

# SSC-JE

# 2025

**Staff Selection Commission**  
Junior Engineer Examination

## Electrical Engineering

### Electrical Machines

(Volume - 1)

(Transformer, Induction Machine and Special Machines)

Well Illustrated **Theory** *with*  
**Solved Examples** and **Practice Questions**



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# Electrical Machines

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# Chapter 1

## Electromagnetic Systems

### 1.1 Introduction

- The electromagnetic system is an essential element of all rotating electric machinery and electromechanical device and static devices like the transformer.
- Electromechanical energy conversion takes place via the medium of a magnetic field or electrical field, but most practical converters use magnetic field as the coupling medium between electrical and mechanical systems.
- In transformers, the electrical energy convert from one electrical circuit to another electrical circuit via the medium of a magnetic field as the coupling medium between one electrical circuit to another electrical circuits.
- The energy storing capacity of magnetic field is much greater than that of the electric field.

### Magnetic Circuits

The complete closed path followed by the lines of flux is called a magnetic circuit.

#### REMEMBER :

In low power electrical machines, magnetic field may be produced by permanent magnets. But in high-power electrical machinery and transformers, coupling magnetic field is produced by electric current.

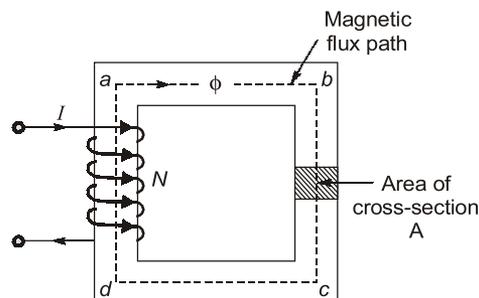
### 1.2 Important Terms Related to Magnetic Circuit

#### Magnetomotive Force (Mmf)

In a magnetic circuit, the magnetic flux is due to the presence of a **magnetomotive force** (Mmf). The mmf is created by a current flowing through one or more turns.

Mmf = Current  $\times$  Number of turns in the coil

Mmf =  $NI$  (ampere-turns) or (ATs)



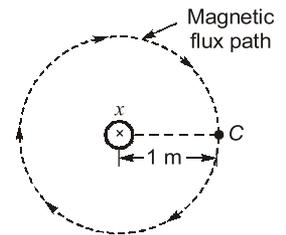
Magnetic circuit with  $N$ -turns and current  $I$

### Permeability of Free Space

Suppose a current  $I$  carrying conductor in a free space as shown in figure.

- According to the right hand grip rule, around the current carrying conductor a magnetic flux path is generated.
- Suppose flux density at  $C$ , caused by magnetic field intensity  $H$  at  $x$  is  $B$  tesla and if  $C$  is one meter away from  $x$ , then permeability of free space  $\mu_0$  is given by

$$\mu_0 = \frac{B}{H} = 4\pi \times 10^{-7}$$



### Reluctance (R)

Opposition offered by the magnetic circuit to magnetic flux is called **reluctance**.

$$R/l = \frac{l}{\mu A} \text{ AT/Wb}$$

where,

$l$  = length of the magnetic path

$A$  = area of cross-section normal to flux path,  $m^2$

$\mu = \mu_0 \mu_r$  = permeability of the magnetic material

$\mu_r$  = relative permeability of the magnetic material

$\mu_0$  = permeability of free space =  $4\pi \times 10^{-7}$  H/m.

### Magnetic Flux ( $\phi$ )

The magnetic flux may be defined as the magnetomotive force per unit reluctance.

$$\phi = \frac{\text{MMF}}{\text{Reluctance}} \text{ or } \phi = \frac{IN \cdot \mu_0 \mu_r \cdot A}{l} \text{ Wb}$$

Direction of magnetic flux produced by coil can be found by right-hand grip rule.

### Right Hand Grip Rule

It is stated that grip the conductor with thumb pointing in the direction of conductor current then four fingers give the direction of magnetic flux created by the current.

### Permeance

Reciprocal of reluctance is called permeance.

$$\text{Permeance} = \frac{1}{\text{Reluctance}} = \frac{\mu_0 \mu_r A}{l} \text{ Wb/AT}$$

### Magnetic Field Density

It is defined as the magnetic flux per unit cross-sectional area of the core.

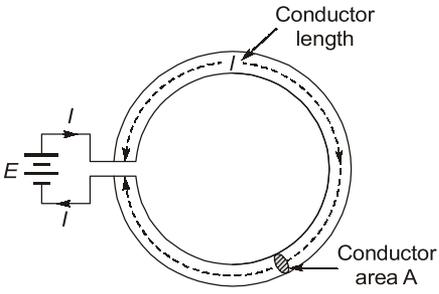
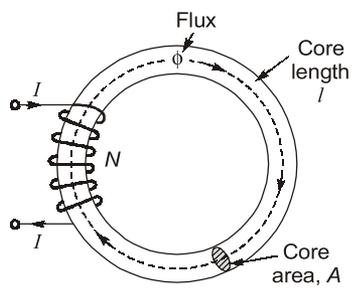
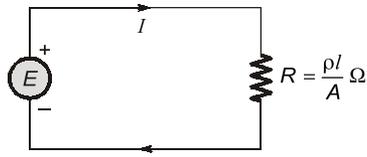
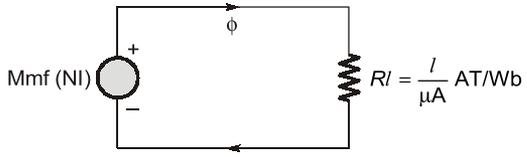
$$B = \frac{\text{Magnetic flux, } \phi}{\text{core area, } A} = \frac{NI \cdot \mu_0 \mu_r}{l} \text{ Wb/m}^2$$

### Magnetic Field Intensity

The magnetomotive force per unit length of magnetic circuit is termed as the magnetic field intensity.

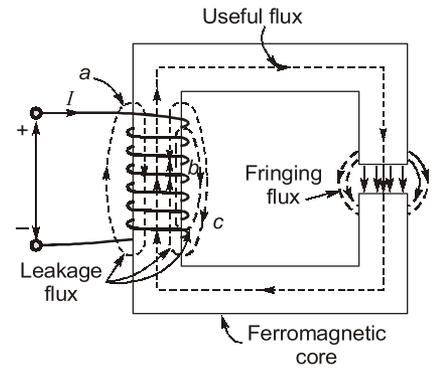
$$H = \frac{\text{MMF}}{\text{mean length of magnetic circuits}} \text{ or } H = \frac{NI}{l} \text{ ATs/m}$$



Comparison between Magnetic and Electric Circuits	
Electrical Circuit	Magnetic Circuit
	
<p>A toroidal copper ring of length <math>l</math>, cross-sectional area <math>A</math> is connected to emf <math>E</math> so that current <math>I</math> flows.</p>	<p>A toroidal iron ring of length <math>l</math>, cross area <math>A</math> is excited by a coil of <math>N</math> turns carrying <math>I</math> amperes so that flux <math>\phi</math> is produced.</p>
<p><b>Similarities:</b></p> <ol style="list-style-type: none"> <li>1. Closed path for electrical current is called an electric circuit.</li> <li>2. Driving force is emf <math>E</math>, volts</li> <li>3. Resistance,  <math display="block">R = \frac{\rho \cdot l}{A} \text{ V/A or } \Omega</math> </li> <li>4. Equivalent circuit,   </li> </ol>	<p><b>Similarities:</b></p> <ol style="list-style-type: none"> <li>1. Closed path for the magnetic flux is called a magnetic circuit.</li> <li>2. Driving force is Mmf = <math>IN</math> ATs</li> <li>3. Reluctance,  <math display="block">Rl = \frac{l}{\mu A} \text{ AT/Wb}</math> </li> <li>4. Equivalent circuit,   </li> </ol>
<ol style="list-style-type: none"> <li>5. Circuit,  <math display="block">I = \frac{\text{Driving force}}{\text{Resistance}} = \frac{E}{R} A</math> </li> <li>6. Current density,  <math display="block">J = \frac{I}{A} \text{ A/m}^2</math> </li> <li>7. Electric field intensity, <math>\epsilon = \frac{E}{l} \text{ V/m}</math>            Also,  <math display="block">\epsilon = \frac{E}{l} = \frac{IR}{l} = \frac{I}{l} \cdot \frac{\rho l}{A} = \rho \cdot \frac{I}{A} = \rho \cdot J \text{ V/m}</math> </li> <li>8. Conductivity of current path, <math>\sigma = 1/\rho</math>            So that,  <math display="block">J = \sigma \cdot \epsilon \text{ A/m}^2</math> </li> </ol>	<ol style="list-style-type: none"> <li>5. Magnetic flux,  <math display="block">\phi = \frac{\text{Driving force}}{\text{Reluctance}} = \frac{\text{Mmf}}{Rl} \text{ Wb}</math> </li> <li>6. Magnetic flux density,  <math display="block">B = \frac{\phi}{A} \text{ T (or Wb/m}^2\text{)}</math> </li> <li>7. Magnetic field intensity, <math>H = \frac{IN}{l} \text{ AT/m}</math>            Also,  <math display="block">H = \frac{IN}{l} = \frac{\text{Mmf}}{l} = \frac{\phi \cdot Rl}{l} = \frac{\phi}{l} \frac{l}{\mu A} = \frac{1}{\mu} \cdot \frac{\phi}{A} = \frac{1}{\mu} \cdot B \text{ AT/m}</math> </li> <li>8. Conductivity of current path, <math>\mu</math>            So that,  <math display="block">B = \mu H \text{ Wb/m}^2 \text{ or T}</math> </li> </ol>
<p><b>Dissimilarities:</b></p> <ol style="list-style-type: none"> <li>1. The electrical current actually flows in an electric circuit. For the existence of this current, energy is drawn from the source continuously. This energy gets dissipated in resistance in the form of heat.</li> <li>2. Electrical insulator confine the current to well defined paths.</li> </ol>	<p><b>Dissimilarities:</b></p> <ol style="list-style-type: none"> <li>1. Strictly speaking, magnetic flux does not flow. Energy is needed for establishing the required flux. Once the requisite flux is created, no more energy is needed in maintaining it.</li> <li>2. There are no magnetic insulators. Even in the best known magnetic insulator air, the flux can be established.</li> </ol>

### Leakage Flux

In Ideal magnetic circuits, all the flux produced by an exciting coil is confined to the desired magnetic path of negligible reluctance. But in practical magnetic circuits, a small amount of flux does follow a path through the surrounding air. Therefore, leakage flux may be defined as that flux which does not follow the intended path in a magnetic circuit. Leakage flux does exist in all practical ferromagnetic device. Its effect on the analysis of electrical machinery is carried out by replacing it by an equivalent leakage reactance.



### Fringing

At an air-gap in a magnetic core, the flux fringes out into neighboring air path as shown in the given. Longer the air gap, more is the flux fringing. The effect of fringing flux is to increase the effective cross-sectional area of the air gap. As a result, flux density in the air gap is not uniform and average flux density gets reduced,

$$\therefore B = \frac{\phi}{A}$$

If area of air gap increase then total area of core with consideration of air gap increases. Then average flux density gets reduced.

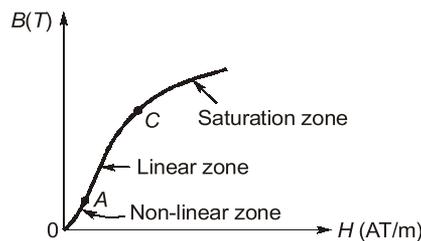


#### Remember

- Longer the air gap, more is the flux fringing.
- The effect of fringing flux is to increase the effective cross-sectional area of the air gap. As a result, flux density in the air gap is not uniform and average flux density gets reduced

### B-H Curve

- A B-H curve, also called **magnetization curve** or **saturation curve**, is the plot of flux density  $B$  as the magnetic field intensity  $H$  is varied.



Typical magnetization curve of a ferromagnetic material

- Figure shows a typical B-H curve of a ferromagnetic material. It has initial non-linear zone OA, zone from A to C is almost linear and zone beyond C is called **saturation zone**.
- The flux density  $B$  in the saturation zone increases less rapidly with  $H$  as compared to its change in the linear zone.
- As B-H curve is not a straight line, relative permeability  $\mu_r = \frac{B}{\mu_0 H}$  of a ferromagnetic material changes with the flux density.
- In free space or non-magnetic materials,  $\mu_0$  is constant, therefore B-H relationship is linear.

**Induced Emf**

Faraday's law of electromagnetic induction states that an e.m.f is induced in a coil when the magnetic flux linking this coil change with time.

$$e \propto \frac{d\Psi}{dt} \propto \frac{d(\phi N)}{dt}$$

$$e = -\frac{Nd\phi}{dt}$$

where,  $e$  = e.m.f. induced in volts  
 $N$  = Number of turns in the coil  
 $\Psi$  =  $N\phi$  = Flux linkages with the coil, wb-turns  
 $t$  = time, seconds.

Here minus (–) sign shows that induced current opposes very cause of its production. This theory is called Lenz's law. According to this law; the induced current develops a flux which always opposes the change responsible for inducing this current.



**Example - 1.4** The laws of electromagnetic induction (Faraday's and Lenz's laws) are summarized in the following equation:

(a)  $e = iR$

(b)  $e = \frac{Ldi}{dt}$

(c)  $e = -\frac{d\Psi}{dt}$

(d) None of these

**Solution: (c)**

**Lenz's Law**

- When the coil circuit is closed, a current begins to flow in the coil. The direction of this induced emf, or induced current, is governed by Lenz's law. According to this law; the induced current develops a flux which always opposes the change responsible for inducing this current.

$$e = -\frac{d\Psi}{dt} = -N\frac{d\phi}{dt}$$

- Lenz's law, in short, is effect opposes the cause.



**Example - 1.5** "In all cases of electromagnetic induction, an induced voltage will cause a current to flow in a closed circuit in such a direction that the magnetic field which is caused by the current will oppose the change that produces the current" is the original statements of

(a) Lenz's law

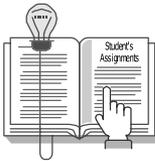
(b) Faraday's law of magnetic induction

(c) Fleming's law

(d) Ampere's law

**Solution: (a)**



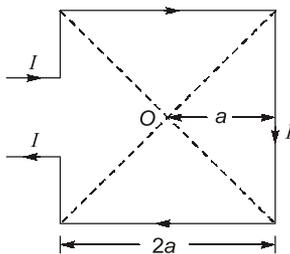


## Student's Assignments

- A mild steel ring with mean diameter of 20 cm has core area of  $10 \text{ cm}^2$ . For a relative permeability of 500, the reluctance of the ring in  $\text{AT/Wb}$  is
  - $1 \times 10^6$
  - $0.1 \times 10^6$
  - $0.01 \times 10^5$
  - $10 \times 10^6$
- The magnetic flux in a homogeneous toroidal core excited by a coil with a given number of turns carrying a fixed current is
  - proportional to cross-sectional area of the toroid.
  - proportional to the diameter of the toroid.
  - inversely proportional to cross-sectional area of the toroid.
  - inversely proportional to diameter of the toroid.

From these, the correct answer is

  - 1 and 3
  - 2 and 3
  - 1 and 4
  - 2 and 4
- Magnetizing force at the centre of a square, each arm of  $2a \text{ m}$  length shown below is given as \_\_\_\_\_.



- $\left[ \left( \frac{\sqrt{2}I}{\pi a} \right) \right] \text{ A/m}$
- $\frac{I}{\pi a} \text{ A/m}$
- $\frac{\pi a}{I} \text{ A/m}$
- $\left[ \left( \frac{\sqrt{2} \pi I}{a^2} \right) \right] \text{ A/m}$

- A circular metallic disc is placed in a vertical magnetic field of constant induction in the downward direction. If the disc is rotated in a horizontal plane, the mmf induced will be \_\_\_\_\_.

- zero
- constant and independent of disc size
- increasing radially in the outward direction
- decreasing radially in the outward direction



STUDENT'S  
ASSIGNMENTS

## ANSWER KEY

1. (a)      2. (c)      3. (a)      4. (c)



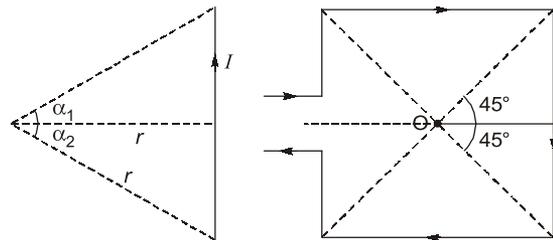
STUDENT'S  
ASSIGNMENTS

## EXPLANATIONS

**3. (a)**

Magnetic field due to a finite length wire,

$$B = \frac{\mu_0}{4\pi} \times \frac{I}{a} (\sin \alpha_1 + \sin \alpha_2)$$



Magnetic field at centre,

$$\begin{aligned} &= 4 \times \frac{\mu_0}{4\pi} \times \frac{I}{a} (\sin 45^\circ + \sin 45^\circ) \\ &= \frac{\mu_0}{4\pi} \times \frac{I}{a} \left( \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}} \right) \\ B &= \frac{\mu_0}{\pi} \times \frac{\sqrt{2} I}{a} \end{aligned}$$

Magnetising force,

$$H = \frac{B}{\mu_0} = \frac{\sqrt{2} I}{\pi a}$$

**4. (c)**

Induced emf in a rotating disc,

$$e = \frac{1}{2} B \omega r^2$$

$r \rightarrow$  Distance from centre, radially out ward.

So, as  $r$  increases 'e' increases.



## 2.1 Introduction

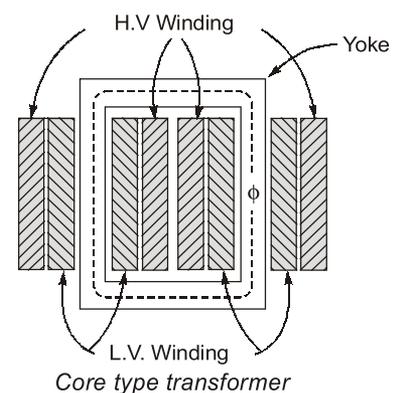
- The transformer is a static device for transferring electrical energy from one alternating current circuit to another without a change in frequency. A transformer may receive energy at one voltage and deliver it at a higher voltage, in which case it is called a step-up transformer. When the energy is received at a higher voltage and delivered at a lower voltage, it is called a step-down transformer.
- The transformer is an electro-magnetic energy conversion device.
- In transformer the energy received by the primary is first converted to magnetic energy and it is reconverted to useful electrical energy in the other circuit (secondary winding, third winding circuit etc.).
- The primary and secondary windings of a transformer are not connected electrically, but are coupled magnetically.

## 2.2 Transformer Construction

There are two general types of transformers, the core type and the shell type, differ from each other by the manner in which the windings are wound around the magnetic cores.

### Core Type Transformer

- The windings surround a considerable part of steel core.
- For a given output and voltage rating, it requires less iron but more conductor material.
- Most of the flux is confined to high permeability core but some leakage flux flows through the core legs and non-magnetic material surrounding the core. For avoiding it, half of the low voltage (L.V.) winding is placed over one leg and other half over the second leg or limb. Similarly for high voltage.
- L.V. windings are placed adjacent to steel core and H.V. winding outside, in order to minimize the amount of insulation required.
- It performs better for high voltage, high power levels.



### Shell Type Transformer

In this type of transformer the L.V. and H.V. windings are wound over the central limb and are inter leaved or sandwiched. It performs better for low-voltage, low power levels, whereas core type construction is used for high voltage, high power transformers.