Ans: The force acting on a charge particle moving in a magnetic field is

$$\vec{F} = q(\vec{v} \times \vec{B})$$

As the charged particles projected right angle to magnetic field then

$$F = qvB$$

And the radius of curvature of charge particle in a magnetic field is

$$r = \frac{mv}{qB} \Rightarrow r \propto m$$

It shows that the r is directly proportional to the mass of moving charge if all other factors are constant. The large radius means less deflection and small radius means more deflection. The mass of electron is less than the mass of proton. So, the electron will deflect more in the magnetic field.

- 10.8 Can a single moving proton produce magnetic field?

Ans: Yes, a single proton can produce magnetic field. The magnetic field is the intrinsic property of moving charges.

When a current flowing through a wire. The moving charges (electrons) in the wire create a magnetic field around the wire. Similarly, a single moving proton can generate a magnetic

$$\text{field } B = \frac{\mu_0 qv}{4\pi r^2}$$

- 10.9 A magnetic field is necessary if there is to be a magnetic flux passing through a coil of wire. Yet, just because there is a magnetic field does not mean that a magnetic flux will pass through a coil. Account for this

situation.

Ans: The magnetic flux is the number of field lines passing through an area. It is calculated as

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

It shows that magnetic flux can be zero if the angle between magnetic field and vector area is 90° , even though the magnetic field is there

CONSTRUCTED RESPONSE QUESTIONS

- 10.1 A charge is lying stationary between the opposite poles of two magnets. Is a magnetic force exerted on it? Why?

Ans: No magnetic force will act on a stationary charge. The magnetic force can only act on moving charge. The fundamental principle behind it is that the similar field interact with each other. The charge at rest have no magnetic field so it has no interaction with magnetic field due magnetic pole. We also have formula for magnetic force on charge particle i.e. $F = qvB$. If $v = 0$ then $F = 0$.

- 10.2 When the switch in the circuit is closed, a current is established in the coil and the metal ring jumps upward. Why? Describe what would happen to the ring if the battery polarity were reversed?



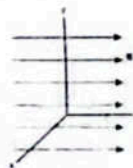
Ans: When the switch in the circuit is closed, the current is set up in the coil which establish magnetic field in it.

This result in change of magnetic flux through the metallic ring and hence an induced emf is produced in it

The induced magnetic field in the ring opposes the magnetic field of the coil (according to Lenz's law). Therefore, the ring experiences a force of repulsion and jumps up.

The same event occurs even if the polarity of the battery is reversed.

- 10.3 The figure shows a coil of wire in the x-y plane with a magnetic field directed along the y-axis. Around which of the three-coordinate axis should the coil be rotated in order to generate an emf and a current in the coil?



Ans:

- The coil must be rotated along x-axis to get change of magnetic flux and an induced current through it.
- If the coil is rotated about y-axis, the flux passing through the coil zero because plane of the coil remains parallel to magnetic field B all the times.
- If the coil is rotated about z-axis then no change of magnetic flux takes place through coil.

10.4 Is it possible to change both the area of the loop and the magnetic field passing through the loop and still not have an induced emf in the loop? Give reason.

Ans: Yes it is possible to change both the area of the loop and the magnetic field passing through the loop and still not have an induced emf in the

loop. The magnetic flux through a vector area \vec{A} placed in uniform magnetic field \vec{B} is given by,

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

Thus if area \vec{A} and magnetic field \vec{B} are changed in such a way that product $\vec{A} \cdot \vec{B}$ remains same, it can be done by increasing area and decreasing magnetic field simultaneously and vice versa. Then $\Delta \phi = 0$, no induced emf is produced in the loop.

$$\varepsilon = -N \frac{\Delta \phi}{\Delta t} = 0$$

10.5 Does the application of uniform magnetic field to a moving charged particle result in a change in kinetic energy of the particle? Explain.

Ans: No, the application of uniform magnetic field does change the kinetic energy of the particle. **Explanation:**

The force on a moving charge in magnetic field is given by $F = q(\vec{v} \times \vec{B})$, it shows that magnetic force always acts perpendicular to both the velocity of the particle and the magnetic field. So no work is done by magnetic force and there will be no change in kinetic energy of the particle. The magnetic force only deflect the particle into circular path.

10.6 A uniform electric field and a magnetic field act in the same direction. A proton is projected, into the space, with a uniform velocity in opposite direction. What will happen to the proton?

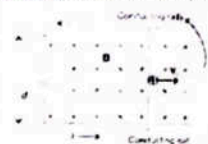
Ans: The projected proton velocity is antiparallel to both electric and magnetic field as both the

field are in the same direction. The electric field will exert electric force ($F_e = qE$) opposite to the direction of proton so the electric force decelerate the electron but the magnetic force ($F_B = q(\vec{v} \times \vec{B}) = evB \sin 180^\circ = 0$) has no effect on proton motion.

10.7 A conductor moves in a magnetic field when a current is passed through the conductor. Would you expect the reverse effect to occur? That is, would a current be produced if a conductor is moved across the magnetic field?

Ans: Yes, the reverse effect will expect according the Faraday's law ($\varepsilon = -N \frac{\Delta \phi}{\Delta t}$) of electromagnetic induction, an induced emf will produced across the end of conductor. If the conductor is the part of closed loop, the induced current flow due to induced emf.

10.8 Consider a conducting rod of length L moving with velocity v to the right as shown in the figure. Left ends of the conducting rails are connected to a bulb. Due to motion of the rod through the magnetic field, an emf is produced across the ends of the rod. This emf gives rise to a current I . As a result, the bulb lights up. Explain where does the electrical energy consumed by the bulb come from?



Ans: The electrical energy for the bulb comes from the mechanical work done to move the rod. As the rod moves through the magnetic field, an EMF is induced, driving a current through the bulb. This current creates a magnetic force that opposes the rod's motion. To keep the rod moving, external mechanical force must be continuously applied, and this mechanical energy is converted into the electrical energy consumed by the bulb.

10.9 What will you do if you want to save a sensitive instrument from stray magnetic fields?

Ans: To save a sensitive instrument from stray magnetic fields, enclose it in a container made of a high magnetic permeability material like soft iron

or mu-metal. This material diverts magnetic field lines around the instrument.

COMPREHENSIVE QUESTIONS

- 10.1 Distinguish between magnetic flux and flux density. How are they related?
- 10.2 Find an expression for the force exerted on a current-carrying conductor placed in a uniform magnetic field.
- 10.3 State and explain Faraday's law and Lenz's law. Also describe factors affecting the induced emf.
- 10.4 Determine the force acting on a charged particle moving through a uniform magnetic field.
- 10.5 What is a velocity selector? Explain its working.
- 10.6 Explain how ferrofluids work?

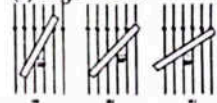
SOLVED EXAMPLES

10.1: A 20.0 cm wire carrying a current of 10.0 A is placed in a uniform magnetic field of 0.30 T. If the wire makes an angle of 40° with the direction of the magnetic field, find the magnitude of the force acting on the wire.

Solution: Length of the wire, $L = 20.0 \text{ cm} = 0.20 \text{ m}$
 Current, $I = 10.0 \text{ A}$
 Strength of magnetic field, $B = 0.30 \text{ T}$
 Angle, $\theta = 40^\circ$
 Using the formula $F = BIL \sin \theta$:
 $F = 10.0 \text{ A} \times 0.30 \text{ T} \times 0.20 \text{ m} \times \sin 40^\circ$
 $F = 3.0 \text{ N/A} \times 0.20 \text{ m} \times 0.6428$
 $F = 0.60 \times 0.6428$
 $F = 0.38568 \text{ N}$
 $F \approx 0.39 \text{ N}$

10.2: A rectangular loop of wire is placed in a uniform magnetic field of magnitude 1.2 T. If the loop is 25 cm long and 20 cm wide, determine the magnetic flux through the loop for three orientations:

- (a) angle between B and area vector A is 60° , (b) angle is 45° , (c) angle is 30° .



Solution: Magnitude of magnetic field, $B = 1.2 \text{ T}$
 Length of loop $= 25 \text{ cm} = 0.25 \text{ m}$
 Width of loop $= 20 \text{ cm} = 0.20 \text{ m}$
 Area of the loop, $A = \text{length} \times \text{width}$

$$= 0.25 \text{ m} \times 0.20 \text{ m} = 0.05 \text{ m}^2 = 5 \times 10^{-2} \text{ m}^2$$

Using the formula $\phi_B = BA \cos \theta$

(a) Orientation (a): Angle $\theta = 90^\circ - 30^\circ = 60^\circ$

$$\phi_B = 1.2 \text{ T} \times (5 \times 10^{-2} \text{ m}^2) \times \cos 60^\circ$$

$$\phi_B = 1.2 \times 5 \times 10^{-2} \times 0.5$$

$$\phi_B = 0.06 \times 0.5 = 0.03 \text{ Wb} = 3 \times 10^{-2} \text{ Wb}$$

(b) Orientation (b): Angle $\theta = 90^\circ - 45^\circ = 45^\circ$

$$\phi_B = 1.2 \text{ T} \times (5 \times 10^{-2} \text{ m}^2) \times \cos 45^\circ$$

$$\phi_B = 1.2 \times 5 \times 10^{-2} \times 0.707$$

$$\phi_B = 0.06 \times 0.707 = 0.04242 \text{ Wb} \approx 4.2 \times 10^{-2} \text{ Wb}$$

(c) Orientation (c): Angle $\theta = 90^\circ - 60^\circ = 30^\circ$

$$\phi_B = 1.2 \text{ T} \times (5 \times 10^{-2} \text{ m}^2) \times \cos 30^\circ$$

$$\phi_B = 1.2 \times 5 \times 10^{-2} \times 0.866$$

$$\phi_B = 0.06 \times 0.866 = 0.05196 \text{ Wb} \approx 5.2 \times 10^{-2} \text{ Wb}$$

10.3: An electron enters a uniform magnetic field perpendicularly with a speed of 104 m s^{-1} . What path will the electron move along inside the field?

($B = 2.5 \text{ Wb m}^{-2}$, $m = 9.11 \times 10^{-31} \text{ kg}$, $e = 1.6 \times 10^{-19} \text{ C}$)

Solution: Speed of electron, $v = 104 \text{ m s}^{-1}$

Magnetic field strength, $B = 2.5 \text{ Wb m}^{-2}$

Mass of electron, $m = 9.11 \times 10^{-31} \text{ kg}$

Charge of electron, $e = 1.6 \times 10^{-19} \text{ C}$

Angle between v and B , $\theta = 90^\circ$

(perpendicularly)

The force (F) acting on the electron is given by

$$F = qvB \sin \theta$$

Since $\theta = 90^\circ$, $\sin 90^\circ = 1$. Also, $q = e$.

$$\text{So, } F = evB$$

This force (F) acts perpendicular to the velocity

(v) and provides the necessary centripetal

force to make the electron move in a circle.

Centripetal force (F_c) is mv^2/r

Equating the magnetic force to the centripetal force:

$$evB = \frac{mv^2}{r}$$

Now, solve for the radius (r).

$$R = mv/(eB)$$

Substitute the given values

$$r = \frac{(9.11 \times 10^{-31} \text{ kg} \times 104 \text{ m s}^{-1})}{(1.6 \times 10^{-19} \text{ C} \times 2.5 \text{ Wb m}^{-2})}$$

$$r = \frac{(9.11 \times 10^{-27})}{(4.0 \times 10^{-19})}$$

$$r = 2.2775 \times 10^{-8} \text{ m}$$

$$r \approx 2.3 \times 10^{-8} \text{ m}$$

Conclusion: The path of the electron will be a circle with a radius of $2.3 \times 10^{-8} \text{ m}$.

10.4: Alpha particles ranging in speed from 1000 m s^{-1} to 2000 m s^{-1} enter a velocity selector where the electric intensity is 300 V m^{-1} and the magnetic induction is 0.20 T . Which

particle will move undeflected through the field?

Solution:
Electric field intensity, $E = 300 \text{ V m}^{-1} = 300 \text{ N C}^{-1}$
Magnetic induction, $B = 0.20 \text{ T}$

Only particles for which the electric force (qE) balances the magnetic force (Bqv) will pass undeflected

$$qE = Bqv$$

$$v = \frac{E}{B}$$

Substitute the values

$$v = \frac{(300 \text{ N C}^{-1})}{(0.20 \text{ N A}^{-1} \text{ m}^{-1})}$$

$$v = 1500 \text{ m s}^{-1}$$

Conclusion: Alpha particles with a speed of 1500 m s^{-1} will move undeflected through the field.

10.5: A charged particle moves through a velocity selector at a constant velocity in a straight line. The electric field of the velocity selector is $4.8 \times 10^3 \text{ N C}^{-1}$, while the magnetic field is 0.2 T . When the electric field is turned OFF, the charged particle travels on a circular path of radius 3.0 cm . Find the charge to mass ratio of the particle.

Solution: Electric field, $E = 4.8 \times 10^3 \text{ N C}^{-1}$

Magnetic field, $B = 0.2 \text{ T}$

Radius of circular path, $r = 3.0 \text{ cm}$
 $= 3.0 \times 10^{-2} \text{ m}$

First, find the velocity (v) of the particle using the velocity selector principle:

$$v = \frac{E}{B}$$

$$v = \frac{(4.8 \times 10^3 \text{ N C}^{-1})}{(0.2 \text{ T})}$$

$$v = 2.4 \times 10^4 \text{ m s}^{-1}$$

When the electric field is turned off, the magnetic force provides the centripetal force for circular motion:
Magnetic force (qvB) = Centripetal force (mv^2/r)

$$Bqv = \frac{mv^2}{r}$$

We need to find the charge to mass ratio (q/m). Rearrange the equation

$$\frac{q}{m} = \frac{v}{Br}$$

Now, substitute the value of ' v ' (from $v = \frac{E}{B}$):

$$\frac{q}{m} = \frac{E}{B^2 r}$$

Substitute the given values for E , B , and r :

$$\frac{q}{m} = \frac{(4.8 \times 10^3 \text{ N C}^{-1})}{(0.2 \text{ T})^2 (3 \times 10^{-2} \text{ m})}$$

$$\frac{q}{m} = \frac{(4.8 \times 10^3)}{(0.04 \times 3 \times 10^{-2})}$$

$$\frac{q}{m} = \frac{(4.8 \times 10^3)}{(0.12 \times 10^{-2})}$$

$$\frac{q}{m} = \frac{(4.8 \times 10^3)}{(1.2 \times 10^{-1})}$$

$$\frac{q}{m} = 4 \times 10^4 \text{ C kg}^{-1}$$

Conclusion: The charge to mass ratio of the particle is $4 \times 10^4 \text{ C kg}^{-1}$.

10.6: A metal rod of length 25 cm is moving at a speed of 0.5 m s^{-1} in a direction perpendicular to a 0.25 T magnetic field. Find the emf produced in the rod.

Solution: Speed of rod, $v = 0.5 \text{ m s}^{-1}$

Length of rod, $l = 25 \text{ cm} = 0.25 \text{ m}$

Magnetic flux density, $B = 0.25 \text{ T} = 0.25 \text{ N A}^{-1} \text{ m}^{-1}$

Induced emf, $\epsilon = ?$

Using the relation for motional emf when ' v ' is perpendicular to ' B ':

$$\epsilon = vBl$$

Substitute the values:

$$\epsilon = 0.5 \text{ m s}^{-1} \times 0.25 \text{ N A}^{-1} \text{ m}^{-1} \times 0.25 \text{ m}$$

$$\epsilon = 0.03125 \text{ V}$$

$$\epsilon \approx 3.13 \times 10^{-2} \text{ V}$$

10.7: A loop of wire is placed in a uniform magnetic field that is perpendicular to the plane of the loop. The strength of the magnetic field is 0.6 T . The area of the loop begins to shrink at a constant rate of $\Delta A/\Delta t = 0.8 \text{ m}^2 \text{ s}^{-1}$. What is the magnitude of emf induced in the loop while it is shrinking?

Solution: Rate of change of area, $\frac{\Delta A}{\Delta t} = 0.8 \text{ m}^2 \text{ s}^{-1}$

Magnetic flux density, $B = 0.6 \text{ T} = 0.6 \text{ N A}^{-1} \text{ m}^{-1}$

Number of turns, $N = 1$ (for a single loop)

Induced emf, $\epsilon = ?$

The magnetic field is perpendicular to the plane of the loop, meaning the angle between B and the area vector A is $\theta = 0^\circ$, so $\cos \theta = 1$.

The rate of change of flux is

$$\Delta \Phi B / \Delta t = B \left(\frac{\Delta A}{\Delta t} \right) \cos \theta = B \left(\frac{\Delta A}{\Delta t} \right)$$

Applying Faraday's Law, the magnitude of induced emf is

$$\epsilon = N(\Delta \Phi B / \Delta t)$$

$$\epsilon = NB(\Delta A / \Delta t)$$

Substitute the values:

$$\epsilon = 1 \times 0.6 \text{ T} \times 0.8 \text{ m}^2 \text{ s}^{-1}$$

$$\epsilon = 0.48 \text{ V}$$

Conclusion: The magnitude of the induced emf is 0.48 V .

NUMERICAL PROBLEMS

10.1 A positively charged particle is projected perpendicularly into a magnetic field at a speed of 1500 m s^{-1} . It experiences a force of magnitude F . At what angle θ with the field, the particle should be projected at a speed of 2000 m s^{-1} , so that it experiences the same magnitude of force?

Given

Projected speed = $v_1 = 1500 \text{ m s}^{-1}$

Angle of projection = $\theta_1 = 90^\circ$

Force experienced = $F_1 = F_2 = F$

Projection speed = $v_2 = 2000 \text{ m s}^{-1}$

Angle of projection = $\theta_2 = \theta = ?$

Solution

As the force is same in both cases

So $qv_1 B \sin 90^\circ = qv_2 B \sin \theta$

$$v_1 = v_2 \sin \theta$$

$$1500 = 2000 \sin \theta$$

$$\sin \theta = \frac{1500}{2000}$$

$$\theta = \sin^{-1} \frac{3}{4} = 48.59 = 49^\circ$$

10.2 Electrons are accelerated from rest through a potential difference of 15 kV in an oscilloscope. The electrons then pass through a 0.35 T magnetic field that deflects them to the desired position on the screen. Find the magnitude of the maximum force that an electron can experience.

Potential difference = $V = 15 \text{ kV} = 15000 \text{ V}$

Magnetic field strength = $B = 0.35 \text{ T}$

Force = $F_{\text{max}} = ?$

Solution

To calculate speed

$$eV = \frac{1}{2} mv^2$$

$$(1.6 \times 10^{-19})(15000) = \frac{1}{2} (9.1 \times 10^{-31})v^2$$

$$v^2 = \frac{2(1.6 \times 10^{-19})(15000)}{(9.1 \times 10^{-31})}$$

$$= 5.27 \times 10^{15} \text{ m}^2 \text{ s}^{-2}$$

$$v = 7.3 \times 10^7 \text{ m s}^{-1}$$

$$F_{\text{max}} = evB$$

$$F_{\text{max}} = (1.6 \times 10^{-19})(7.3 \times 10^7)(0.35)$$

$$F_{\text{max}} = 4.06 \times 10^{-12} \text{ N}$$

10.3 A square coil of side 15 cm each consists of 60 turns. Initially, it is located in a uniform magnetic field of magnitude 0.8 T such that plane of the coil is perpendicular to the field. The coil is then turned through an angle of $\theta =$

30° in a time of 2 s . Determine the average induced emf.

Length of side of square coil = $l = 15 \text{ cm} = 0.15 \text{ m}$

Area of square coil = $A = l^2 = 0.15^2 = 0.0225 \text{ m}^2$

Number of turns = $N = 60$ turns

magnetic field = $B = 0.8 \text{ T}$

Initial angle = $\theta_1 = 0^\circ$

Initial flux = $\Phi_1 = BA \cos 0 = 0.8 \times 0.0225 \times 1 = 0.018$

Final angle = $\theta_2 = 30^\circ$

Final magnetic flux = $\Phi_2 = BA \cos 30^\circ = 0.8 \times 0.0225 \times 0.866 = 0.0156$ weber

Change in flux = $\Delta \Phi = \Phi_2 - \Phi_1 = 0.018 - 0.0156 = 0.0024$ weber

Time interval = $\Delta t = 2 \text{ s}$

To Find:

Induced emf, $\epsilon = ?$

Calculation:

According to Faraday's law of electromagnetic induction,

$$\epsilon = -N \frac{\Delta \Phi}{\Delta t}$$

Putting respective values,

$$\epsilon = -60 \times \frac{0.0024}{2}$$

$$\epsilon = -0.07 \text{ V}$$

Since minus sign indicates the direction of induced emf, hence:

$$\epsilon = 0.07 \text{ V}$$

10.4 A metallic rod is moving through a uniform magnetic field of 0.2 T . The emf induced across its ends is found to be 0.8 V . It is required to induce an emf of 2.4 V across its ends. How much field strength is needed for this?

Given:

Induced emf, $\epsilon_1 = 0.8 \text{ V}$

Magnetic field, $B_1 = 0.2 \text{ T}$

Required induced emf, $\epsilon_2 = 2.4 \text{ V}$

To Find:

Magnetic field for required emf = $B_2 = ?$

Calculation:

We know that magnitude of motional emf is,

$$\epsilon_1 = B_1 l \sin \theta \quad \text{--- (i)}$$

$$\text{Also } \epsilon_2 = B_2 l \sin \theta \quad \text{--- (ii)}$$

As V , l and θ remain the same. So dividing eq (i) by eq (ii), we get,

$$\frac{\epsilon_1}{\epsilon_2} = \frac{B_1 l \sin \theta}{B_2 l \sin \theta}$$

$$\text{Or } B_2 = \frac{\epsilon_2}{\epsilon_1} B_1$$

Putting respective values,

$$B_2 = \frac{2.4}{0.8} \times 0.2$$

$$B_2 = 0.6 \text{ T}$$

- 10.5 A copper ring has a radius of 4.0 cm and resistance of 1.0 m Ω . A magnetic field is applied over the ring, perpendicular to its plane. If the magnetic field increases from 0.2 T to 0.4 T in a time interval of 5×10^{-3} s, what is the current in the ring during this interval?

Given:

Radius of ring, $R = 4.0 \text{ cm} = 0.04 \text{ m}$

Resistance of ring, $R = 1.0 \text{ m}\Omega = 1 \times 10^{-3}$

Initial magnetic field, $B_1 = 0.2 \text{ T}$

Final magnetic field, $B_2 = 0.4 \text{ T}$

Time interval, $\Delta B = B_2 - B_1 = 0.4 \text{ T} - 0.2 \text{ T} = 0.2 \text{ T}$

$$\Delta t = 5 \times 10^{-3} \text{ s}$$

To Find:

Induced emf, $\epsilon = ?$

Induced current, $I = ?$

Calculation:

According to Faraday's law of electromagnetic induction;

$$I = \frac{\epsilon}{R}$$

$$\epsilon = N \frac{\Delta \phi}{\Delta t} = \frac{\Delta(BA)}{\Delta t}$$

$$\epsilon = \frac{\Delta(BA)}{\Delta t} = \frac{(\Delta B)A}{\Delta t}$$

$$\epsilon = \frac{\Delta B \pi r^2}{\Delta t}$$

$$\epsilon = \frac{0.2 \times (3.14) \times (0.04)^2}{5 \times 10^{-3}}$$

$$\epsilon = 0.2 \text{ V}$$

$$I = \frac{\epsilon}{R}$$

$$I = \frac{0.201}{1 \times 10^{-3}}$$

$$I = 201 \text{ A}$$

- 10.6 A coil of 10 turns and 35 cm² area is in a perpendicular magnetic field of 0.5 T. The coil is pulled out of the field in 1.0 s. Find the induced emf in the coil as it is pulled out of the field.

Given:

Number of turns, $N = 10$

Area of coil, $A = 35 \text{ cm}^2 = 35 \times 10^{-4} \text{ m}^2$

Magnetic field, $\Delta B = 0.5 \text{ T} - 0 = 0.5 \text{ T}$

Time interval, $\Delta t = 1.0 \text{ s}$

To Find: Induced emf, $\epsilon = ?$

Calculation: According to Faraday's law of electromagnetic induction,

$$\epsilon = N \frac{\Delta \phi}{\Delta t}$$

$$\text{Or } \epsilon = N \frac{\Delta(BA)}{\Delta t}$$

$$\epsilon = N \frac{\Delta BA}{\Delta t}$$

$$\epsilon = 10 \times \frac{0.5 \times 35 \times 10^{-4}}{1} \times 10$$

$$\epsilon = 1.75 \times 10^{-2} \text{ V} \quad \text{Ans.}$$

- 10.7 A proton is accelerated by a potential difference of 6×10^5 volts. It then enters perpendicularly in a uniform magnetic field $B = 1.0$ weber m⁻². Find the radius of curvature of the path of the proton. $m = 1.67 \times 10^{-27} \text{ kg}$, $e = 1.6 \times 10^{-19} \text{ C}$.

Given

Potential difference = $V = 6 \times 10^5$ volts

Magnetic field = $B = 1.0$ weber m⁻²

Mass of proton = $m = 1.67 \times 10^{-27} \text{ kg}$

Charge on proton = $e = 1.6 \times 10^{-19} \text{ C}$

Radius of curvature = $r = ?$

Solution

To calculate speed

$$eV = \frac{1}{2} mv^2$$

$$(1.6 \times 10^{-19})(6 \times 10^5) = \frac{1}{2} (1.67 \times 10^{-27})v^2$$

$$v^2 = \frac{2(1.6 \times 10^{-19})(6 \times 10^5)}{(1.67 \times 10^{-27})} = 11.5 \times 10^{13} \text{ m}^2 \text{ s}^{-2}$$

$$v = 1.07 \times 10^7 \text{ m s}^{-1}$$

$$r = \frac{mv}{qB}$$

$$r = \frac{(1.67 \times 10^{-27})(1.07 \times 10^7)}{(1.6 \times 10^{-19})(1)}$$

$$r = 1.12 \times 10^{-1} = 11.2 \times 10^{-2} \text{ m}$$

$$r = 11.2 \text{ cm}$$

- 10.8 A proton enters a uniform magnetic field $B = 0.3$ weber m⁻² in a direction making an angle 45° with the magnetic field. What will be the radius of the circular path if the velocity of proton is 10^4 m s^{-1} .

Given

Magnetic field = $B = 0.3$ weber m⁻²

Entrance angle with magnetic field = $\theta = 45^\circ$

Mass of proton = $m = 1.67 \times 10^{-27} \text{ kg}$

Charge on proton = $e = 1.6 \times 10^{-19} \text{ C}$

Velocity of proton = $v = 10^4 \text{ m s}^{-1}$

Radius of circular path = $r = ?$

Solution

$$qv \sin \theta = \frac{m(v \sin \theta)^2}{r}$$

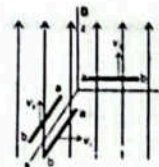
$$r = \frac{mv \sin \theta}{qB}$$

$$r = \frac{(1.67 \times 10^{-27})(10^4) \sin 45}{(1.6 \times 10^{-19})(0.3)}$$

$$r = 2.46 \times 10^{-4} \text{ m}$$

- 10.9 Three identical conducting rods L_1 , L_2 and L_3

are moving in different planes with the same speeds $v_1 = v_2 = v_3 = 2.5 \text{ m s}^{-1}$ as shown in the figure. The length of each rod is 60 cm. A constant magnetic field of magnitude $B = 0.5 \text{ T}$



is directed along z-axis. Find the magnitude of induced emf in each rod and indicate which end of the rod is positive.

Given

$L_1 = L_2 = L_3 = 60 \text{ cm} = 0.6 \text{ m}$

$v_1 = v_2 = v_3 = 2.5 \text{ m s}^{-1}$

magnetic field strength = $B = 0.5 \text{ T}$

induce emf in rod 1 = $\epsilon_1 = ?$

induce emf in rod 2 = $\epsilon_2 = ?$

induce emf in rod 3 = $\epsilon_3 = ?$

Solution

$\epsilon_1 = v_1 B L_1 \sin 90$

$\epsilon_1 = 2.5 \times 0.5 \times 0.6 \times 1 = 0.75 \text{ V}$

(End a is positive)

$\epsilon_2 = v_2 B L_2 \sin 0$

$\epsilon_2 = 2.5 \times 0.5 \times 0.6 \times 0 = 0 \text{ V}$

$\epsilon_3 = v_3 B L_3 \sin 0$

$\epsilon_3 = 2.5 \times 0.5 \times 0.6 \times 0 = 0$

- 10.10 An emf of 0.5 V is induced across the ends of a metal rod moving through a magnetic field of 0.4 T. If an emf of 1.5 V has to be induced, what field strength would be needed for that? Assume that all other factors remain the same.

Given:

Induced emf, $\epsilon_1 = 0.5 \text{ V}$

Magnetic field, $B_1 = 0.4 \text{ T}$

Required induced emf, $\epsilon_2 = 1.5 \text{ V}$

To Find:

Magnetic field for ϵ_2 , $B_2 = ?$

Calculation:

We know that magnitude of motional emf is;

$\epsilon_1 = B_1 L \sin \theta$ (i)

$\epsilon_2 = B_2 L \sin \theta$ (ii)

As V , L and θ remain the same. So dividing

eq (i) by eq (ii), we get;

$$\frac{\epsilon_1}{\epsilon_2} = \frac{B_1 L \sin \theta}{B_2 L \sin \theta}$$

$$\frac{\epsilon_1}{\epsilon_2} = \frac{B_1}{B_2}$$

$$\text{Or } B_2 = \frac{\epsilon_2}{\epsilon_1} B_1$$

Putting respective values,

$$B_2 = \frac{1.5}{0.5} \times 0.4$$

$$B_2 = 1.2 \text{ T}$$

- 10.11 A charged particle moves through a velocity selector at a constant velocity of $4.96 \times 10^4 \text{ m s}^{-1}$ in a direction perpendicular to both E and B . If the magnetic field strength is 0.114 T, what should be the magnitude of electric field intensity so that the particle moves undeflected?

Given:

Speed of particle, $v = 4.96 \times 10^4 \text{ m s}^{-1}$

Magnetic field, $B = 0.114 \text{ T}$

To Find:

Electric field, $E = ?$

Calculation:

The magnetic force experienced by charged particle in magnetic field is;

$$F_m = qvB \quad \text{--- (i)}$$

Electric force experienced by particle in electric field is;

$$F_e = qE \quad \text{--- (ii)}$$

According to given conditions,

$$qE = qvB$$

$$E = vB$$

$$E = 4.96 \times 10^4 \times 0.114 = 0.565 \times 10^4$$

$$E = 5.65 \times 10^3 \text{ N C}^{-1}$$

- 10.12 A current-carrying

conductor PQ of length

2 m is placed

perpendicularly to a

magnetic field of flux

density 0.5 T as shown

in the figure. The

resulting force on the

conductor is 1 N acting into the plane of the

paper. What is the magnitude and direction

of the current?

Given

Length of conductor = $L = 2 \text{ m}$

Magnetic flux density = $B = 0.5 \text{ T}$

Magnetic force on conductor = $F = 1 \text{ N}$

Current in a conductor = $I = ?$

Solution

$$F = ILB \sin \theta$$

$$1 = I \times 2 \times 0.5 \sin 90$$

$$I = 1 \text{ A}$$

By right hand rule or Fleming left hand rule the

direction of current is from Q end to P

