RRB-JE 2024

Railway Recruitment Board

Junior Engineer Examination

Electrical Engineering

Electrical Machines

(Volume - 1)

(Transformer, Induction Machine and Special Machines)

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

MADE EASY PUBLICATIONS

Electrical Machines

Contents

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.

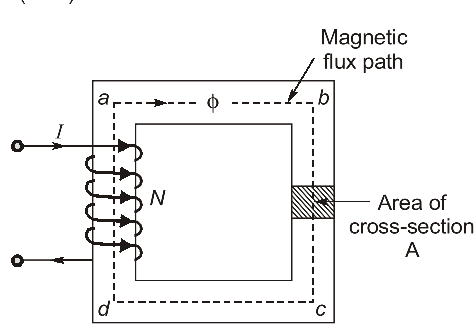
1.2 Important Terms Related to Magnetic Circuit

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.

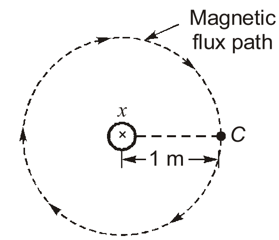
Mmf = Current × Number of turns in the coil

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 μ_0 is given by

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

Reluctance (Rl)

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

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

where, l = length of the magnetic path
A = area of cross-section normal to flux path, m^2
μ = $\mu_0 \cdot \mu_r$ = permeability of the magnetic material
μ_r = relative permeability of the magnetic material
μ_0 = permeability of free space = $4\pi \times 10^{-7}$ H/m.

Magnetic Flux (ϕ)

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

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

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.

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

NOTE

- In magnetic system there are no magnetic insulators. Even in the best known magnetic insulator air, the flux can be established.
- Energy is needed for establishing the required flux once the requisite flux is created then no more energy is needed in maintaining it.

Example - 1.1 What will be the produced mmf (in Amp-turns) in a coil, if the coil has 160 turns and carries a current of 0.15 A?

(a) 32 (b) 24
(c) 16 (d) 8

Solution: (b)

MMF (Ampere turns) = $N \times I$

Given,
$$N = 160 \text{ turns}$$
$$I = 0.15 \text{ A}$$
$$\text{MMF} = 160 \times 0.15 = 24 \text{ A-turns}$$

Example - 1.2 Determine the reluctance (in Amp-turns/Wb) of a coil, when the flux through the coil is 25 Wb and the value of produced mmf is 50 Amp-turns.

(a) 2 (b) 4
(c) 6 (d) 8

Solution: (a)

$$\text{MMF} = \text{Flux} \times \text{Reluctance}$$
$$\text{Reluctance} = \frac{\text{MMF}}{\text{Flux}}$$

Given,
$$\text{MMF} = 50 \text{ A-turns}$$
$$\text{Flux} = 25 \text{ Wb}$$
$$\text{Reluctance} = \frac{50}{25} = 2 \text{ A-turns/Wb}$$

Example - 1.3 Determine the magnetic field intensity (in Amp- turns/m) of 5 metre long coil when the coil has 100 turns and carries a current of 0.6 A.

(a) 15 (b) 12
(c) 10 (d) 8

Solution: (b)

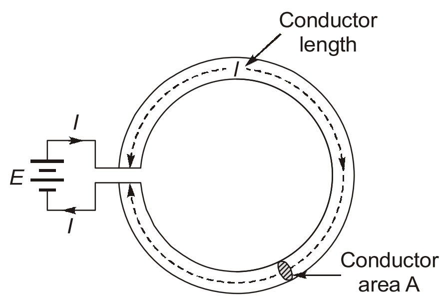
$$\text{Magnetic field intensity} = \frac{NI}{L}\left(\frac{\text{Amp-turns}}{\text{m}}\right)$$
$$N = \text{Number of turns}$$
$$I = \text{Current in ampers}$$
$$L = \text{Length in meters}$$

Hence, substituting given data

$$B = \frac{100 \times 0.6}{5} = 12 \text{ A-turns/m}$$

Comparison between Magnetic and Electric Circuits

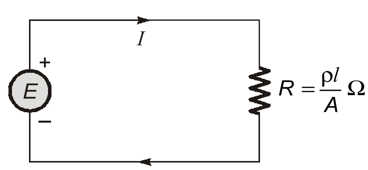
Electrical Circuit



A torodial copper ring of length l, cross-sectional area A is connected to emf E so that current I flows.

Similarities:

1. Closed path for electrical current is called an electric circuit.
2. Driving force is emf E, volts
3. Resistance,
$$R = \frac{\rho \cdot l}{A} \text{ V/A or } \Omega$$
4. Equivalent circuit,

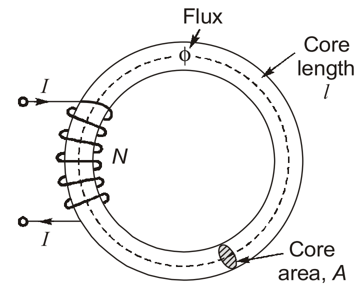


5. Circuit, $$I = \frac{\text{Driving force}}{\text{Resistance}} = \frac{E}{R} A$$
6. Current density,
$$J = \frac{I}{A} \text{ A/m}^2$$
7. Electric field intensity, $\varepsilon = \dfrac{E}{l}$ V/m
Also,
$$\varepsilon = \frac{E}{l} = \frac{IR}{l} = \frac{I}{l} \cdot \frac{\rho l}{A} = \rho \cdot \frac{I}{A} = \rho \cdot J \text{ V/m}$$
8. Conductivity of current path, $\sigma = 1/\rho$
So that, $J = \sigma \cdot \varepsilon$ A/m^2

Dissimilarities:

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.
2. Electrical insulator confine the current to well defined paths.

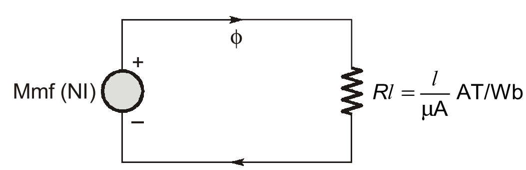
Magnetic Circuit



A torodial iron ring of length l, cross area A is excited by a coil of N turns carrying I amperes so that flux ϕ is produced.

Similarities:

1. Closed path for the magnetic flux is called a magnetic circuit.
2. Driving force is Mmf = IN ATs
3. Reluctance,
$$Rl = \frac{l}{\mu A} \text{ AT/Wb}$$
4. Equivalent circuit,

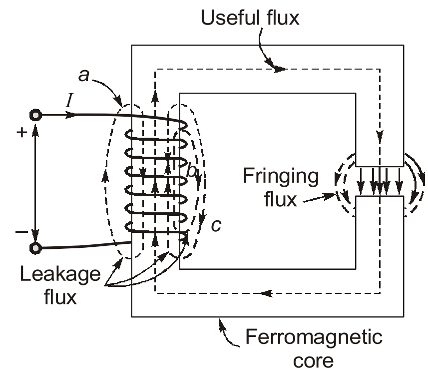


5. Magnetic flux, $$\phi = \frac{\text{Driving force}}{\text{Reluctance}} = \frac{\text{Mmf}}{Rl} \text{Wb}$$
6. Magnetic flux density,
$$B = \frac{\phi}{A} \text{ T (or Wb/m}^2\text{)}$$
7. Magnetic field intensity, $H = \dfrac{\text{IN}}{l}$ AT/m
Also,
$$H = \frac{\text{IN}}{l} = \frac{\text{Mmf}}{l} = \frac{\phi \cdot Rl}{l} = \frac{\phi}{l} \cdot \frac{l}{\mu A} = \frac{1}{\mu} \cdot \frac{\phi}{A} = \frac{1}{\mu} \cdot B \text{ AT/m}$$
8. Conductivity of current path, μ
So that, $B = \mu H$ Wb/m^2 or T

Dissimilarities:

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.
2. There are no magnetic insulators. Even in the best known magnetic insulator air, the flux can be established.

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,

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

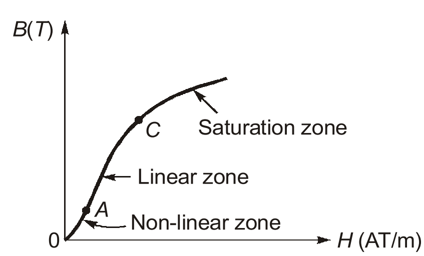
If area of air gap increases then total area of core with consideration of air gap increases. Then average flux density gets reduced.

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 $\mu_r = \dfrac{B}{\mu_0 H}$ of a ferromagnetic material changes with the flux density.
- In free space or non-magnetic materials, μ_0 is constant, therefore B-H relationship is linear.

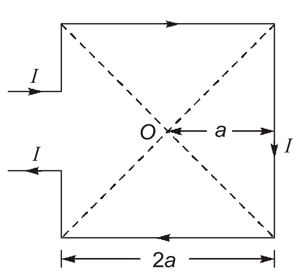
Student's Assignments

1. A mild steel ring with mean diameter of 20 cm has core area of 10 cm^2. For a relative permeability of 500, the reluctance of the ring in AT/Wb is
(a) 1×10^6 (b) 0.1×10^6
(c) 0.01×10^5 (d) 10×10^6

2. The magnetic flux in a homogeneous toroidal core excited by a coil with a given number of turns carrying a fixed current is
1. proportional to cross-sectional area of the toroid.
2. proportional to the diameter of the toroid.
3. inversely proportional to cross-sectional area of the toroid.
4. inversely proportional to diameter of the toroid.

From these, the correct answer is
(a) 1 and 3 (b) 2 and 3
(c) 1 and 4 (d) 2 and 4

3. Magnetizing force at the centre of a square, each arm of $2a$ m length shown below is given as ______.



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

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

4. 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 ______.
(a) zero
(b) constant and independent of disc size
(c) increasing radially in the outward direction
(d) decreasing radially in the outward direction

STUDENT'S ASSIGNMENTS ANSWER KEY

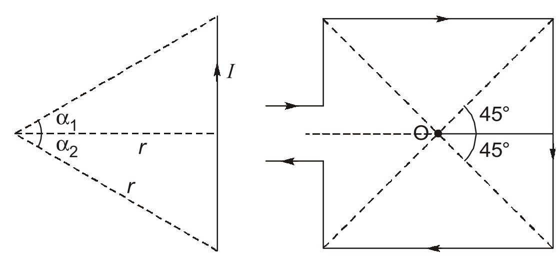
1. (a) **2.** (c) **3.** (a) **4.** (c)

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,

$$= 4 \times \frac{\mu_0}{4\pi} \times \frac{I}{a}(\sin 45° + \sin 45°)$$

$$= \frac{\mu_0}{4\pi} \times \frac{I}{a}\left(\frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\right)$$

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

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, an r increases 'e' increases.