110+ Video Solutions With QR Codes

GATE•ESE•PSUs•SSC-JE•AE

ELECTRICAL MACHINES

Volume-I

Transformers & DC Machine

Electrical Engineering | Electrical & Electronics Engineering

Highlights :

- Concise in-depth explanations of all course concepts
- 450+ practice problems with step-by–step solution
- Video solution with QR Code for explicit question to enhance problem solving skills
- Self-assessment test after each topic
- Concept building MCQs and NATQs at the end of each chapter
- Value addition for ESE/PSUs/DRDO/SAIL/ISRO & other competitive exams

GATE Since 2004
GATE ACADEMY®
steps to success...

Electrical Machines

(Volume - I)

- Transformers
- DC Machines

Electrical Engineering (EE)

Electronics & Electrical Engineering (EEE)

Umesh Dhande

GATE ACADEMY®

steps to success...

Electrical Machines

Volume - I

Electrical Engineering (EE)

Electrical & Electronics Engineering (EEE)

Cover Design : Gajendra Banjare

Type & Formatting : Vikas Deshmukh

Book Code : GATE-EM-787-1

First Edition : January 2021

ISBN : 978-93-86699-78-7

GATE ACADEMY Learning Pvt. Ltd.

A 115, Ground Floor, Shopping Complex, Smriti Nagar, Bhilai - 490 020 (C.G.)

Phone : 0788 - 4034176

Help Desk No. - +91-97131-13156

For Feedback & Suggestions...

gatebook@gateacademy.co.in

Price : ₹ 999/-

GATE SYLLABUS

Single phase transformer: equivalent circuit, phasor diagram, open circuit and short circuit tests, regulation and efficiency; Three-phase transformers: connections, vector groups, parallel operation; Auto-transformer, Electromechanical energy conversion principles; DC machines: separately excited, series and shunt, motoring and generating mode of operation and their characteristics, speed control of dc motors; Three-phase induction machines: principle of operation, types, performance, torque-speed characteristics, no-load and blocked-rotor tests, equivalent circuit, starting and speed control; Operating principle of single-phase induction motors; Synchronous machines: cylindrical and salient pole machines, performance and characteristics, regulation and parallel operation of generators, starting of synchronous motors; Types of losses and efficiency calculations of electric machines

ESE SYLLABUS

Single phase transformers, three phase transformers - connections, parallel operation, auto-transformer, energy conversion principles, DC machines - types, windings, generator characteristics, armature reaction and commutation, starting and speed control of motors, Induction motors - principles, types, performance characteristics, starting and speed control, Synchronous machines - performance, regulation, parallel operation of generators, motor starting, characteristics and applications, servo and stepper motors.

SSC-JE/AE SYLLABUS

D.C. Machine (Weightage : 4-6 Marks) : Construction, Basic Principles of D.C. motors and generators, their characteristics, speed control and starting of D.C. Motors. Method of braking motor, Losses and efficiency of D.C. Machines.

1 phase and 3 phase transformers (Weightage: 6-8 Marks) : Construction, Principles of operation, equivalent circuit, voltage regulation, O.C. and S.C. Tests, Losses and efficiency. Effect of voltage, frequency and wave form on losses. Parallel operation of 1 phase /3 phase transformers. Auto transformers.

Single Phase Induction Motors (Weightage: 4-6 Marks) : Characteristics and applications.

3 phase Induction Motors (Weightage: 4-6 Marks) : Rotating magnetic field, the principle of operation, equivalent circuit. Torque-speed characteristics, starting and speed control of 3 phase induction motors. Methods of braking, the effect of voltage and frequency variation on torque speed characteristics. Fractional Kilowatt Motors.

Synchronous Machines (Weightage: 4-6 Marks) : Generation of 3-phase e.m.f. armature reaction, voltage regulation. Parallel operation of two alternators, synchronizing, control of active and reactive power. Starting and applications of synchronous motors.

CONTENTS

GATE 2021(EE) RESULT UNDER 1000


EE-20
Krishna Meerendra


EE-26
Deepak Kumar


EE-27
Nilay Srivastava


EE-46
Ajay Kumar Gupta


EE-46
Ramraja Patel


EE-46
Rahul Chauhan


EE-53
Pritam Saurav

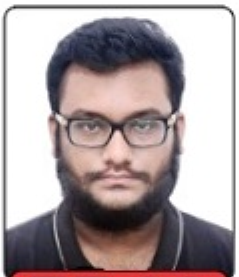

EE-53
Arihant Jain


EE-53
B Anurag


EE-70
Lokesh Garg


EE-86
Divakar Chaudhary


EE-86
Tushar Chaudhary


EE-93
Ashutosh Singh


EE-108
Sanket Tekawade


EE-127
Subham Dutta


EE-137
Mona Kumari

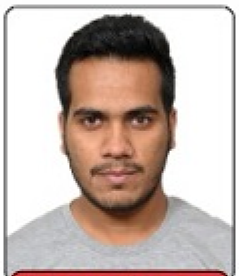

EE-146
Divyansh Trivedi


EE-146
Abantika Sengupta


EE-170
Hritik Jaiswal


EE-170
Aman Kumar

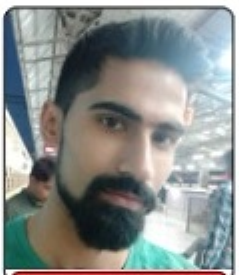

EE-170
Wasim Ahmed


EE-170
Nikhit Yerne

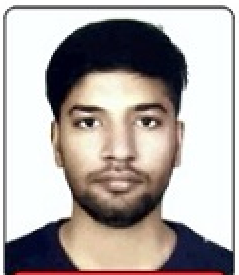

EE-184
Anant Kumar


EE-194
Anagha Paul


EE-194
Ashwin Kumar


EE-204
Ashish Jhamnani


EE-217
Nimesh Nahar


EE-229
Shagun Garg


EE-259
Manikarna Indurthy


EE-268
K Srikanth

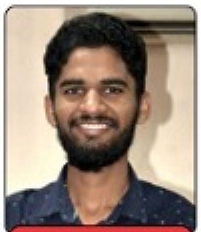
GATE 2021(EE) RESULT UNDER 1000


EE-281
Mantavya Goyal


EE-300
Simranpreet Singh


EE-308
Kailash Goyal

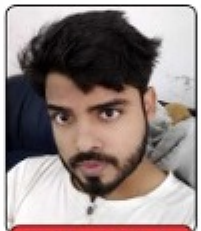

EE-321
Naresh Bajiya


EE-321
Mahesh Patil


EE-364
Himanshu Agrawal


EE-396
Subhadeep Roy


EE-396
Deepankar Tiwari


EE-400
Surakshit Kumar


EE-416
Himank Aggarwal


EE-438
Manoj Kumar Singh


EE-438
Shubham Singh

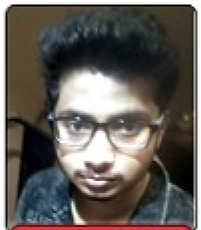

EE-484
Rishabh Gupta


EE-484
Aindri Shree

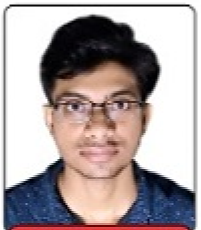

EE-530
Shreyash Shrivastava


EE-569
Dushyant Gupta


EE-569
Aakash Gosavi


EE-595
Jitendra Sahu


EE-595
Prathmesh Bhunje

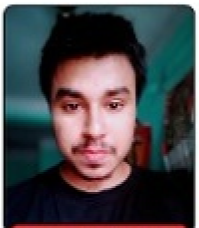

EE-630
Sreejit Mahanta


EE-682
Deepak Sharma

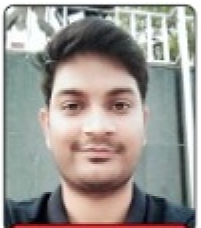

EE-682
Lakshya Malav


EE-719
Aman Kumar


EE-747
Sagnik Nandi

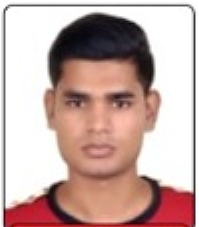

EE-747
Raghuvar Jee Jha


EE-747
Prakash Verma


EE-775
Nishant Srivastava


EE-780
Nikhil Singh


EE-808
Ganesh Kumar


EE-842
Shubham Verma


EE-842
Bhawesh Chandrakar


EE-881
M Prabal Reddy


EE-881
Arunit Raj


EE-881
Piyush Yadav


EE-881
Sagar Gupta


EE-958
Nihal Neekra


EE-958
Abhishek Verma

CHAPTER 1

Basics of Magnetic Circuits

Learning Objectives :

After reading this chapter you should be able to :

- Understand : Basic of magnetic circuit
- Explain leakage flux and fringing
- Explain law of electromagnetism
- Describe coefficient of coupling
- Explain energy stored in magnetic field
- Understand dot convention

Table of Contents

1.1 Magnetic Circuit

Definition : The closed path followed by magnetic lines of forces is called the magnetic circuit. In the magnetic circuit**,** magnetic flux or magnetic lines of force starts from a point and ends at the same point after completing its path.

A magnetic circuit is made up of magnetic materials having high permeability such as iron, soft steel, etc.

Magnetic circuits are used in various devices like electric motor, transformers, relays, generators, galvanometer, etc.

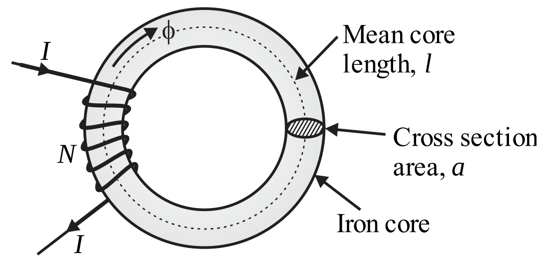


Figure shows a Solenoid having N turns wound on an iron core. The magnetic flux of ϕ Weber sets up in the core when the current of I ampere is passed through a solenoid. The length of the magnetic path is given by the mean circumference is of the toroid.

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

1.1.1 Magnetic Flux (ϕ)

The number of magnetic lines of forces set up in a magnetic circuit is called **Magnetic Flux**. It is analogous to electric current, I in an electric circuit. Its SI unit is Weber (Wb) and its CGS unit is Maxwell. It is denoted by ϕ. The magnetic flux measures through flux meter.

$$1\,(\text{Wb}) = 10^8 \text{ lines of forces/Maxwell}$$

It is analogous to electric current in an electric circuit.

Properties of magnetic flux :

1. They always form a closed loop.
2. They always start from the north pole and ends in the south pole.
3. They never intersect each other.
4. Magnetic lines of forces that are parallel to each other and are in the same direction repel each other.

1.1.2 Magnetic Flux Density (B)

The magnetic flux density at a point is the flux per unit area at right angles to the flux at that point. SI unit of flux density is Wb/m^2 and CGS unit is tesla (T).

Flux density, $B = \dfrac{\phi}{a}$

1.1.3 Permeability (μ)

The permeability is defined as the ability or ease with which the magnetic material forces the magnetic flux through a given medium.

The flow of flux produced by the magnet not only depends on the magnetic field strength but also on one important property of the magnetic material called permeability. It is related to the medium in which magnet is placed. The force exerted by one magnetic pole on other depends on the medium in which magnets are placed. It is denoted by the symbol μ.

Permeability, $\mu = \mu_0 \mu_r$

where, μ_0 = Permeability of air/vacuum $= 4\pi \times 10^{-7}$, $\mu_r = 1$ (in case of air/vacuum).

1.1.4 Magnetic Intensity or Magnetizing Force (*H*) or Magnetic Field Strength (*H*)

The magnetic intensity at a point in the magnetic field is the force acting on a unit N-pole (1 weber) placed at that point.

Magnetic intensity, $H = \dfrac{B}{\mu} = \dfrac{B}{\mu_0 \mu_r}$

and by Amperes law, $Hl = NI$

1.1.5 Reluctance (*S*)

The obstruction offered by a magnetic circuit to the magnetic flux is known as reluctance**.** As in electric circuit, there is resistance similarly in the magnetic circuit, there is a reluctance, but resistance in an electrical circuit dissipates the electric energy and the reluctance in magnetic circuit stores the magnetic energy.

Its SI unit is **AT / Wb (ampere-turns / Weber).** The reluctance of the magnetic circuit is directly proportional to the length of the conductor and inversely proportional to the cross-section area of the conductor.

Reluctance, $S = \dfrac{l}{a\mu} = \dfrac{l}{a(\mu_0 \mu_r)}$

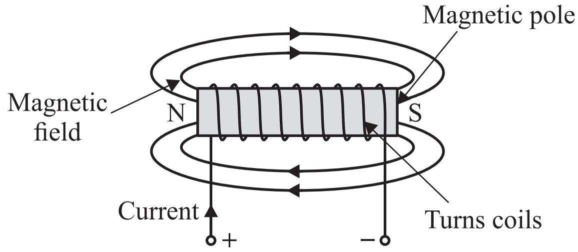
where, l = length in metres, a = Area of cross section in m^2.

The reciprocal of the magnetic reluctance is known as the magnetic permeance**.** It is given by the expression

Permeance, $P = \dfrac{1}{\text{Reluctance}} = \dfrac{1}{S}$

1.1.6 Magnetic Motive Force (MMF)

The current flowing in an electric circuit is due to the existence of electromotive force similarly, Magneto Motive Force (MMF) is required to drive the magnetic flux in the magnetic circuit. The magnetic pressure, which sets up the magnetic flux in a magnetic circuit is called Magneto Motive Force. The SI unit of MMF is Ampere-turn (AT), and their CGS unit is *G* (gilbert). The MMF for the inductive coil shown in the figure below is expressed as,



The strength of the MMF is equivalent to the product of the current around the turns and the number of turns of the coil.

$\therefore$ Force, $F = NI$ where, N = Numbers of turns of the inductive coil and I = Current.

Or magneto motive force, $\text{MMF} = \phi S = N I = H l$ = ampere-turns (or AT)

where, ϕ is the magnetic flux and S is the reluctance of the magnetic circuit,

N = Number of turns of coil, I = Electric current through circuit,

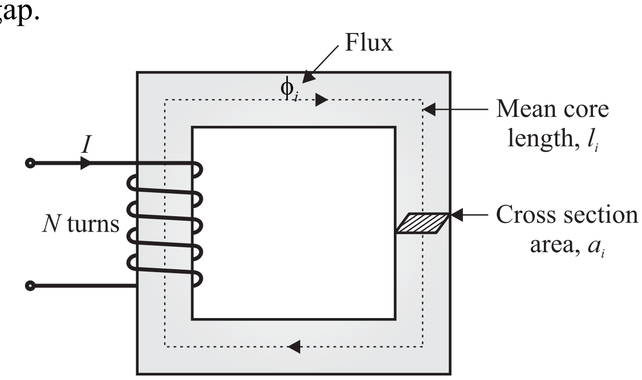
H = Magnetic force or Magnetizing strength, l = Mean length of solenoid.

1.2 Series Magnetic Circuit

Definition : The **Series Magnetic Circuit** is defined as the magnetic circuit having a number of parts of different dimensions and materials carrying the same magnetic field. Consider different cases of a solenoid having different dimensions as shown in the figure below,

Case 1 : Series magnetic circuit without air gap.

Let-us consider a magnetic circuit without air gap shown in the figure below,



1. **Flux :** $\phi_i = B_i \times a_i$

   where, B_i = Flux density in iron core, a_i = Cross sectional area of iron core

2. **Flux density :**

$$B_i = \frac{\phi_i}{a_i} = \mu_i H_i$$

   where, H_i = Magnetic field intensity of iron core, μ_i = Permittivity of iron core

3. **Reluctance :**

$$S_i = \frac{l_i}{a_i \mu_i} = \frac{l_i}{a_i \mu_0 \mu_r}$$

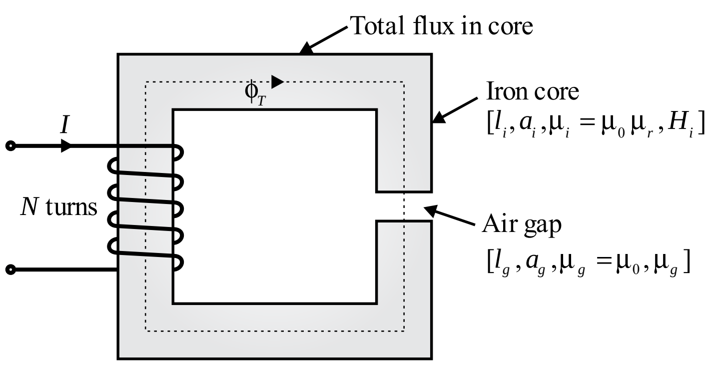
   where, l_i = Mean core length.

4. **Magnetic motive force (MMF) :**

$$\text{MMF} = \phi_i S_i = N I = H_i l_i$$

Case 2 : Series magnetic circuit with air gap.

Let-us consider a magnetic circuit with air gap shown in the figure below,



1. **Flux :**

   Flux in iron core, $\phi_i = B_i \times a_i$

   Flux in air gap, $\phi_g = B_g \times a_g$

   Total flux, $\phi_T = \phi_i + \phi_g$

2. **Flux density :**

   Flux density in iron core,

$$B_i = \frac{\phi_i}{a_i} = \mu_i H_i$$

   Flux density in air gap, $B_g = \dfrac{\phi_g}{a_g} = \mu_g H_g$

   Total flux density, $B_T = B_i + B_g$

3. Reluctance :

Reluctance in iron core, $S_i = \dfrac{l_i}{a_i \mu_i} = \dfrac{l_i}{a_i \mu_0 \mu_r}$

Reluctance in air gap, $S_g = \dfrac{l_g}{a_g \mu_g} = \dfrac{l_g}{a_g \mu_0}$ [$\mu_r = 1$ for air gap]

Total reluctance, $S_T = S_i + S_g$

4. Magnetic motive force (MMF) :

$$\text{MMF} = N\,I = H_i\,l_i + H_g\,l_g$$

Solved Example 1

An iron ring of mean circumference equal to 80 cm is uniformly wound with 500 turns of a wire. When a current of 1 A is passed through the coil, a flux density of 1.1 T is produced in the iron. Calculate the relative permeability of the iron core under this condition.

Sol. **Given :** Mean length of iron ring $l_i = 80\,\text{cm}$, Number of turns $N = 500$,

Current $I = 1$ A, Flux density $B = 1.1$ T.

Total MMF, $NI = H_i l_i = \dfrac{B_i}{\mu_0 \mu_r} l_i$ $\left[H_i = \dfrac{B_i}{\mu_0 \mu_r} \right]$

$$\mu_r = \frac{B_i l_i}{\mu_0 NI} = \frac{1.1 \times 80 \times 10^{-2}}{4\pi \times 10^{-7} \times 500 \times 1} = \mathbf{1400.56}$$ **Ans.**

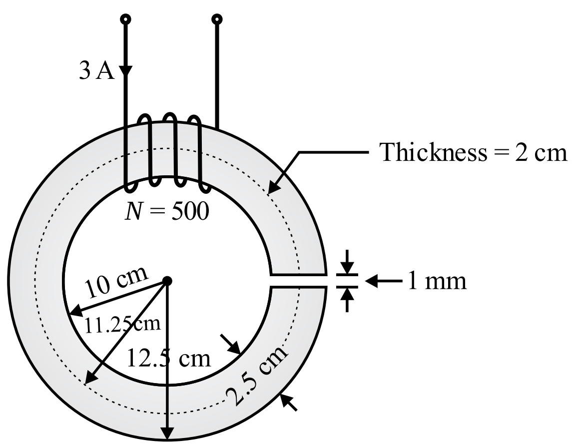
Solved Example 2

A ring of magnetic material has a rectangular cross-section. The inner diameter of the ring is 20 cm and the outer diameter is 25 cm, its thickness being 2 cm. An air-gap of 1 mm length is cut across the ring. The ring is wound with 500 turns and when carrying a current of 3 A produces a flux density of 1.2 T in the air-gap. Find :

(i) Magnetic field intensity in the magnetic material and in the air-gap.

(ii) Relative permeability of the magnetic material and

(iii) Total reluctance of the magnetic circuit and component values.



Sol. **Given :** Inner diameter of ring $= 20\,\text{cm}$, $\therefore\ R_1 = \frac{20}{2} = 10\,\text{cm}$,

Outer diameter of ring $= 25\,\text{cm}$, $\therefore\ R_2 = \frac{25}{2} = 12.5\,\text{cm}$,

Air gap length $l_g = 1\,\text{mm} = 1\times10^{-3}\,\text{m}$, Number of turns $N = 500$,

Current $i = 3\,\text{A}$, Flux density $B = 1.2\,\text{T}$

Mean radius of core, $x = \frac{R_1 + R_2}{2} = \frac{10+12.5}{2} = 11.25\,\text{cm}$

Mean circumference, $l_i = 2\pi x = 2\times\pi\times11.25 = 70.68\,\text{cm}$

Equivalent radius of core, $r = \frac{R_2 - R_1}{2} = \frac{12.5-10}{2} = 1.25\,\text{cm}$

Cross section area of core, $a = \pi r^2 = \pi\times(1.25)^2 = 4.9087\,\text{cm}^2 = 4.9087\times10^{-4}\,\text{m}^2$

(i) Magnetic field intensity in air-gap,

$$H_g = \frac{B}{\mu_0\mu_r} = \frac{1.2}{4\pi\times10^{-7}} = \mathbf{9.549\times10^5\ AT/m}$$ **Ans.**

Total mmf, $Ni = H_g l_g + H_i l_i$

$$500\times3 = 9.549\times10^5\times1\times10^{-3} + H_i\times70.68\times10^{-2}$$

Magnetic field intensity of magnetic material,

$$H_i = \frac{1500-954.9}{70.68\times10^{-2}} = \mathbf{771.22\ AT/m}$$ **Ans.**

(ii) Magnetic field intensity of magnetic material,

$$H_i = \frac{B}{\mu_0\mu_r}$$

$$771.22 = \frac{1.2}{4\pi\times10^{-7}\times\mu_r}$$

Relative permeability, $\mu_r = \frac{1.2}{4\pi\times10^{-7}\times771.22} = \mathbf{1238.20}$ **Ans.**

(iii)Total reluctance, $S_T = S_i + S_g$

Reluctance of iron core, $S_i = \frac{l_i}{\mu_0\mu_r a_i}$

$$S_i = \frac{70.68\times10^{-2}}{4\pi\times10^{-7}\times1238.20\times4.9087\times10^{-4}} = 925531.75\ \text{AT/Wb}$$

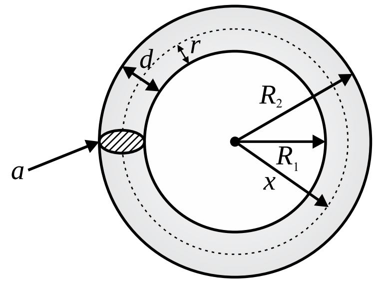
Reluctance of air gap, $S_g = \frac{l_g}{\mu_0 a_i} = \frac{1\times10^{-3}}{4\pi\times10^{-7}\times4.9087\times10^{-4}} = 1621151.66\ \text{AT/Wb}$

Total reluctance, $S_T = S_i + S_g = 925531.75 + 1621151.66 = \mathbf{2.5\times10^6\ AT/Wb}$ **Ans.**

Remember

Assuming inner radius of a conductor is R_1 and outer radius R_2 as shown in figure. Then

- Mean Radius of core, $x = \dfrac{R_1 + R_2}{2}$
- Mean Circumference of core, $l = 2\pi x$
- Equivalent Radius of core, $r = \dfrac{R_1 - R_2}{2}$
- Equivalent Diameter, $d = 2r$
- Cross sectional area, $a = \pi r^2$



TEST 1

Q.1 A ring having a cross-sectional area of 500 cm^2, a circumference of 400 cm and ϕ = 80 mWb has a coil of 200 turns wound around it. Calculate the flux density of the ring.

(A) 1.6 T (B) 2.6 T
(C) 3.6 T (D) 4.6 T

Q.2 A long straight conductor carries steady current of 20 A. The intensity of magnetic field produced at a point 300 mm from the axis of the conductor is ______ and Flux density of field at that point is ______.

Q.3 A solenoid of 300 turns is wound on a continuous ring of magnetic material of relative permeability 1000. Mean diameter of the solenoid is 100 mm. If the flux density in the magnetic material of the core in the solenoid is 1.3 T, the current in the solenoid is ______.

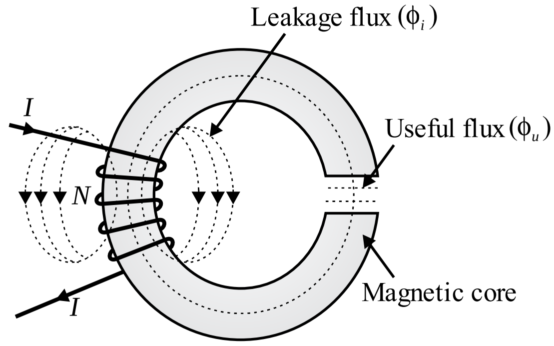
Q.4 An iron ring of mean length 60 cm has an air gap of 2 mm. It is wound with 300 turns of wire. If the relative permeability of iron is 300 when a current of 0.7 A flows through the coil, the flux density is ______.

1.4 Leakage Flux

Definition : Leakage flux is defined as the magnetic flux which does not follow the particularly intended path in a magnetic circuit.

Most of the flux is set up in the core of the solenoid and passes through the particular path that is through the air gap and is utilised in the magnetic circuit. This flux is known as useful flux ϕ_u

As practically it is not possible that all the flux in the circuit follows a particularly intended path and sets up in the magnetic core and thus some of the flux also sets up around the coil or surrounds the core of the coil, and is not utilised for any work in the magnetic circuit as shown in figure. This type of flux which is not used for any work is called Leakage flux and is denoted by ϕ_l



Therefore, the total flux ϕ produced by the solenoid in the magnetic circuit is the sum of the leakage flux and the useful flux and is given by the equation shown below,

$$\phi = \phi_u + \phi_l$$

The ratio of the total flux produced to the useful flux set up in the air gap of the magnetic circuit is called a leakage coefficient or leakage factor. It is denoted by (λ).

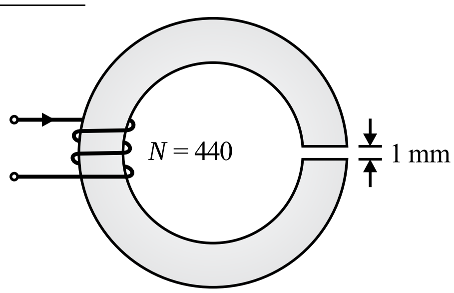
$$\lambda = \frac{\phi}{\phi_u}$$

Leakage flux does exist in all practical ferromagnetic device.
On analysis of electrical machine leakage flux is replaced by an equivalent leakage reactance.

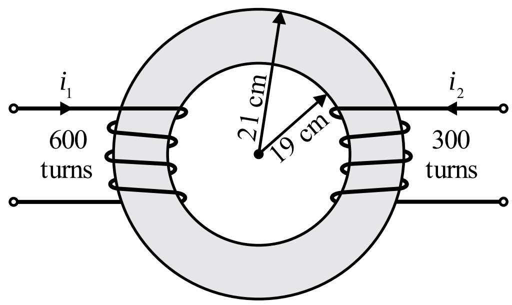
Numerical Answer Type Questions

Q.1 A flux density of $1.2\ \text{Wb/m}^2$ is required in the 2 mm air gap of an electromagnet having an iron path of 1 m long. If the electromagnet has 1273 turns and relative permeability of iron to be 1500, the total current required is _______.

Q.2 An iron ring with a mean length of magnetic path of 20 cm and of small cross- section has an air gap of 1 mm. It is wound uniformly with a coil of 440 turns. A current of 1 A in the coil produces a flux density $16\pi\times10^{-3}$ Wb/m^2. Neglecting leakage and fringing, the relative permeability of iron is _______.



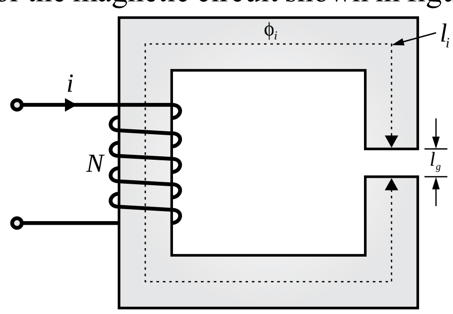
Q.3 Two coils are wound on a toroidal core as shown in figure.



The core is made of silicon sheet steel and has a square cross section. The coil currents are, i_1 = 0.28 A and i_2 = 0.56 A. The magnetic field intensity H in AT/m is _______.

Q.4 An iron ring of mean length 50 cm has an air gap of 1 mm and a winding of 200 turns. If the permeability of the iron is 300 when a current of 1 A flows through the coil, the flux density is _______.

Q.5 For the magnetic circuit shown in figure,



$N = 400$ turns, mean core length $l_i = 50$ cm, air gap length $l_g = 1$ mm, cross sectional area $a_i = a_g = 15\,\text{cm}^2$, relative permeability of core, $\mu_r = 3000$, current $i = 1$ A. Find :

(i) Flux and flux density in the air gap

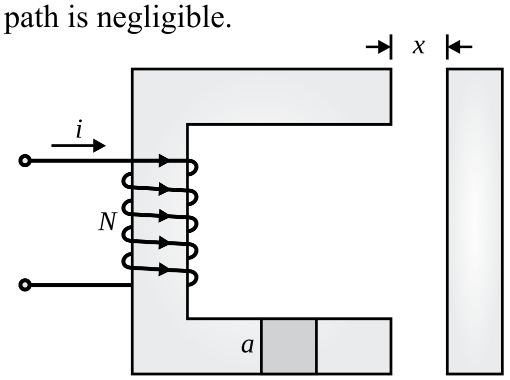
(ii) Inductance of the coil

Multiple Choice Questions

Q.1 A magnetic circuit has 150 turns-coil, the cross-sectional area $5\times10^{-4}\text{m}^2$ and the length of the magnetic circuit 25×10^{-2} m.
What are the values of magnetic field intensity and relative permeability when the current is 2 A and total flux is 0.3×10^{-3} Wb? **[ESE 2015]**
(A) 1200 AT/m and 397.9
(B) 300 AT/m and 500×10^{-6}
(C) 300 AT/m and 397.9
(D) 1200 AT/m and 500×10^{-6}

Q.2 Magnetic field intensity at centre of circular coil, of diameter 1 m and carrying a current of 2 A is
(A) 1 A/m (B) 2 A/m
(C) 4 A/m (D) 8 A/m

Q.3 In the electromagnetic relay of given figure below the reluctance of the iron path is negligible.



The coil self-inductance is given by the expression
(A) $\dfrac{\mu_0 N^2 a}{x}$ (B) $\dfrac{\mu_0 N}{2ax}$
(C) $\dfrac{\mu_0 N^2 a}{2x}$ (D) $\dfrac{\mu_0 N^2}{2ax}$

Q.4 An iron-cored choke with 1 mm air-gap length, draws 1 A when fed from a constant voltage AC source of 220 V. If the length of air-gap is increased to 2 mm, the current drawn by the choke would
(A) become nearly one half
(B) remain nearly the same
(C) become nearly double
(D) become nearly zero

Q.5 An iron ring of $300\,\text{mm}^2$ mean length of circular path of 500 mm. It has a constant relative permeability of 1200. For a certain current through magnetising coil the flux produced is 250 mWb. Find the flux produced for the same current if a radial air-gap of 1 mm is to cut into the ring.
(A) 73.61 Wb (B) 73.61 mWb
(C) 7.361 mWb (D) 7.361 Wb

Answers of Test - 1

1.	**A**	**2.**	*****	**3.**	**1.08 A**	**4.**	*****		

* **2. 10.61 A/m, 133.3×10^{-7} T (or Wb/m^2)**

4. 0.066 Wb/m^2

Explanation of Test - 1

Sol.1

Given :

Cross sectional area $= 500\ \text{cm}^2 = 500\times10^{-4}\ \text{m}^2$,

Mean length $l_i = 400\ \text{cm} = 400\times10^{-2}$ m,

Flux $\phi = 80\ \text{mWb} = 80\times10^{-3}$ Wb,

Turns $N = 200$

Flux density, $B = \dfrac{\phi}{A} = \dfrac{80\times10^{-3}}{500\times10^{-4}} = \mathbf{1.6\ T}$ **Ans.**

Sol.2

Given :

Current carried by the conductor $I = 20$ A,

Distance $r = 300\,\text{mm} = 0.3\,\text{m}$

(i) Magnetic field intensity,

$$H = \frac{I}{2\pi r} = \frac{20}{2\pi\times0.3} = \mathbf{10.61\ A/m}\ \textbf{Ans.}$$

(ii) Flux density,

$$B = \mu_0\mu_r H = 4\pi\times10^{-7}\times1\times10.61$$

$$B = \mathbf{133.3\times10^{-7}\ T\ (or\ Wb/m^2)}\ \textbf{Ans.}$$

Sol.3

Given :

Number of turns of the solenoid $N = 300$,

Relative permeability $\mu_r = 1000$,

Flux density $B = 1.3\,\text{T}$

Mean diameter of the solenoid

$d = 100\,\text{mm} = 0.1\,\text{m}$

$$l = 2\pi r = 2\pi\times\frac{0.1}{2} = 0.314\ \text{m}$$

Current in the solenoid,

$$B = \frac{\mu_0\mu_r NI}{l}$$

$$1.3 = \frac{4\pi\times10^{-7}\times1000\times300\times I}{0.314}$$

$$\therefore\quad I = \frac{1.3\times0.314}{4\pi\times10^{-7}\times1000\times300} = \mathbf{1.08\ A}\ \textbf{Ans.}$$

Sol.4

Given :

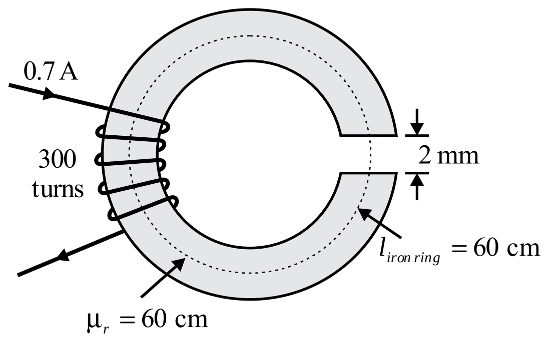
Iron ring of mean length = 60 cm $= 60\times10^{-2}$ m,

Air gap length = 2 mm $= 2\times10^{-3}$ m,

Number of turns wound = 300,

Relative permeability = 300,

Current = 0.7 A.



Total (MMF) AT $= \phi\times S_{ring} + \phi\times S_{gap}$

$$N\times I = \phi\times\frac{l_{iron}}{\mu_0\mu_r a} + \phi\times\frac{l_{gap}}{\mu_0\times1\times a}$$

$$300\times0.7 = \frac{\phi}{a\mu_0}\left[\frac{l_{iron}}{\mu_r} + l_{gap}\right]$$

$$210 = \frac{B}{\mu_0}\left[\frac{60\times10^{-2}}{300} + 2\times10^{-3}\right]$$

Flux density, $B = 0.066\ \text{Wb/m}^2$ **Ans.**

Explanations to Multiple Choice Questions

Sol.1

Given : Number of turns $N = 150$,

Area $a = 5\times10^{-4}\,\text{m}^2$,

Length of core $l = 25\times10^{-2}$ m, Current $i = 2$,

Total flux $\phi = 0.3\times10^{-3}$

(i) Magnetic field intensity, $Ni = Hl$

$$H = \frac{Ni}{l}$$

$$H = \frac{150 \times 2}{25 \times 10^{-2}} = 1200 \text{ AT}$$ **Ans.**

(ii) $\phi = Ba = \mu_0 \mu_r Ha$

$$\mu_r = \frac{\phi}{\mu_0 Ha}$$

$$\mu_r = \frac{0.3 \times 10^{-3}}{4\pi \times 10^{-7} \times 1200 \times 5 \times 10^{-4}}$$

$$\mu_r = 397.88$$ **Ans.**

Hence, the correct option is (A).

Sol.2

Magnetic field intensity at centre of circular coil

$$= \frac{I}{2R} = \frac{2}{1} = 2 \text{A/m}$$ **Ans.**

Hence, the correct option is (B).

Sol.3

Self-inductance, $L = \frac{N^2 \mu_0 \mu_r a}{l}$

For air gap, $L = \frac{N^2 \mu_0 a}{2x}$ **Ans.**

Hence, the correct option is (C).

Sol.4

Given :

$l_g = 1 \text{mm} = 1 \times 10^{-3} \text{m}$, Current $i = 1 \text{A}$

If supply is constant the flux is also constant,

$$Ni = Hl$$

For old case, $i_1 = 1$, $l_1 = 1 \times 10^{-3} \text{m}$

For new case, $l_2 = 2 \times 10^{-2} \text{m}$

$$\frac{i_1}{i_2} = \frac{l_1}{l_2}$$

$$\frac{1}{i_2} = \frac{1 \times 10^{-3}}{2 \times 10^{-3}}$$

$\therefore$ $i_2 = 2$ A **Ans.**

Hence, the correct option is (C).

Sol.5

Given :

Area of cross section

$a = 300 \text{mm}^2 = 300 \times 10^{-6} \text{ m}$,

Length of iron ring

$l_i = 500 \text{mm} = 500 \times 10^{-3} \text{ m}$,

Relative permeability $\mu_r = 1200$,

Flux produced $\phi = 250 \text{mWb} = 250 \times 10^{-3} \text{ Wb}$,

Total MMF, $NI = Hl_i$

$$NI = \frac{B}{\mu_0 \mu_r} l_i \qquad [\because B = \mu_0 \mu_r H]$$

$$NI = \frac{\phi}{a \mu_0 \mu_r} l_i$$

$$NI = \frac{250 \times 10^{-3}}{300 \times 10^{-6} \times 4\pi \times 10^{-7} \times 1200} \times 500 \times 10^{-3}$$

$$NI = 276310.66 \text{ AT}$$

Now, an air gap of 1 mm introduced and current remains constant so total ampere turns is not changed.

Length of iron ring, $l_i = 500 - 1 = 499 \text{ mm}$

$$l_i = 499 \times 10^{-3} \text{m} = 0.499 \text{ m}$$

Length of air gap = 1 mm $= 1 \times 10^{-3}$ m

Total MMF, $NI = H_i l_i + H_g l_g$

$$NI = \frac{B}{\mu_0 \mu_r} l_i + \frac{B}{\mu_0} l_g = \frac{\phi}{a \mu_0} \left[\frac{l_i}{\mu_r} + l_g \right]$$

$$276310.66 = \frac{\phi}{300 \times 10^{-6} \times 4\pi \times 10^{-7}} \left(\frac{499 \times 10^{-3}}{1200} + 1 \times 10^{-3} \right)$$

$$1.0416 \times 10^{-4} = \phi [1.415 \times 10^{-3}]$$

$$\phi = 0.07361 = 73.61 \text{ mWb}$$ **Ans.**

Hence, the correct option is (B).

❖❖❖❖

12 YEARS GATE SOLVED PAPERS

4 Years ESE Solved Papers

GATE 2022

GENERAL APTITUDE

UMESH DHANDE

AG BM CY CH EC IN PI EY MA MT PH TF XH
AE AR BT CE CS EE ME ES GG MN PE ST XE XL

Topic-wise Previous 12 Years GATE Solutions

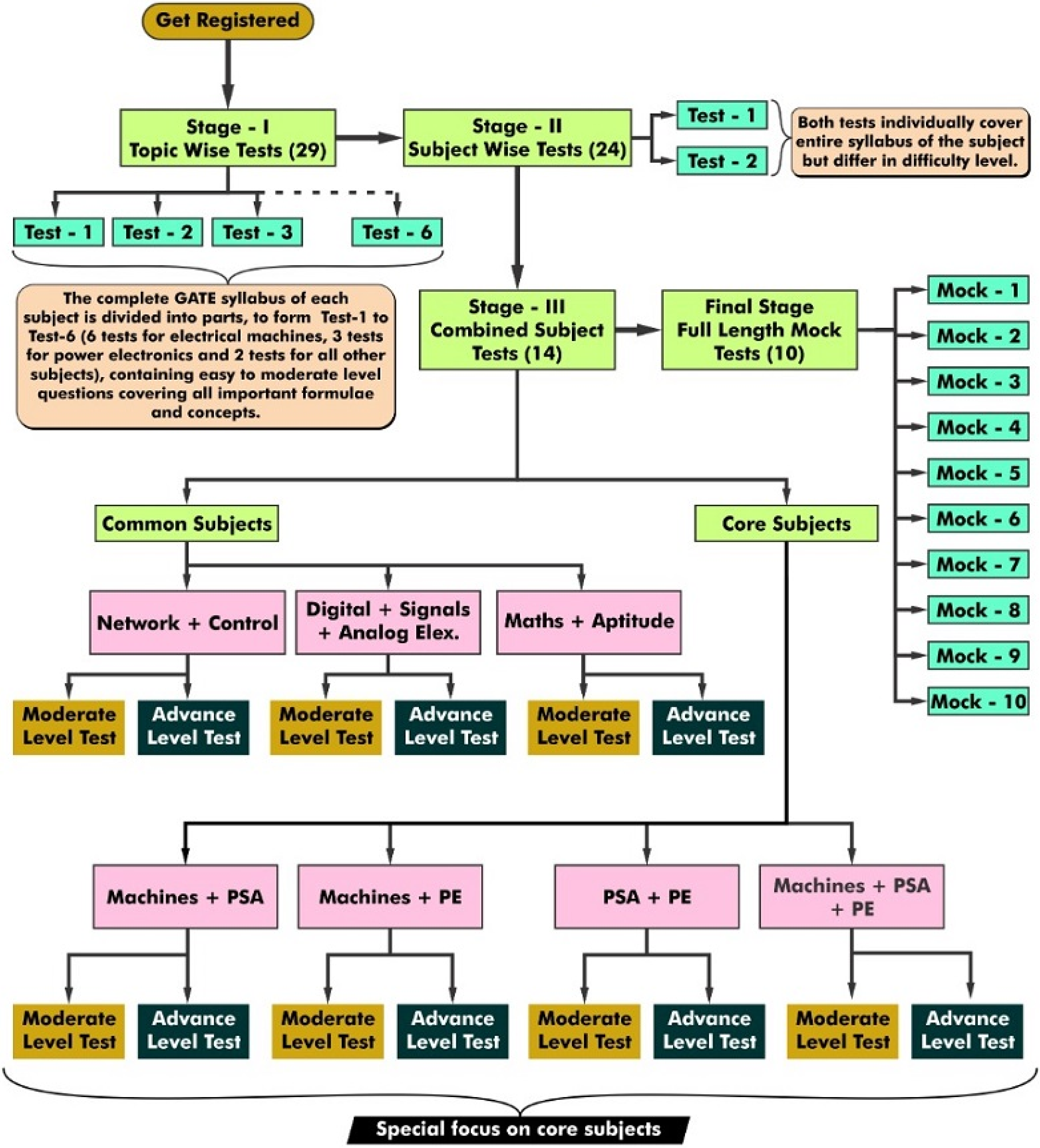
- Diligent solutions of GATE previous year questions (2010-2021)
- Multi method approach for a single problem to develop crystal clear concepts
- Video solution for conspicuous questions to enhance problem solving skills

GATE ACADEMY®
steps to success...

GATE ACADEMY

TEST SERIES STRUCTURE (EE)

(One Year Program)



CHAPTER 2

Single Phase Transformer

Learning Objectives :

After reading this chapter you should be able to :

- Understand basic of transformer.
- Explain construction of transformer.
- Understand equivalent circuit and phasor diagrams.
- Understand voltage regulation and efficiency of transformer.
- Explain different test of transformer.
- Understand auto transformer.

Table of Contents

2.1 Transformer Basics

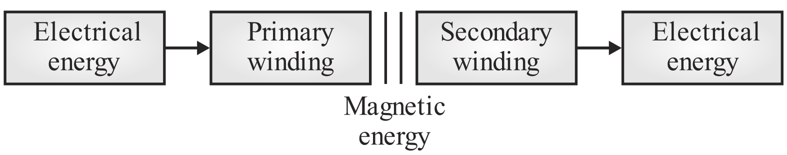
Definition : Transformer is a static device which transfers power from one circuit to another circuit without change in frequency.

Main function of transformer :

1. Changing voltage and current levels
2. Maintaining constant frequency, power and flux
3. Matching source and load impedance for maximum power transfer.
4. Isolating d.c. while permitting the flow of a.c. between two circuits or isolating one circuit from another.

Features of transformer :

1. **Constant frequency device :** Transformer does not change the frequency of the system, so it can be treated as constant frequency device.
2. **Constant power device :** Transformer transfers almost same amount of power from one circuit to another circuit, so it can be treated as constant power device.
3. **Constant-flux device :** As the amount of flux in the core is constant irrespective of power transfer, it can be treated as "Constant-flux device".
4. **Static device :** Transformer is a static device as it has no moving or rotating parts due to which there are no friction and windage loss.
5. **Singly excited device :** Transformer is a singly excited device, since it requires only one external voltage source to energise any number of windings placed on its core.
6. **Electromagnetic energy conversion device :** Transformer is an electromagnetic energy conversion device (If internal conversion process is considered). However, the transformer is not a complete energy conversion device, as the input and output are of electrical nature.



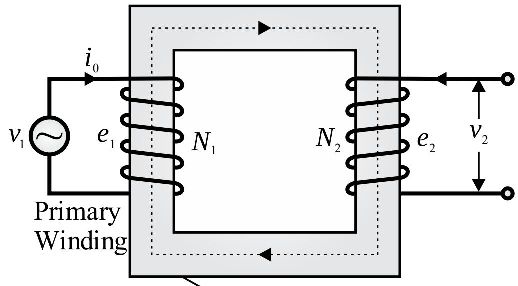
7. **Phase-shifting device :** Transformer can be treated as "Phase-Shifting Device", since it offers a displacement of approximate 180^0 between two circuits.
8. **Two port network :** Transformer is a four terminal 2-port network used in transmission line (ABCD parameters).
9. **Negative feedback circuit :** Transformer is a negative feedback circuit or control circuit.

2.2 Working of Transformer

Definition : It consists of two inductive coils which are electrically separated but linked through a common magnetic circuit through a path of low reactance.

One of the transformer windings is connected to a source of a.c. electric power, and the second transformer winding supplies electric power to loads. The transformer winding connected to the power source is called the primary winding or input winding and the winding connected to the loads is called the secondary winding. Transformer works on the principle of electromagnetic induction.

The principle of electromagnetic induction states that when two coils are inductively coupled and if current in one coil is changed uniformly then an emf gets induced in the other coil. This emf can drive a current, when a closed path is provided to it and so, electric energy is transferred (entirely magnetically) from the first coil to second coil. In transformer the emf induced in primary and secondary by change of flux (time varying field) with respect to coil and it is achieved without physical movement of coil or magnet. So this type of emf is known as statically induced emf.



Application of transformer :

1. To change the level of voltage and current in electrical power system network.
2. In electrical power engineering transformer makes it possible to convert a generated voltage of about 11 kV (as determined by generator design limitations) to higher values of 132 kV, 220 kV, 400 kV, 500 kV and 765 kV thus permitting transmission of huge amounts of power along long distances to appropriate distribution points at tremendous savings in the cost of transmission lines.
3. At distribution points, transformers are used to reduce these high voltages to a safe level of 400/230 volts for use in homes, offices and other consumer premises.
4. Current Transformer and Potential Transformer also used to measure the currents and voltages and for protection purpose.
5. Impedance-matching transformer : A transformer used to match the impedance of the source and the impedance of the load.
6. Audio-frequency transformer : A transformer used in audio-frequency circuits to transfer audio-frequency signals from one circuit to another.
7. Radio-frequency transformer : A transformer used in a radio-frequency circuit to transfer radio-frequency signals from one circuit to another.

2.2.1 Why Transformer Cannot Work on DC?

If a rated DC voltage is applied across the primary, a flux of constant magnitude will be set up in the core. Hence, there will be no induced emf.

Induced emf, $E = \frac{Nd\phi}{dt}$

where, $\frac{d\phi}{dt} = 0$ [$\because$ $\phi =$ Constant for DC]

$E = 0$

The resistance of primary winding is very low so primary current will be very high which will damage the insulation, because of high I^2R losses.

2.3 Transformer Construction

Definition : The transformer mainly consists of the magnetic circuit, electric circuit, dielectric circuit, tanks, and accessories. The main elements of the transformer are the **windings or coil** and the **magnetic core**.

2.3.1 Magnetic Core

The basic function of the core is to couple the winding magnetically and restrict all the flux to core without any leakage which is called tight coupling. The core material should be superior magnetic material as well as should have good mechanical properties. Steel is preferred but alloyed with 3.5% to 4% of silicon. More silicon content destroys the mechanical properties.

The core of the transformer is made up of silicon steel in order to provide a continuous magnetic path. Usually, the core of the transformer is laminated for minimizing the eddy current loss.

Feature of silicon steel :

1. Silicon steel is a ferromagnetic material, with superior magnetic properties.
2. High permeability (μ) and low reluctance to flow of flux.
3. Small hysteresis coefficient :

   Hysteresis loss, $P_h = \eta B_{\max}^x fV$

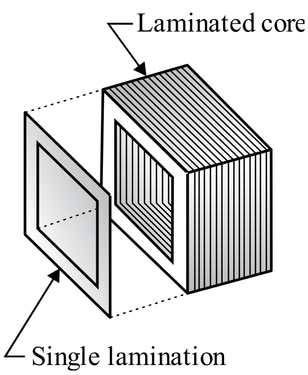
   (i) where x *is* hysteresis coefficient and range of hysteresis coefficient is 1.5 to 2.5.

   (ii) In silicon steel the value of hysteresis coefficient is 1.65 and it is lower side of range.

   (iii)Due to lower side of range the hysteresis loss will be less.
4. **Low eddy current loss :** Pure steel is good magnetic material and it has high conductivity. Due to conductivity of the pure steel, the emf is introduced in the core. This emf produces circulating current in the core which produces eddy current losses.

   To reduce the eddy current loss, conductivity of steel has to be reduced without disturbing permeability. 3.5% to 4% of silicon has added to steel, so conductivity of steel decreases. If conductivity decreases, the eddy current losses also decreases. To further reduce the conductivity of steel, transformer core are laminated, so that eddy current losses are reduced.
5. **Lamination of iron core :** For minimizing the eddy current loss, the steel sheet is laminated each other by a light coat of core-plate varnish or by an oxide layer on the surface. The thickness of lamination varies from 0.35 mm for a frequency of 50 Hz to 0.5 mm for a frequency of 25 Hz.

   The laminations used in a transformer construction are very thin strips of insulated metal joined together to produce a solid but laminated core as shown below.

   These laminations are insulated from each other by a insulating material to increase the effective resistivity of the core thereby increasing the overall resistance to limit the flow of the eddy currents.

   Oxide paint, China clay, Japan varnish and thin impregnated paper are used as insulating material in the lamination process. Oxide paint is mostly used in all transformers to withstand high temperature.

6. **Stacking factor :** By adding transformer oil, the dielectric strength of the insulation will be increased.

$$\text{Stacking factor} = K_s = \frac{\text{Net cross sectional area of core}}{\text{Gross cross sectional area of core}} = \frac{A_i}{A_{gi}}$$

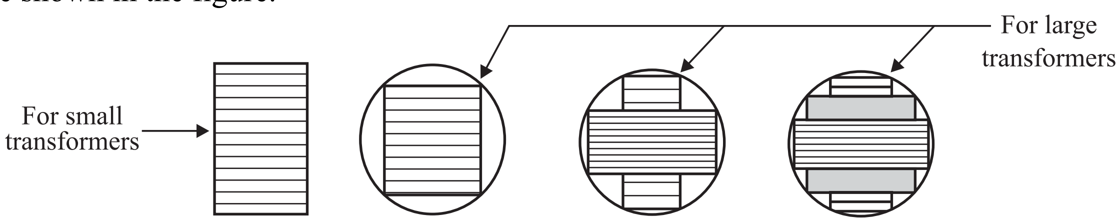
where, gross cross sectional area of core,

A_{gi} = Length × Breath of core and net cross sectional area of core

A_i = Gross cross sectional area of core – Area occupied by insulating material.

Stacking factor depends on thickness of lamination. For thin lamination the value of Stacking factor is 0.5 and for thick lamination the value of Stacking factor is 0.95.

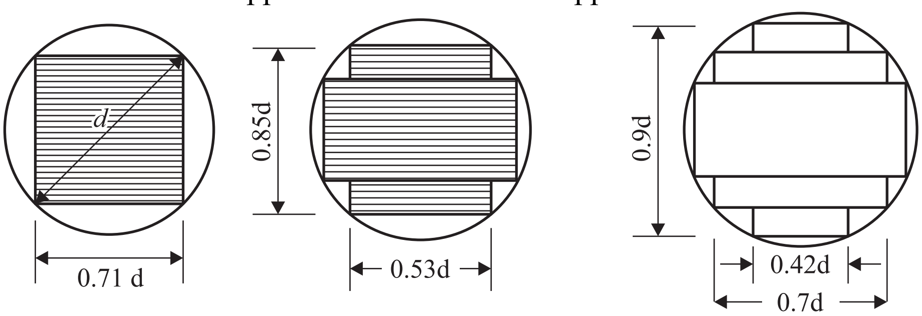
7. **Cross section of iron core :** The cross-section of the limb depends on the type of coil to be used either circular or rectangular. The different cross-sections of limbs, practically used are shown in the figure.



Rectangular **Square** **Cruciform** **3 stepped Cruciform**

For small rating of transformer, rectangular cross sectional area type core are used but generally square cross sectional area type core are preferred as they have high mechanical strength. As the rating increases, stepped core or cruciform core are preferred.

As the space utilization is better with stepped cores, the length of mean turn of copper is reduced and therefore copper losses and cost of copper also reduced.



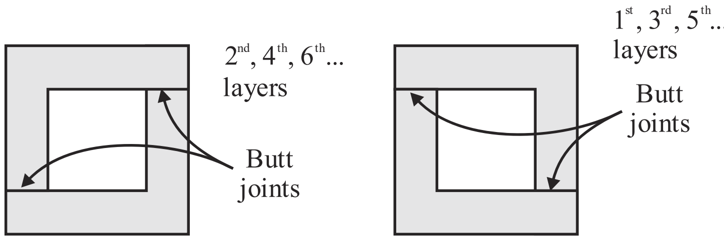
Square core **Two stepped core** **Three stepped core**

Due to the above reasons size, weight, and cost of transformer is less with cruciform core. Flux is uniformly distributed.

$$\text{Utilization factor} = \frac{\text{Effective cross sectional area}}{\text{Total cross sectional area}}$$

So, the utilization factor of cruciform core is high (85% to 95%) as compared to square core.

8. **Staggering :** To avoid the high reluctance at the joints because of laminations, the alternate layers are stacked differently to eliminate the joints. This is called staggering. The butt joints are staggered in alternate layers. It is shown in the below figure.



The advantages of staggering in transformer are :

(i) It has continuous air gap.

(ii) Reluctance of magnetic circuit gets reduced.

(iii) The continuous air gap reduces the mechanical strength of the core and in staggering helps to increase the mechanical strength of the core.

(iv) We can reduce the noise level only by good core staggering.

Remember

Stepped core reduces core volume and core loss and it also reduces the amount of copper required.

Numerical Answer Type Questions

Observation of EMF Equation

Q.1 A single phase transformer with 10 : 1 turn-ratio and rated at 50 kVA, 2400/240 V, 50 Hz is used to step down the voltage of a distribution system. The low tension voltage is to be kept constant at 240 V. find the value of load impedance of the LV side so that the transformer will be loaded fully. Find also the value of maximum flux inside the core if the LV side has 23 turns.

Q.2 A magnetic circuit with a cross sectional area of 15 cm^2 is to be operated at 60 Hz from a 120 V rms supply. The number of turns required to achieve a peak magnetic flux density of 1.8 T in the core is _______.

Q.3 The rating of primary winding of a transformer, having 60 turns is 250 V, 50 Hz. If the core cross section area is 144 cm^2 then the flux density in the core is _______ T.

Q.4 A 1-phase transformer has 400 primary and 1000 secondary turns. Net cross-sectional area of core is 60 cm^2. If primary windings be connected to 50 Hz supply at 520 V, the peak value of flux density in the core is _______ Wb/m^2.

Q.5 A single phase, ideal transformer of voltage rating 200/400 V, 50 Hz produces a flux density of 1.3 T when its LV side is energized from a 200 V, 50 Hz source. If the LV side is energized from a 180 V, 40 Hz source, the flux density in the core will become _______ T.

Practical Transformer with no Load

Q.1 The core loss and exciting volt amperes for the core at B_{max} = 1.5 T and 60 Hz is found to be P_c = 16 W and $(VI)_{rms}$ = 20 VA and the induced voltage was 194 V, when the winding has 200 turns. Find :

(i) No load power factor

(ii) Core loss current

(iii) Magnetizing current

Q.2 Find active and reactive components of no-load current and the no-load current of a 400/220 V single phase transformer if power input of HV winding is 100W. The low voltage winding is kept open. The power factor at no-load is 0.2 lag.

Q.3 5 kVA, 50 Hz single phase transformer has ratio 200/400 V. The data taken on the LV side at rated voltage shows the open circuited wattage as 100W. The mutual inductance between the primary and secondary winding is 2 H. Neglect winding resistance and leakage reactance. What value will be the current taken by the transformer. If the load test conducted on HV side.

(A) 0.4 A (B) 0.318 A

(C) 0.25 A (D) 0.296 A

Q.4 A non-sinusoidal voltage

$$V = 150\sin 314t - 75\sin 1570t$$

is applied to the 250 turns winding of a transformer. Find the core flux as a function of time.

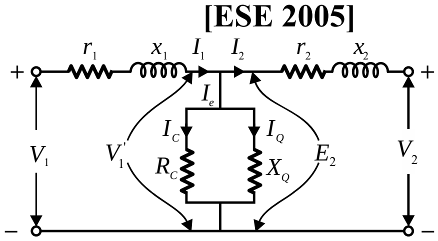
Q.5 A voltage $V = 200\sin 314t$ is applied to the transformer winding in a no load test. The resulting current is found to be $i = 3\sin(314t - 60^0)$. Determine core loss and r.m.s value of exciting current.

Multiple Choice Questions

Equivalent Circuit of Transformer

Q.1 The exact equivalent circuit of a two winding transformer is given in the figure given above. For affecting simplification, the parallel magnetizing branch, consisting of R_C and X_Q is shifted to the left of the primary leakage impedance $(r_1 + jx_1)$. This simplification introduces the inaccuracy, in the neglect of

[ESE 2005]



(A) Voltage drop in the primary impedance due to the secondary current

(B) Voltage drop in the primary impedance due to the exciting current

(C) Voltage drop in the secondary impedance due to the exciting current

(D) Reduction in values of R_C and X_Q of the exciting circuit

Q.2 A 120/2400 V, 60 Hz, 50 kVA transformer has a magnetizing reactance (as measured from the LV side) of 34.6 Ω. The leakage reactance on LV side is 27.4 mΩ and on HV side is 11.2 H.

With the secondary open circuited and 120 V applied to the primary, the primary current and the secondary voltage are

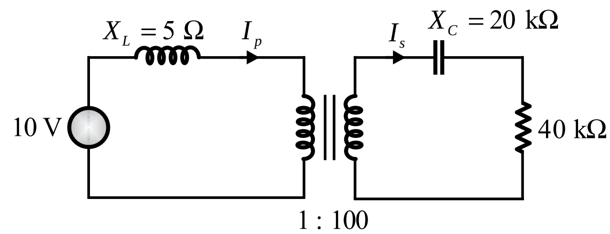
(A) 3 A, 2400 V
(B) 3.46 A, 2398 V
(C) 3.8 A, 2390 V
(D) None of these

Per Unit Value

Q.1 A 4 kVA, 400 V/200 V single phase transformer has resistance of 0.02 pu and reactance of 0.06 pu. The resistance and reactance referred to high voltage side are **[ESE 2011, 2002]**

(A) 0.2 ohm and 0.6 ohm
(B) 0.8 ohm and 2.4 ohm
(C) 0.08 ohm and 0.24 ohm
(D) 2 ohm and 6 ohm

Q.3 The primary current I_p in figure is



(A) 2 A
(B) 0.04 A
(C) 0.004 A
(D) none of the above

Explanation of Numerical Answer Type Question (Based on EMF Equation)

Sol. 1

Given : Turn ratio $\frac{N_1}{N_2} = 10:1$,

VA rating $S_{FL} = 50\,\text{kVA}$, $V_1 = 2400$,

$V_2 = 240\,\text{V}$, Frequency $f = 50\,\text{Hz}$,

Secondary number of turns $N_2 = 23$

Full load secondary current,

$$I_2 = \frac{S_{FL}}{V_2} = \frac{50\times10^3}{240} = 208.33\,\text{A}$$

Load impedance in secondary side,

$$Z_L = \frac{V_2}{I_2} = \frac{240}{208.33} = 1.15\ \Omega \qquad \textbf{Ans.}$$

Induced emf,

$$E_2 = 4.44\times\phi_m\times f\times N_2$$

$$\therefore \quad \text{Flux, } \phi_m = \frac{E_2}{4.44\times f\times N_2}$$

$$\phi_m = \frac{240}{4.44\times50\times23} = 0.047\ \text{Wb} \qquad \textbf{Ans.}$$

Sol. 2

Given :

Cross sectional area $A = 15\,\text{cm}^2 = 15\times10^{-4}\,\text{m}^2$,

Frequency $f = 60\,\text{Hz}$, Voltage $E = 120\,\text{V}$

and Peak flux density $B_m = 1.8\,\text{T}$

Induced emf, $E = 4.44\times\phi_m\times f\times N$

$$E = 4.44\times B_m\times A\times f\times N$$

$$\text{Number of turn, } N = \frac{E}{4.44\times B_m\times A\times f}$$

$$N = \frac{120}{4.44\times1.8\times15\times10^{-4}\times60}$$

$$N = 166.85 \cong 167\ \text{turns} \qquad \textbf{Ans.}$$

Sol. 3

Given : Number of turns $N = 60$,

Voltage $E = 250\,\text{V}$, Frequency $f = 50\,\text{Hz}$,

Cross sectional area

$A = 144\,\text{cm}^2 = 144\times10^{-4}\,\text{m}^2$

Induced emf, $E = 4.44\times\phi_m\times f\times N$

$$E = 4.44\times B_m\times A\times f\times N$$

$$\text{Flux density, } B_m = \frac{E}{4.44\times A\times f\times N}$$

$$B_m = \frac{250}{4.44\times144\times10^{-4}\times50\times60}$$

$$B_m = 1.3\ \text{T} \qquad \textbf{Ans.}$$

Sol. 4

Given : Primary turns $N_1 = 400$,

Secondary turns $N_2 = 1000$,

Net cross sectional area

$A = 60\,\text{cm}^2 = 60\times10^{-4}\,\text{m}^2$,

Frequency $f = 50\,\text{Hz}$,

Primary voltage $E_1 = 520\,\text{V}$

Induced emf in primary winding,

$$E_1 = 4.44\times\phi_m\times f\times N_1$$

$$E_1 = 4.44\times B_m\times A\times f\times N_1$$

Peak value of flux density,

$$B_m = \frac{E_1}{4.44\times A\times f\times N_1}$$

$$B_m = \frac{520}{4.44\times60\times10^{-4}\times50\times400}$$

$$B_m = 0.976\ \text{T} \qquad \textbf{Ans.}$$

Sol. 5

Given :

Case 1 : Voltage $V_{old} = 200\,\text{V}$,

Frequency $f_{old} = 50\,\text{Hz}$,

and Flux density $B_{old} = 1.3\,\text{T}$

Case 2 : Voltage $V_{new} = 180\,\text{V}$,

Frequency $f_{new} = 40\,\text{Hz}$,

and Flux density $B_{new} = ?$

$$\text{Flux density} \propto \frac{\text{Voltage}}{\text{Frequency}}$$

Then, $\frac{B_{new}}{B_{old}} = \frac{V_{new}/f_{new}}{V_{old}/f_{old}} = \frac{V_{new}}{V_{old}} \times \frac{f_{old}}{f_{new}}$

$$B_{new} = B_{old} \times \frac{V_{new}}{V_{old}} \times \frac{f_{old}}{f_{new}}$$

$$B_{new} = 1.3 \times \frac{180}{200} \times \frac{50}{40} = 1.46 \text{ T}$$ **Ans.**

Scan for Video Solution

Explanation of Numerical Answer Type Question (Based on Practical Transformer with No Load)

Sol.1

Given : Maximum flux density $B_{max} = 1.5\,\text{T}$,

Frequency $f = 60\,\text{Hz}$, Core loss $P_c = 16\,\text{W}$,

VA rating $= 20\,\text{VA}$, Voltage $V_1 = 194\,\text{V}$,

No of turns $N_1 = 200$

No load current,

$$I = \frac{\text{VA rating}}{\text{Voltage}} = \frac{20}{194} = 0.1030\,\text{A}$$

(i) No load power, $P_0 = V_1 I_0 \cos\phi_0$

$\therefore$ No load power factor,

$$\cos\phi_0 = \frac{P_0}{V_1 I_0} = \frac{16}{194 \times 0.1030}$$

$$\cos\phi_0 = 0.8$$ **Ans.**

No load power factor angle,

$\therefore$ $\phi_0 = \cos^{-1} 0.8 = 36.86^0$

(ii) Core loss current,

$$I_c = I_0 \cos\phi_0$$

$$I_c = 0.1030 \times 0.8 = 0.0824 \text{ A}$$ **Ans.**

(iii) Magnetizing current,

$$I_m = I_0 \sin\phi_0 = 0.1030 \times \sin 36.86^0$$

$$I_m = 0.0617 \text{ A}$$ **Ans.**

Sol.2

Given : $V_1 = 400\,\text{V}$, $V_2 = 220\,\text{V}$,

No load power $P_0 = 100\,\text{W}$,

No load power factor $\cos\phi_0 = 0.2$

No load power factor angle,

$\therefore$ $\phi_0 = \cos^{-1} 0.2 = 78.46^0$

$\because$ No load power, $P_0 = V_1 I_0 \cos\phi_0$

$\therefore$ No load current,

$$I_0 = \frac{P_0}{V_1 \cos\phi_0} = \frac{100}{400 \times 0.2} = 1.25\,\text{A}$$

Active component or core loss component,

$$I_c = I_0 \cos\phi_0 = 1.25 \times 0.2 = 0.25 \text{ A}$$ **Ans.**

Reactive component or magnetizing component,

$$I_m = I_0 \sin\phi_0$$

$$I_m = 1.25 \sin 78.46^0 = 1.224 \text{ A}$$ **Ans.**

Sol.3

Given : VA rating $= 5\,\text{kVA}$,

Frequency $f = 50\,\text{Hz}$, $E_1 = 200$, $E_2 = 400\,\text{V}$,

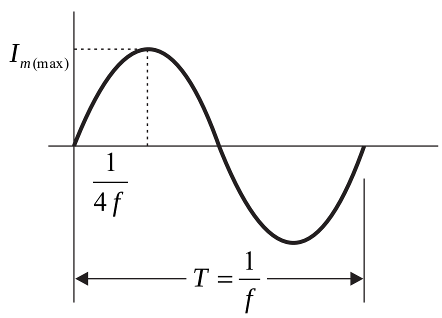
No load power $P_0 = 100\,\text{W}$,

Mutual inductance $M = 2\,\text{H}$

$$P_0 = V_1 I_0 \cos\phi_0 = V_1 I_c$$

$\therefore$ Core loss component,

$$I_c = \frac{P_0}{V_1} = \frac{100}{200} = 0.5\,\text{A}$$



Secondary induced emf, $E_2 = M\dfrac{di_m}{dt}$

$$400 = 2\times\frac{I_{m(\max)}-0}{\frac{1}{4f}}$$

$$400 = 2I_{m(\max)}\times 4\times 50$$

$$I_{m(\max)} = \frac{400}{400} = 1\,\text{A}$$

$$I_{m(rms)} = \frac{1}{\sqrt{2}} = 0.707\,\text{A}$$

$$I_0 = \sqrt{I_m^2 + I_c^2}$$

$$I_0 = \sqrt{0.707^2 + 0.5^2} = 0.86\,\text{A}$$

HV side current $= I_0\times\dfrac{N_1}{N_2}$

$$= 0.86\times\frac{200}{400} = 0.43\ \text{A}$$ **Ans.**

Sol.4

Given :

Voltage $V = 150\sin(314t) - 75\sin(1570t)$,

Number of turns $N = 250$

Voltage, $V = N\dfrac{d\phi}{dt}$

$$\therefore \qquad \phi = \frac{1}{N}\int V dt$$

$$= \frac{1}{250}\int\left(150\sin 314t - 75\sin 1570t\right)dt$$

$$\phi = \frac{1}{250}\times\left[\frac{150}{314}(-\cos 314t) + \frac{75}{1570}\cos 1570t\right]$$

$$\phi = \begin{bmatrix}-1.911\cos 314t \\ +0.1911\cos 1570t\end{bmatrix}\text{mWb}$$ **Ans.**

Sol.5

Given : Voltage $V = 200\sin 314t$,

$i = 3\sin(314t - 60^0)$

Rms value of voltage, $V_{rms} = \dfrac{V_{\max}}{\sqrt{2}} = \dfrac{200}{\sqrt{2}}$

Rms value of exciting current,

$$I_0 = \frac{I_{\max}}{\sqrt{2}} = \frac{3}{\sqrt{2}}$$

$$I_0 = 2.122\ \text{A}$$ **Ans.**

Power factor cycle, $\phi_0 = 60^0$

[Angle between voltage and current]

Core loss P_c = No load power P_0,

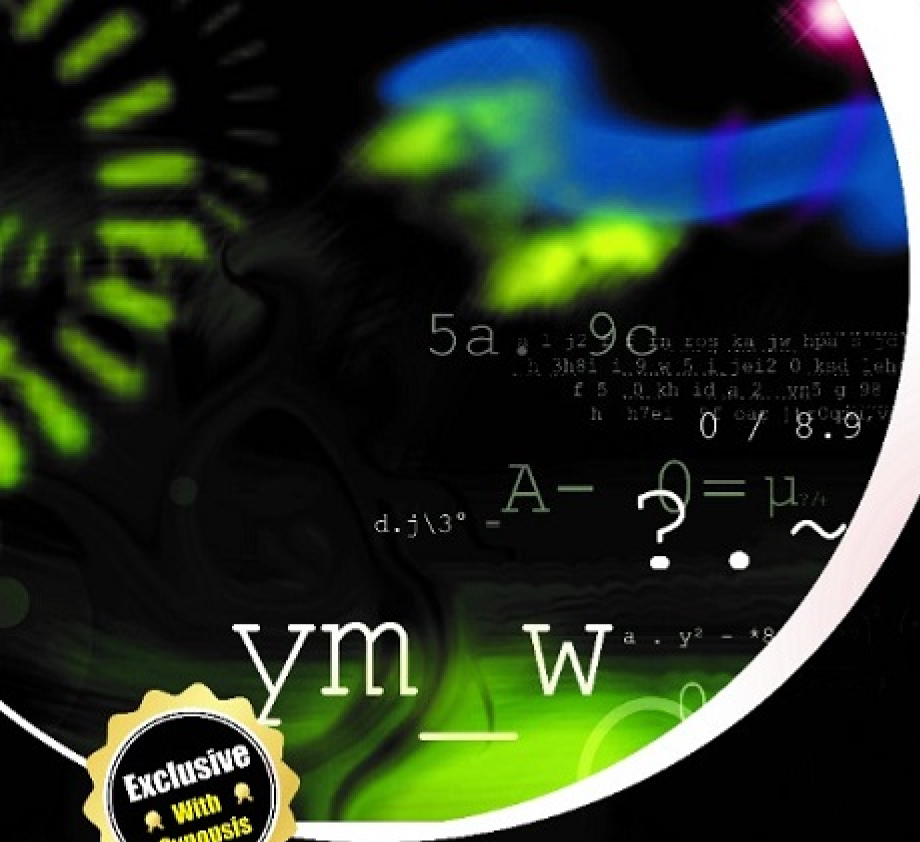
$$P_c = P_0 = V_1 I_0\cos\phi_0 = \frac{200}{\sqrt{2}}\times\frac{3}{\sqrt{2}}\times\cos 60^0$$

Core loss, $P_c = P_0 =$ 150 W **Ans.**

RMS value of excitation current,

$$I_m = I_0\sin\phi_0 = 2.122\sin 60$$

$$I_m = 1.837\ \text{A}$$ **Ans.**



29 YEARS GATE SOLVED PAPERS

4 Years ESE Solved Papers

Exclusive With Synopsis

GATE 2022

UMESH DHANDE

ENGINEERING MATHEMATICS

EE CE CH EC ME IN PI

Topic-wise Previous 29 Years GATE Solutions

- Diligent solutions of GATE previous year questions (1993-2021)
- Multi method approach for a single problem to develop crystal clear concepts
- This book is also a value addition for ESE/PSUs/DRDO/ISRO
- Video Solution for Conspicuous Questions to Enhance problem solving Skills

GATE ACADEMY®
steps to success...

GATE ACADEMY®

GATE Since 2004

steps to success...

Pen Drive & G-Drive Course

- It is best offline mode of video course.
- Dedicated discussion and doubt portal managed by our faculties.
- Complete packaged course with all reading content and Online Test Series.
- Ready to ship course, It will be shipped to you within 2 days of ordering.

Tablet Course

- Tablet course will be delivered through Samsung Galaxy Tab A (WiFi only).
- All GATE ACADEMY apps will come pre loaded.
- Tablet will be controlled by our team for the course duration.
- After course duration the tablet will be made open for your use.
- The Course content will be exactly same as VOD course but you do not need Internet connection to play the video (as it is an offline course

For Doubt and Discussion you need to download GATE ACADEMY learning app, Subject matter expert/ faculty will be there to solve your query

A DEDICATED TECH TEAM TO SOLVE TECH QUERIES AND HANDLE TECHNICAL ISSUES.

Finally... How to get registered for Test Series ?

Step - I	Step - II
Visit http://onlinetestseries.gateacademy.co.in Click on New Registration Fill the Form, You will be Redirected to the Test Portal Click on buy Package Make Payment using Coupon code (For gate academy student) or by online payment.	Send completely filled registration form to our office (for gate academy student)

CHAPTER 3

Three Phase Transformer

Learning Objectives :

After reading this chapter you should be able to :

- Understand three phase transformer connection.
- Explain open delta connection.
- Explain scott connection.
- Understand three winding transformer.
- Understand harmonics in single phase and three phase transformers.

Table of Contents

3.1 Introduction

Definition : The generation of an electrical power is usually three phase and at higher voltages like 13.2 kV, 22 kV or somewhat higher. Transmission of an electrical power is also at very high voltages like 110 kV, 132 kV or 400 kV. To step up the generated voltages for transmission purposes it is necessary to have three phase transformers. At the time of distribution it is necessary to reduce the voltage level up to 6600 V, 440 V, 230 V etc., for which step down three phase transformers are essential.

A three-phase system is used to generate and transmit large amount of electric power. Three phase transformers are required to step-up or step down voltage in various stages of a power system. A three-phase transformer can be built in two ways viz.

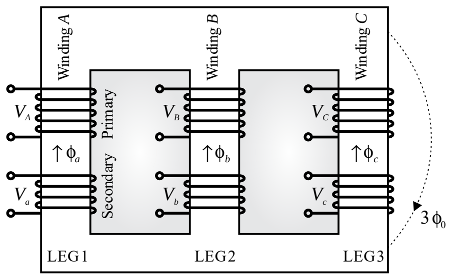
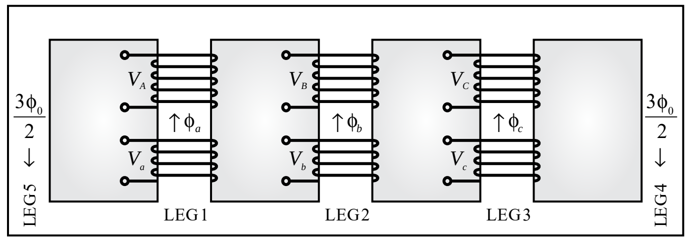
1. By connecting a bank of three single-phase transformers.
2. By constructing a three phase transformer on a common magnetic structure.

3.2 Advantages of Three Phase Bank Transformer Over Single Unit Transformer

1. A three phase transformer occupies less space for same rating, compared to a bank of three single phase transformers.
2. Its weight is less.
3. Its cost is less.
4. Only one unit is required to be handled which makes it easy for the operator.
5. It can be transported easily.
6. The core will be of smaller size and the material required for the core is less.
7. Single three phase unit is more efficient.
8. In case of three single phase units, six terminals are required to be brought out while in case of one three phase unit, only three terminals are required to be brought out.
9. The overall bus bar structure, switchgear and installation of single three phase unit is simpler.
10. In contrast to above, a bank of three single phase transformers is used in underground work such as in mines as it is easier to transport these units. The bank of three single phase transformers also offers the advantage of open delta operation with reduced rating when one of the units in the bank is inoperative.
11. But it is common practice to use a single three phase transformer unit due to its reduced cost.

3.3 Difference Between Three Phase Core Type & Shell Type Transformer

S. No.	Core Type	Shell Type
1.	Less Mechanical support	More mechanical support
2.	Copper requirement is less	More copper requirement
3.	Less insulation required	More insulation required
4.	High voltage, low KVA rating transformer	Low voltage, high KVA rating transformer
5.	3^{rd} harmonic flux is absent	Closed path for 3^{rd} harmonic flux

6.	emf is always sinusoidal	emf is non sinusoidal but sinusoidal for a connection
7.	 Fig. Three-leg core type transformer	 Fig. Five-leg shell type transformer

3.4 Three Phase Transformer Connections

Definition : The primary and secondary windings of three phase transformers as three phase windings can be connected in different ways such as in star or in delta.

3.4.1 Star Connection

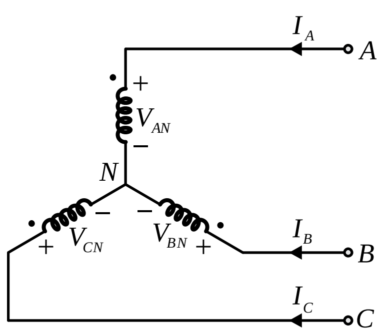
In a star connection, the similar ends (either start or finish) of the three windings are connected to a common point called as Star or Neutral point.

Usually the circuit is a three phase three wire star connected system. However, sometimes a fourth wire is carried from a star point to the external circuit called as the neutral wire.

Relationship between line and phase voltages and currents in a balanced 3-phase star connection :

Line voltage : The potential difference between any two lines is known as **line voltage** as shown in the figure.

Phase voltage : The potential difference between one line and neutral is known as phase voltage. Under balanced conditions all voltages have equal magnitudes and 120^0 phase displacement. The connection diagram of star connected system shown below,



$$|V_{AN}| = |V_{BN}| = |V_{CN}| = V_P$$

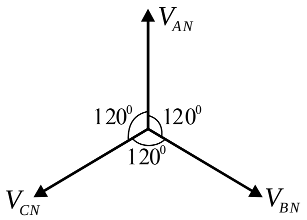
or $$V_{AN} = V_P \angle 0^0$$

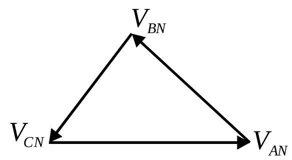
$$V_{BN} = V_P \angle -120^0$$

$$V_{CN} = V_P \angle -240^0 = V_P \angle 120^0$$

$\therefore$ $$V_{AN} = V_{BN} = V_{CN} = V_P (1\angle 0^0 + 1\angle -120^0 + 1\angle 120^0) = 0$$

Phasor of phase voltage :





Net resultant $= 0$

Line voltages : Assuming $V_{AB} = V_{BC} = V_{CA} = V_L$

$$V_{AB} = V_{AN} - V_{BN} = V_P \angle 0^0 - V_P \angle -120^0 = V_P(1 - 1\angle -120^0)$$

$$V_{AB} = \sqrt{3}\, V_P \angle 30^0$$

$$V_{BC} = V_{BN} - V_{CN} = V_P \angle -120^0 - V_P \angle 120^0$$

$$V_{BC} = \sqrt{3}\, V_P \angle -90^0$$

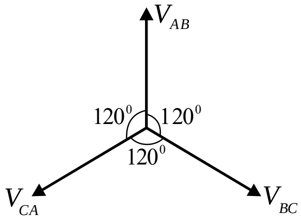
$$V_{CA} = V_{CN} - V_{AN} = V_P \angle 120^0 - V_P \angle 0^0$$

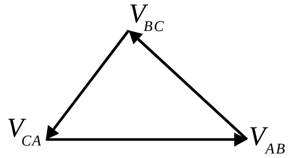
$$V_{CA} = \sqrt{3}\, V_P \angle 150^0$$

$\therefore$ $$|V_{AB}| = |V_{BC}| = |V_{CA}| = \sqrt{3}\, V_P$$

$\therefore$ $$V_L = \sqrt{3}\, V_P$$

Phasor diagram of line voltage :



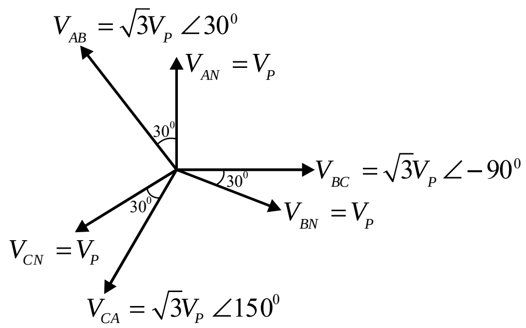


$\therefore$ $$V_{AB} + V_{BC} + V_{CA} = \sqrt{3}\, V_P \angle 30^0 + \sqrt{3}\, V_P \angle -90^0 + \sqrt{3}\, V_P \angle 150^0$$

$$V_{AB} + V_{BC} + V_{CA} = 0$$

Net resultant $= 0$

Relation between line and phase voltage :

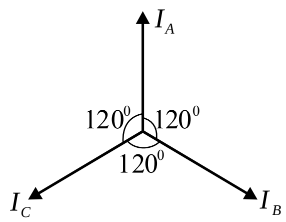


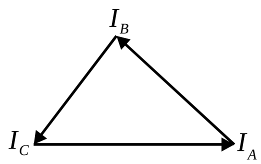
Line current and phase current :

$$I_L = I_P = |I_A| = |I_B| = |I_C|$$

$$I_A = I_P \angle 0^0,\ I_B = I_P \angle -120^0,\ I_C = I_P \angle 120^0$$

$$\therefore \quad I_A + I_B + I_C = 0 \text{ (Resultant = 0)}$$





Conclusion :

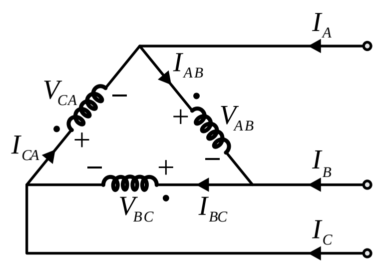
1. Line voltage and phase voltage, $V_L = \sqrt{3} V_P$
2. Line current and phase current, $I_L = I_P$
3. For ABC phase sequence V_L leads V_P by 30^0.

3.4.2 Delta Connection

In a delta or mesh connection, the end terminal of one winding is connected to the start terminal of the other phase and so on. This gives a closed circuit.

Relation between line and phase value of voltage and currents in case of delta connected system :

The three lines are run from the three junctions of the mesh called as the line **conductors** as shown in figure below,



Line current : Current flowing through the line A, B and C.

Phase current : Current flowing between to line.

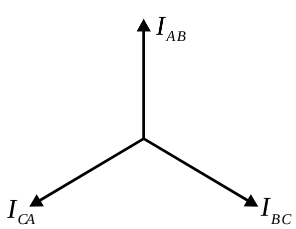
Under balanced condition phase current have equal magnitude and 120^0 phase displacement i.e.,

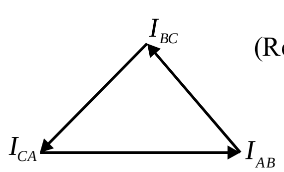
$$|I_{AB}| = |I_{BC}| = |I_{CA}| = I_P$$

$$I_{AB} = I_P \angle 0^0,\ I_{BC} = I_P \angle -120^0,\ I_{CA} = I_P \angle 120^0$$

$$\therefore \quad I_{AB} + I_{BC} + I_{CA} = I_P \angle 0^0 + I_P \angle -120^0 + I_P \angle 120^0 = 0$$

Phasor diagram of phase currents,





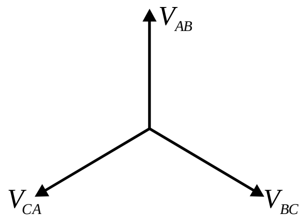
(Resultant = 0)

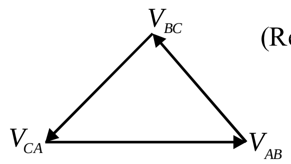
Line voltage and phase voltage :

$$V_L = V_P = |V_{AB}| = |V_{BC}| = |V_{CA}|$$

$$V_{AB} = V_P \angle 0^0,\ V_{BC} = V_P \angle -120^0,\ V_{CA} = V_P \angle 120^0$$

$$V_{AB} + V_{BC} + V_{CA} = 0 \text{ (Resultant = 0)}$$





(Resultant= 0)

Line currents : Assume $I_A = I_B = I_C = I_L$

$$I_A = I_{AB} - I_{CA} = I_P \angle 0^0 - I_P \angle 120^0$$

$$I_A = \sqrt{3} I_P \angle -30^0$$

$$I_B = I_{BC} - I_{AB} = I_P \angle -120^0 - I_P \angle 0^0$$

$$I_B = \sqrt{3} I_P \angle -150^0$$

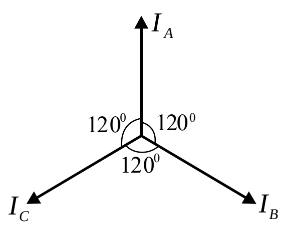
$$I_C = I_{CA} - I_{BC} = I_P \angle 120^0 - I_P \angle -120^0$$

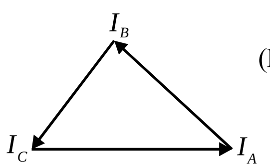
$$I_C = \sqrt{3} I_P \angle 90^0$$

$$|I_A| = |I_B| = |I_C| = \sqrt{3} I_P$$

$$\therefore \quad I_L = \sqrt{3} I_P$$

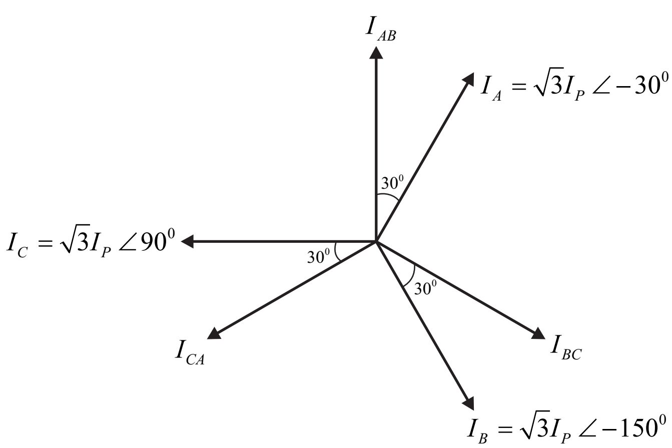
Phasor diagram of line current :





(Resultant = 0)

Relation between line and phase current :



Conclusion :

1. Line voltage and phase voltage, $V_L = V_p$.
2. Line current and phase current, $I_L = \sqrt{3} I_p$.
3. For ABC phase sequence I_L leg I_p by 30^0.

3.4.3 Expression of 3-Phase Power in AC Circuit

1. The power in a single phase AC circuit is given by,

$$P_{1\phi} = VI\cos\phi \qquad \text{[where, } \cos\phi \text{ is the power factor of circuit]}$$

∴ In a three phase system the power will be,

$$P_{3\phi} = 3\times V_{ph}\times I_{ph}\times\cos\phi$$

2. **In star connection :**

$$P_{3\phi} = 3\times V_{ph}\times I_{ph}\times\cos\phi$$

$$P_{3\phi} = 3\times\frac{V_L}{\sqrt{3}}\times I_L\times\cos\phi = \sqrt{3}V_L I_L\cos\phi \qquad \left[\because\ V_L = \sqrt{3}\,V_{ph}\right]$$

3. **In delta connection :**

$$P_{3\phi} = 3V_{ph}\times I_{ph}\times\cos\phi$$

$$P_{3\phi} = 3V_L\times\frac{I_L}{\sqrt{3}}\times\cos\phi \qquad \left[\because\ I_L = \sqrt{3}\,I_{ph}\right]$$

$$P_{3\phi} = \sqrt{3}V_L I_L\cos\phi$$

where, V_L = line voltage, I_L = line current, V_{ph} = phase voltage, I_{ph} = phase current.

Solved Example 1

A 3-phase transformer is used to step-down the voltage of a 3-phase, 11 kV feeder line. Per-phase turns ratio is 12. For a primary line current of 20 A, calculate the secondary line voltage, line current and output kVA for Star-Star connection.

Sol. Primary line voltage, $V_{L_1} = 11000\text{ V}$, Turns ratio, $a = 12$, Primary line current $I_{L_1} = 20\text{ A}$,

Phase voltage of primary side (Y-connection), $V_{P_1} = \dfrac{V_{L_1}}{\sqrt{3}} = \dfrac{4000}{\sqrt{3}} = 6350.85\text{ V}$

Secondary phase voltage $V_{P_2} = \dfrac{V_{P_1}}{a} = \dfrac{6350.85}{12} = \mathbf{529.23\ V}$ **Ans.**

Secondary line voltage (Δ-connection) $V_{L_2} = \sqrt{3}V_{P_2} = \sqrt{3}\times 529.23 = \mathbf{916.67\ V}$ **Ans.**

Phase current at primary side (Y-connection) $I_{P_1} = I_{L_1} = 20\text{ A}$

Secondary phase current $I_{P_2} = I_{P_1}\times a = 20\times 12 = 240\text{ A}$

Secondary line current (Y-connection) $I_{L_2} = I_{P_2} = \mathbf{240\ A}$ **Ans.**

Output kVA $= 3V_{P_2}I_{P_2} = 3\times 529.23\times 240 = \mathbf{381.06\ kVA}$ **Ans.**

Scan for Video Solution

TEST 2

Q.1 A 3-phase transformer bank consists of three identical 2300/230 V, 15 kVA single phase transformers connected in delta/delta. The bank supplies a 20 kVA, unity power factor 3-phase load. If one of the single phase transformer develops a fault and is removed, the load carried by each of the two transformers now operating in open delta will be :

(A) 10 kVA (B) 15 kVA

(C) $20/\sqrt{3}$ kVA (D) 20 kVA

Q.2 A Δ/Δ connected transformer is connected as V/V connected transformer. The ratio of VA rating of V/V connected transformer and Δ/Δ connected transformer is **[ESE 2012]**

(A) 57.7% (B) 100%

(C) 50% (D) 75%

Q.3 When one transformer is removed from a Δ-Δ bank of 30 kVA transformer, the capacity of the resulting 3-phase transformer in V-V connection will be **[ESE 2011]**

(A) 11.5 kVA (B) 17.3 kVA

(C) 20 kVA (D) 25.9 kVA

Q.4 The primary line current of an open delta connected transformer is measured to be 100 A. If the turns ratio between the primary and secondary coils is 2 : 1, the secondary line current is

(A) 173.2 A (B) 200 A

(C) 150 A (D) 50 A

Q.5 Three 1100/110 V transformers connected in Δ-Δ supply a load of 100 kW. One of these transformers is removed. What ratio of current will flow in each transformer when three transformers were in service to the two transformers in service?

(A) 1.73 (B) 1

(C) 0.577 (D) None of these

Numerical Answer Type Questions

Three Phase Connections

Q.1 An 11000/440 V, 50 Hz, 3-phase transformer is delta connected on the HV side and the LV windings are star connected. There should be 12 V per turn and the flux density is not to exceed 1.2 Wb/m^2. Calculate the number of turns per phase on each winding and the net iron cross-sectional area of the core.

Q.2 If the primary line voltage rating is 3.3 kV (Y-side) of a 25 kVA, Y-Δ transformer (per phase ratio is 10 : 1). What is line current rating of secondary side of transformer?

Q.3 The winding of a Q kVAR $\frac{V_1}{V_2}$ V, 3-phase, Δ-connected, core type transformer are reconnected to work as 1-phase transformer. The maximum voltage and power rating of the new configuration is $\eta = 95.55\%$

Q.4 A 1000 kVA, 12/0.6 kV, 3 phase delta-star transformer has ohmic loss of 4 kW on H.V. side and 3 kW on L.V. under rated load. The total leakage reactance is 0.09 p.u. Calculate the ohmic values of the resistance on both sides.

Q.5 A 3-phase transformer is used to step-down the voltage of a 3-phase, 11 kV feeder line. Per phase turns ratio is 12. For a primary line current of 20 A, calculate the secondary line voltage, line current and output kVA for Delta-Delta connection.

Open Delta or V-V Connection

Q.1 Two 40 KVA single phase transformer are connected in open delta to supply 230 V balanced 3-phase load.

(i) What is the total load that can be supplied without over loading either transformer?

(ii) When the delta is closed by the addition of third 40 kVA transformer what total load now can be supplied.

(iii) % increase in load.

Q.2 Three single phase transformer connected in Δ-Δ supply a balanced 3-phase load of 1500 kW at 4400 V at 0.8 power factor lagging. The transformer are supplied from 3 phase mains at 11000 V. Find the current in the winding of each transformer. If one transformer is found faulty and the other two are connected in V-V determine the current in the winding of each transformer and its power factor.

Q.3 Three single phase transformer are connected in mesh. If one transformer is found faulty and removed. What will be the reduction in rating of each at the other transformer? What must be rating at each transformer in V-V connection to supply a three phase balanced load at 200 kVA. If a third similar transformer is included what will be the rated capacitor at set.

Q.4 Two identical 1 phase transformers are connected in open delta across 3 phase mains and deliver a balanced load of 3000 kW at 11 kV and 0.8 pf. lagging. Calculate

(i) the line and phase currents and the power factors at which the two transformers are working.

(ii) If one more identical unit is added and the open delta is converted to closed delta, calculate the additional load of the same power factor that can now be supplied for the same temperature rise. Also calculate the phase and line currents.

Q.5 Two transformers, each rated 250 kVA, 11/2 kV and 50 Hz, are connected in open delta on both the primary and secondary.

(i) Find the load kVA that can be supplied from this transformer connection.

(ii) A delta-connected three-phase load of 250 kVA, 0.8 pf, 2 kV is connected to the LV terminals of this open-delta transformer. Determine the transformer currents on the 11 kV side of this connection.

Answer of Test - 2 (Based on Open Delta or V-V Connection)

1.	C	2.	A	3.	B	4.	B	5.	C

Explanation of Test - 2 (Based on Open Delta or V-V Connection)

Sol.1

kVA rating of each transformer $=15\,\text{kVA}$,

Total load $=20\,\text{kVA}$

Total kVA load $=\sqrt{3}\times$kVA load carried by each transformer

kVA load carried by each transformer

$$=\frac{\mathbf{20}}{\sqrt{\mathbf{3}}}\,\textbf{kVA} \qquad \textbf{Ans.}$$

Hence, the correct option is (C).

Sol.2

$$\frac{\text{kVA rating of V-V connection}}{\text{kVA rating of }\Delta\text{-}\Delta\text{ connection}}=\frac{1}{\sqrt{3}}=0.5773$$

$$=\mathbf{57.73\%} \quad \textbf{Ans.}$$

Hence, the correct option is (A).

Sol.3

kVA rating at Δ-Δ connection $=30\,\text{kVA}$

$$\frac{\text{kVA rating of V-V connection}}{\text{kVA rating of }\Delta\text{-}\Delta\text{ connection}}=\frac{1}{\sqrt{3}}$$

kVA rating of V-V connection

$$=\frac{1}{\sqrt{3}}\times\text{ kVA rating at }\Delta\text{-}\Delta\text{ connection}$$

$$=\frac{1}{\sqrt{3}}\times 30=\mathbf{17.32\ kVA} \qquad \textbf{Ans.}$$

Hence, the correct option is (B).

Sol.4

Given : Primary line current in V-V connection $I_{L_1}=100\text{A}$, Turns ratio $=2:1$,

For V-V connection $I_{L_1}=I_{p_1}=100\,\text{A}$

Secondary phase current,

$$I_{p_2}=I_{p_1}\times\frac{N_1}{N_2}=100\times 2=200\,\text{A}$$

Secondary line current, $I_{L_2}=I_{p_2}=\mathbf{200\,A}$ **Ans.**

Hence, the correct option is (B).

Sol.5

Given : 3-ϕ load $=100\,\text{kW}$, $V_{P_1}=1100\text{V}$,

$V_{P_2} = 110\text{ V}$

kVA rating at $\Delta - \Delta = 3V_{P_n} I_{P(\Delta-\Delta)}$

kVA rating at $V - V = \sqrt{3} V_{P_n} I_{P(V-V)}$

Ratio of current, $\frac{I_{P(\Delta-\Delta)}}{I_{P(V-V)}} = \frac{1}{\sqrt{3}} = \mathbf{0.577}$ **Ans.**

Hence, the correct option is (C).

Explanation of NAT Questions (Based on Three Phase Connection)

Sol.1

Given : $V_{L1} = 11000\text{ V}$, $V_{L2} = 440\text{ V}$,

Emf per turns $= 12\text{ V}$,

Flux density $B = 1.2\text{ Wb/m}^2$

Phase voltage of primary side (Δ),

$V_{P1} = V_{L1} = 11000\text{ V}$

Phase voltage of secondary side (Y),

$$V_{P2} = \frac{V_{L2}}{\sqrt{3}} = \frac{440}{\sqrt{3}}$$

Emf per turn in primary side $= \frac{V_{P1}}{N_1} = 12$

$$\frac{11000}{N_1} = 12$$

$\therefore$ Primary number of turns,

$$N_1 = \frac{11000}{12} = 917\text{ turns}$$ **Ans.**

Emf per turn in secondary side $= \frac{V_{P2}}{N_2} = 12$

$$\frac{440}{\sqrt{3} \times N_2} = 12$$

$\therefore$ Secondary number of turns,

$$N_2 = \frac{440}{\sqrt{3} \times 12} = 21\text{ turns}$$ **Ans.**

Induced emf per turn,

$$\frac{V_{P2}}{N_2} = 4.44\, B_m A \times f$$

$$12 = 4.44 \times 1.2 \times 50 \times A$$

Cross sectional area,

$$A = \frac{12}{4.44 \times 1.2 \times 50} = 450\text{ cm}^2$$ **Ans.**

Sol.2

Given : VA rating = 25 kVA, $V_{L_1} = 3.3\text{ kV}$,

$$\frac{V_1}{V_2} = 10:1$$

Transformation ratio, $K = \frac{1}{10}$

Phase voltage of primary side (Y-connected),

$$V_{P_1} = \frac{V_{L_1}}{\sqrt{3}} = \frac{3.3 \times 10^3}{\sqrt{3}} = 1905.25\text{ V}$$

Using transformation ratio, $\frac{V_{P_2}}{V_{P_1}} = \frac{N_2}{N_1}$

$$\therefore \quad V_{P_2} = 1905.25 \times \frac{1}{10} = 190.52\text{ V}$$

Phase current of secondary side,

$$I_{P_2} = \frac{25 \times 10^3}{3 \times V_{P_2}}$$

$$I_{P_2} = \frac{25 \times 10^3}{3 \times V_{L_2}} = \frac{25 \times 10^3}{3 \times 190.52} = 43.73\text{ A}$$

Line current of secondary side, (Δ-connected)

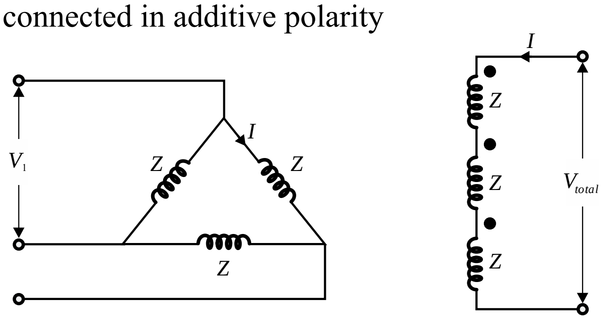
$$I_{L_2} = \sqrt{3} \times I_{P_2} = \sqrt{3} \times 43.73\text{ A} = 75.75\text{ A}$$

Ans.

Sol.3

Delta connected transformer are reconnected as 1-ϕ transformer the connection diagram.

For maximum voltage all winding must be connected in additive polarity



In single phase transformer,

Total voltage,

$$V_{total} = \text{Sum of all phase voltage} = 3V_P$$

If current rating is same, so power rating of delta connection,

$$Q = 3V_P I$$

Power rating of 1-ϕ connection,

$$Q = (3V_P)I = 3V_P I$$

∴ Power rating of new configuration is same as delta connected system.

Sol.4

Given : VA rating = 1000 kVA, $V_{L_1} = 12$ kV,

$V_{L_2} = 0.6$ kV,

Full load copper loss in HV side = 4 kW,

Full load copper loss in LV side = 3kW,

$X_{PU} = 0.09$ pu

Phase voltage of primary side (Δ-connection),

$$V_{P_1} = V_{L_1} = 12 \text{ kV}$$

Phase voltage of secondary side (Y-connection),

$$V_{P_2} = \frac{V_{L_2}}{\sqrt{3}} = \frac{0.6}{\sqrt{3}} \text{kV}$$

Phase current on primary side,

$$I_{P_1} = \frac{1000 \times 10^3}{3 \times V_{P_1}}$$

$$I_{P_1} = \frac{1000 \times 10^3}{3 \times 12 \times 10^3} = 27.77 \text{ A}$$

Phase current on secondary side,

$$I_{P_2} = \frac{1000 \times 10^3}{3 \times V_{P_2}}$$

$$I_{P_2} = \frac{1000 \times 10^3}{3 \times \frac{0.6}{\sqrt{3}} \times 10^3} = 962.52 \text{ A}$$

Full load copper loss in primary side $= 3I_{P_1}^2 R_{01}$

$$4 \times 10^3 = 3 \times (27.77)^2 R_{01}$$

Resistance in H.V. side, $R_{01} = 1.728\ \Omega$ **Ans.**

Full load copper loss in secondary side

$$3 \times 10^3 = 3 \times (962.25)^2 R_{02}$$

Resistance in L.V. side, $R_{02} = 1.08$ mΩ **Ans.**

Scan for Video Solution

Sol.5

Given : Primary line voltage $V_{L_1} = 11000$ V,

Turns ratio = 12, Primary current $I_{L_1} = 20$ A,

Primary phase voltage (Δ-connection),

$V_{P_1} = V_{L_1} = 11000$ V.

Secondary phase current,

$$V_{P_2} = V_{P_1} \times \frac{N_2}{N_1} = \frac{V_{P_1}}{12}$$

$$V_{P_2} = \frac{11000}{12} = 916.67 \text{ V}$$

Secondary line voltage (Δ-connection),

$$V_{L_2} = V_{P_2} = 916.67 \text{ V}$$ **Ans.**

Primary phase current (Δ-connection),

$$I_{P_1} = \frac{I_{L_1}}{\sqrt{3}} = \frac{20}{\sqrt{3}} = 11.54 \text{ A}$$

Secondary phase current,

$$I_{P_2} = I_{P_1} \times \frac{N_1}{N_2} = 11.54 \times 12 = 138.56 \text{ A}$$

Secondary lime current (Δ-connection),

$$I_{L_2} = \sqrt{3} I_{P_2} = \sqrt{3} \times 138.56 = 240 \text{ A}$$ **Ans.**

Output kVA $= 3V_{P_2} I_{P_2}$

$$= 3 \times 916. \times 67 \times 138.56 = 381 \text{ kVA}$$ **Ans.**

Explanation of NAT Questions (Based on Open Delta or V-V Connection)

Sol.1

(i) KVA load carried by each transformer,

$$(\text{kVA})_{V-V} = \frac{(\text{kVA})_{\Delta-\Delta}}{\sqrt{3}} = \frac{40\times 3}{\sqrt{3}} = 69.28$$

Ans.

(ii) When Δ is closed,

$$(\text{kVA})_{\Delta-\Delta} = 3\times 40 = 120 \text{ kVA}$$ **Ans.**

(iii) % increase in load kVA

$$= \frac{120-69.28}{69.28}\times 100 = 73.2\%$$ **Ans.**

Sol.2

For Δ-Δ connection :

Phase voltage of secondary side,

$V_{P2} = V_{L2} = 4400\,\text{V}$

Phase current of secondary side,

$$I_{P_2} = \frac{1500\times 10^3}{3\times V_{P_2}\times\cos\phi}$$

$$I_{P_2} = \frac{1500\times 10^3}{3\times 4400\times 0.8} = 142.04\,\text{A}$$

Transformation ratio,

$$K = \frac{4400}{11000} = 0.4$$

Phase current in primary side,

$$I_{P1} = I_{P2}\times\frac{N_2}{N_1}$$

$$I_{P1} = 142.04\times 0.4 = 56.81\,\text{A}$$

For V-V connection :

Phase current of secondary side,

$$I_{P2} = \frac{1500\times 10^3}{\sqrt{3}\times V_{P2}\times\cos\phi}$$

$$\left[\because S_{V-V} = \sqrt{3}V_P I_P\right]$$

$$I_{P2} = \frac{1500\times 10^3}{\sqrt{3}\times 4400\times 0.8} = 246\,\text{A}$$ **Ans.**

Phase current in primary side,

$$I_{P1} = I_{P2}\times\frac{N_2}{N_1}$$

$$I_{P1} = 246\times 0.4 = 98.4\,\text{A}$$ **Ans.**

Power factor of transformer in V-V connection $= 0.866$ times the power factor in Δ-Δ connection

$= 0.866\times 0.8 = 0.6928$ (lagging). **Ans.**

Scan for Video Solution

Sol.3

Given : Total load $=$ 200 kVA

Let the rating at each transformer $= S_1$

Total rating of three transformer $= 3S_1$

Total rating of two transformer at V-V connection $= 2S_1$

Ratio of V-V bank to Δ-Δ bank transformer rating

$$\frac{\text{V-V rating}}{\Delta\text{-}\Delta\text{ rating}} = \frac{1}{\sqrt{3}}$$

$$(\text{kVA})_{\Delta-\Delta} = 3S_1$$

$$(\text{kVA})_{V-V} = 0.577\times 3S_1 = 1.731\,S_1$$

Reduction in rating for V-V set

$$= 2S_1 - 1.751\,S_1 = 0.269\,S_1$$

Reduction in rating of each transformer

$$= \frac{0.269 S_1}{2} = 13.4\% \text{ of its rating}$$

$\because$ Total load kVA = 200 kVA

Load shared by one transformer

$$= \frac{200}{2} = 100\,\text{kVA}$$

Let S_2 be the rating at each transformer

$$S_2 - 0.1345\,S_2 = 100\,\text{kVA}$$

$$0.8655 S_2 = 100$$

$$S_2 = 115.54$$

Rating of each transformer in V-V connection = 115.54 kVA **Ans.**

If third transformer of 115.54 kVA is included rating of new set

$$= 3 \times 115.54 = 346.42 \text{ kVA}$$ **Ans.**

Sol.4

Given : Power $P = 3000 \text{ kW}$,

Line voltage $V_{L_2} = 11 \text{ kV}$,

Power factor $\cos\phi = 0.8$

For Δ connected transformer :

(i) Power supplied by transformer $= 3000$ kW

$$P = \sqrt{3} V_{L_2} I_{L_2} \cos\phi$$

Line current, $I_{L_2} = \dfrac{P}{\sqrt{3} V_{L_2} \cos\phi}$

$$I_{L_2} = \frac{3000 \times 10^3}{\sqrt{3} \times 11 \times 10^3 \times 0.8} = 197 \text{ A}$$ **Ans.**

In open delta line current and phase current are same,

$\therefore$ Phase current = 197 A

Power factor of V-V connection transformer

= 86.6% of power factor of Δ-Δ connection

$$= 0.866 \times 0.8 = 0.6928$$ **Ans.**

(ii) Additional load carried = 72.5% of original load $= 0.725 \times 3000 = 2175 \text{ kW}$ **Ans.**

Total load $= 3000 + 2175 = 5175 \text{ kW}$

$$P = \sqrt{3} V_L I_L \cos\phi$$

Line current, $I_{L_2} = \dfrac{P}{\sqrt{3} V_{L_2} \cos\phi}$

$$I_{L_2} = \frac{5175 \times 10^3}{\sqrt{3} \times 11 \times 10^3 \times 0.8} = 340 \text{ A}$$

In Δ-Δ connection, $I_{L_2} = \sqrt{3} I_{ph_2}$ i.e.,

Phase current, $I_{ph_2} = \dfrac{I_{L_2}}{\sqrt{3}} = \dfrac{340}{\sqrt{3}} = 196 \text{ A}$

Scan for Video Solution

Sol.5

Given :

kVA rating of each transformer = 250 kVA,

$V_{P1} = 11 \text{ kV}$, $V_{P2} = 2 \text{ kV}$

Phase current in secondary side,

$$I_{P2} = \frac{250 \times 10^3}{2 \times 10^3} = 125 \text{ A}$$

(i) kVA rating of V-V connection

$$= \sqrt{3} V_{P2} I_{P2}$$

$$= \sqrt{3} \times 2 \times 10^3 \times 125 = 433 \text{ kVA}$$ **Ans.**

(ii) If a delta connected 3-ϕ load connected to L.V. side,

Two phase current in secondary side,

$$I_{P2} = \frac{250 \times 10^3}{\sqrt{3} \times V_{P2}} = \frac{250 \times 10^3}{\sqrt{3} \times 2 \times 10^3} = 72.2 \text{ A}$$

Transformation ratio,

$$K = \frac{2000}{11000} = 0.1818$$

Phase current in primary side,

$$I_{P1} = I_{P2} \times \frac{N_2}{N_1}$$

$$I_{P1} = 72.2 \times 0.1818 = 13.12 \text{ A}$$ **Ans.**

CHAPTER 4

DC Machine

Learning Objectives :

After reading this chapter you should be able to :

- Understand : Working of dc motor and generator.
- Explain EMF and torque equations.
- Explain losses and efficiency of dc machines.
- Describe characteristics of dc machines.
- Understand starting of dc motor.
- Understand speed control of dc machine.
- Explain various braking method.

Table of Contents

4.1 Introduction

The field of industrial direct current usage-being very wide, dc machines are produced both as generators and motors for a very large range of output, voltage, speed, etc.

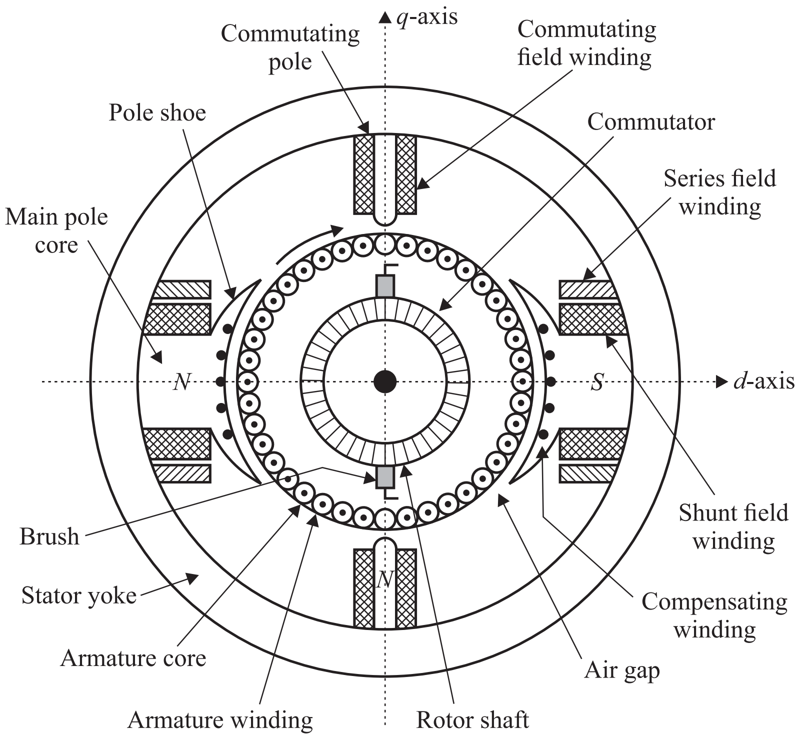
DC generator : A machine that converts mechanical power to electrical power of dc nature is called a dc generator. The basic principle of working of a dc generator is Faraday's law of electromagnetic induction, which states that if there is a relative motion between a conductor and a magnetic field, a dynamically induced emf is produced in the conductor. The direction of the induced emf depends upon the direction of magnetic field and the direction of motion and is given by Fleming's right hand rule. Normally, the armature of the dc generator, carrying a number of conductors suitably arranged, is made as the rotating member, whereas the field is kept stationary. The mechanical energy for the rotation of the armature may be derived from a steam engine, an internal combustion engine, a steam or water turbine.

DC motor : A dc machine that converts electrical power into mechanical power is known as dc motor, that is in action the dc motor, is converse of the dc generator. The dc motor basically works on the principle that when a conductor carrying current is placed in a magnetic field, mechanical force acts on the current carrying conductor, and as a result the conductor starts rotating in a direction depending upon the direction of current and the field, and is given by Fleming's left hand rule.

4.2 Basics of Construction

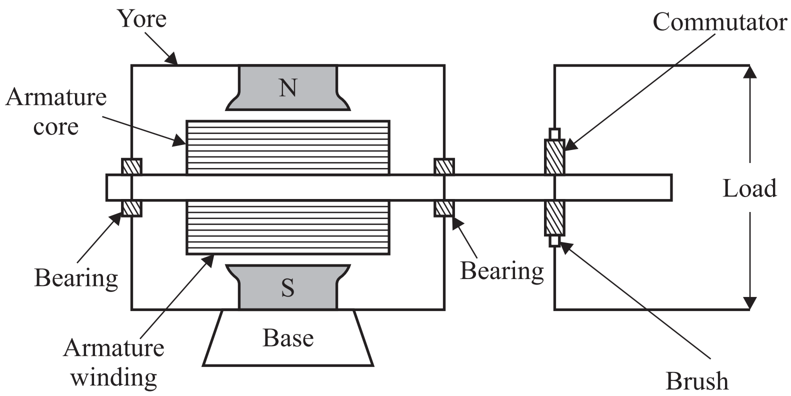
4.2.1 Common Features of All Rotating Electrical Machine

- The poles contains alternate north and south poles of even number.
- Excitation should be essentially in DC.



- There will be stator (stationary part) and rotor (rotating part) with a least possible air gap between them (0.5 to 2 mm).
- There is a magnetic circuit comprising flux path and an electric circuit comprising load current.

Side view of DC machine :



4.2.2 Parts of DC Machine

1. **Stator :** Stationary part of the machine. The stator carries a field winding that is used to produce the required flux. Main parts of stator are :

(i) Yoke (ii) Field pole
(iii)Field winding (iv)Inter pole
(v) Compensating winding (vi)Brushes
(vii) End cover (viii) Bearing
(ix)Base

2. **Rotor :** Rotating part of the machine. The rotor carries a distributed winding, and is the winding where the emf is induced. It is also known as the armature.

Main parts of rotor are :

(i) Armature core (ii) Armature winding
(iii)Shaft (iv)Commutator
(v) Spider (for large machines)

4.2.3 Stator Parts

1. **Yoke or outer frame or magnetic frame :**
   - It protects the entire machine and also supports the poles.
   - It offers flux path completion of $\phi / 2$ (ϕ is flux per pole).
   - Yoke should be good magnetic material.
     (i) Cast iron are used for small machines.
     (ii) Cast steel are used for large machines.
   - No need of laminations since flux is stationary i.e. no eddy current and hysteresis losses.
   - If dc machines is under power electronic converter operation, laminated yokes are preferred.

Advantage of using cast steel for yoke material :

The yoke was made up of cast iron earlier but now it is replaced by cast steel due to following advantages :

(i) This is due to fact that cast iron is saturated by a flux density of 0.8 Wb/m^2 whereas the saturation flux density of cast steel is about 1.5 Wb/m^2.

(ii) The working flux density of cast steel is approximately twice than that of cast iron.

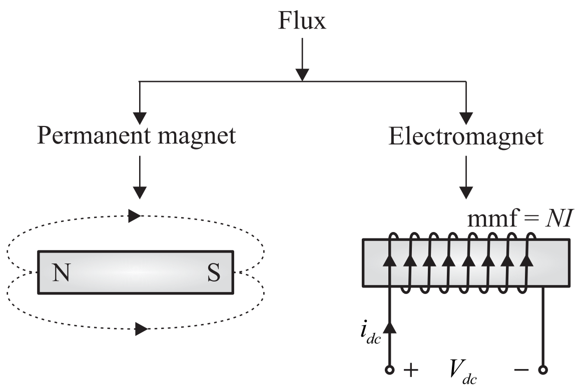
(iii)The cross section area and hence weight of cast steel is one half that of cast iron.

(iv)The mechanical and magnetic properties of cast iron are uncertain due to blow holes in the material.

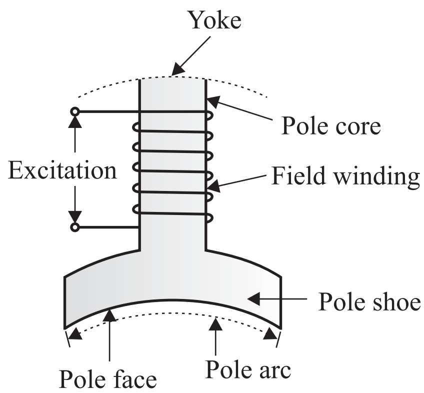
2. Field poles :

- The purpose of a pole is to produce working flux in the machine.
- There are two principle sources of flux as shown in figure,

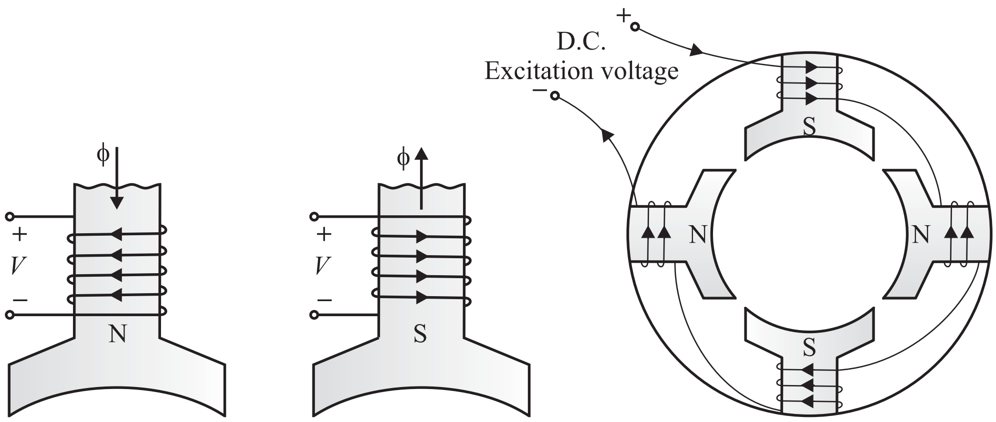
  (i) Permanent magnet (ii) Electromagnet



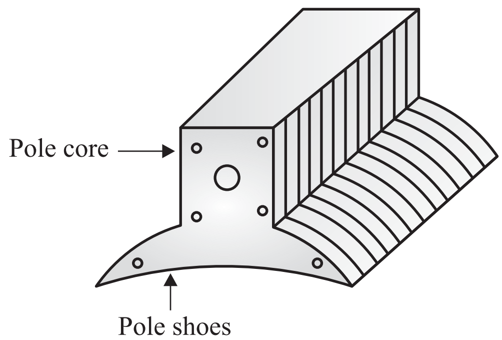
- The basic source of the flux is permanent magnet. Here, the flux can not be controlled as shown in figure.
- In order to have control on the machine in term of say speed, flux need to be controlled. Therefore, electromagnets are preferred as shown in figure, required winding and a dc voltage source across it called as excitation.
- Excitation is essentially dc because it produce fixed polarity.
- The pole shape is broad in order to distribute the flux uniformly, so that wave form of voltage induced improve and air gap is also reduced and hence permeability is increased.
- The pole is spread out as pole shoes because to reduce the reluctance in the air gap and to spread flux uniformly on the armature conductor as shown in above figure.



- The polarity of a pole depends on the polarity of excitation and orientation or sense of winding as shown in below figure,



- Poles are also made up at steel lamination for reducing eddy current loss,



(i) Functions of pole shoe :

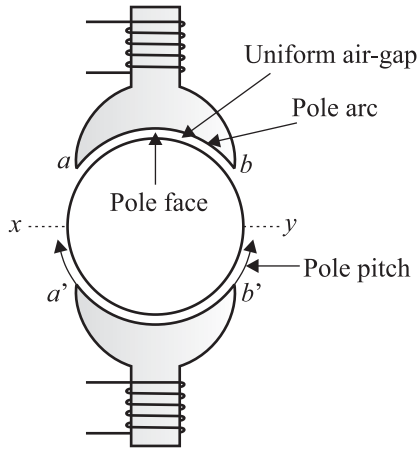
- Provides mechanical support to field winding.
- Spread out flux uniformly into air gap.
- Provide low reluctance path for main field flux.
- There are two type of pole shoe :

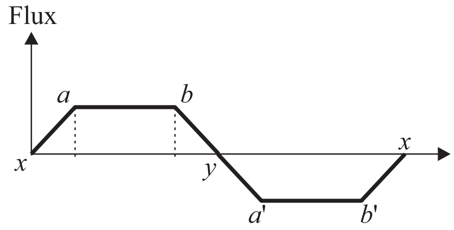
  (a) Arc shaped pole shoe (b) Chamfered pole shoe
- In DC Machine, arc shaped pole shoe are used, therefore at no-load flux produced in air gap of DC machine is flat topped or trapezoidal, then shape of induced emf is flat topped which has higher average value and therefore output of DC generator increases and ripples are eliminated.
- Flat topped emf consists of harmonics in addition to fundamental but in DC Machines quantity is more important than quality.
- In AC Machine, chamfered pole shoes are used and therefore at no-load condition air gap flux is sinusoidal so induced emf is sinusoidal which is free from harmonics. In AC Generator, quality is most important factor.

(ii) Pole pitch :

The angular distance between two adjacent poles in a machine.

- It is always 180^0 electrical.
- Pole pitch is distance of x to y.
- Pole pitch $= \dfrac{\text{Number of slot}}{\text{Number of pole}}$





(iii)Pole arc :

- Pole arc is also expressed in terms of slots *ab* like pole pitch.
- The length of pole arc is always less than pole pitch.
- Design value of pole arc to pole pitch ratio are 0.7. This will cause an induced emf or main field flux 70 % flat-lapped in nature.
- The ratio of pole arc and pole pitch is given by,

$$\frac{\text{Pole arc } (ab)}{\text{Pole pitch } (xy)} = 0.7 \text{ to } 0.9$$

3. Field winding :

- The field winding of DC machine are made with field coils (copper wire) wound over the slots of the pole shoes in such a manner that when field current flows through it, then adjacent poles have opposite polarity are produced.
- The field winding basically form an electromagnet, that produces field flux within which the rotor armature of the DC motor rotates, and results in the effective flux cutting.
- The field winding is wound on the pole core with a definite direction. It carry current due to which pole core, on which the field winding is placed behaves as an electromagnet, producing necessary flux.
- Field winding is divided into various coils called field coils. These are connected in series with each other and wound in such a direction around pole cores, such that alternate '*N*' and '*S*' poles are formed.

Remember

At full load condition, field winding content maximum Ampere turn. Hence, it is most powerful electromagnet in dc machine.

4. Inter pole :

- Inter poles are small poles compared to main poles and placed in Inter polar region between the main poles.
- These are also electromagnets and are connected in series with armature windings through the brushes.

Function of inter poles :

(i) It produces a counter flux on the coil which is undergoing commutation to nullify the reactance voltage.

(ii) It also nullifies the armature flux in the inter-polar region automatically.

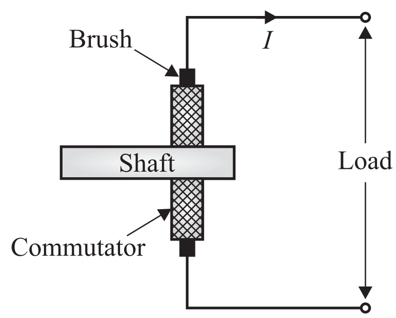
(iii) Inter poles are tapered in shape in order to avoid the saturation of flux in the inter polar windings.

5. Compensating winding :

- The compensating windings consist of a series of coils embedded in slots in the pole faces.
- These coils are connected in series with the armature. The series-connected compensating windings produce a magnetic field, which varies directly with armature current.
- Because the compensating windings are wound to produce a field that opposes the magnetic field of the armature, they tend to cancel the cross magnetizing effect of the armature magnetic field.
- The neutral plane will remain stationary and in its original position for all values of armature current. Because of this, once the brushes have been set correctly, they do not have to be moved again.

6. Brushes :

- Brushes offer electrical connection between rotating commutator and stationary load as shown in figure.
- They collect current from the winding placed on the commutator through brush holders and spring.
- These are stationary sliding contacts.
- If the brushes collect current without any sparking then the commutation is successful.
- In order to insure successful commutation mechanical as well as electrical conduction should be proper.
- For small dc machine carbon brushes are used, for large DC machine electro graphite are used as brush material and extra high voltage DC machine copper graphite are used.



- In order to insure good mechanical conduction the brushes are placed in a brush holder and placed on the commulator through spring.
- In order to insure good electric conduction and successful commutation, the brushes should be always placed on magnetic neutral axis (MNA).
- Carbon brushes are used generally to improve commutation.

Remember

Brushes are in contact with rotating part and stationary part. Thus, if more amount of current is to be carried, it requires more number of brushes. Hence brush number depends directly on the amount of current that needs to be collected and fed up in or out.

7. End housings :

- End housings are attached to the ends of the mainframe and provide support to the bearings.
- The front housings support the bearing and the brush assemblies whereas the rear housings usually support the bearings only.

8. Bearing :

- The ball or roller bearings are fitted in the end housings.
- The function of the bearings is to reduce friction between the rotating and stationary parts of the machine.
- Mostly high carbon steel is used for the construction of bearings as it is very hard material.

9. Shaft :

- The shaft is made of mild steel with a maximum breaking strength.
- The shaft is used to transfer mechanical power from or to the machine.
- The rotating parts like armature core, commutator, cooling fans, etc. are keyed to the shaft.

Numerical Answer Type Questions

Basic of Construction

Q.1 A 4-pole, lap wound, d.c. generator has a useful flux of 0.07 Wb per pole. Calculate the generated e.m.f. when it is rotated at a speed of 900 r.p.m. with the help of prime mover. Armature consists of 440 number of conductors. Also calculate the generated e.m.f. if lap wound armature is replaced by wave wound armature.

Q.2 A dc generator has an armature emf of 100 V when the useful flux per pole is 20 mWb and the speed is 800 rpm. Calculate the generated emf

(i) with the same flux and a speed of 1000 rpm.

(ii) with a flux per pole of 24 mWb and a speed of 900 rpm.

Q.3 A 4-pole dc generator has 48 slots and 8 conductors per slot. The useful flux per pole is 30 mWb and speed is 800 rpm. The generator emf is E_1 if the machine is lap wound and it is E_1 if the machine is wave wound. Find the values of E_1 and E_2.

Q.4 An 8 pole lap wound armature rotated at 350 rpm is required to generate 260 V. The useful flux per pole is about 0.05 Wb. If the armature has 120 slots, calculate a suitable number of conductors per slot and hence determine the actual value of flux required to generate the same voltage.

EMF & Torque Equation of DC Machines

Q.1 A 10 kW, 6 pole dc generator develops an emf of 200 V at 1500 rpm. The armature has a lap connected winding. The average flux density over a pole pitch is 0.9 Tesla. The length and diameter of the armature are 0.25 m and 0.2 m respectively. Calculate :

(i) The flux per pole

(ii) The total number of active conductors in the armature.

(iii) The torque developed by the machine when the armature supplies a current of 50 A.

Q.2 An 8 pole lap connected dc generator has 500 armature conductors, a useful flux of 0.05 Wb and runs at 1203 rpm. The speed at which it is to be driven to produce the same emf, if it is wave wound is _______ rpm.

Q.3 A dc motor runs steadily drawing an armature current of 15 A. To develop the same amount of torque at 20 A armature current, flux should be

(A) reduced by 25%

(B) increased by 25%

(C) reduced by 33%

(D) increased by 33%

Q.4 The armature of 4 pole lap wound dc machine has core, length = 30 cm, diameter = 40 cm. total conductor = 500, speed = 1200 rpm, current = 20 A. For average flux density of 0.5T. find electromagnetic power developed and internal torque.

Separately Excited DC Machines

Q.1 A 250 V, 10 kW separately excited generator has an induced e.m.f. of 255 V at full load. If the brush drop is 2 V per brush, calculate the armature resistance of the generator.

Q.2 A separately excited dc generator, running at a speed of 1200 rpm delivers 150 A, at 400 V to a constant resistive load. The armature resistance of the generator is $0.12\,\Omega$. If the current is reduced to 100 A and the armature reaction is neglected then find the speed of the generator.

Q.3 A separately excited dc motor is driving a fan load whose torque is proportional to the square of the speed. When 100 V is applied to the motor, the current taken by the motor is 8 A, with the speed being 500 rpm. At what applied voltage does the speed reach 750 rpm and then what is the current drawn by the armature? Assume the armature circuit resistance to be $1\,\Omega$. Neglect brush drop and mechanical losses.

Q.4 A 220 V, 1.5 kW, 859 rpm separately excited dc motor has armature resistance of $2.5\,\Omega$ and it draws a current of 8 A at rated load condition. If the field current and armature voltage are fixed at the value of the rated speed at rated load, what will be the no load speed of the motor? Assume losses remain constant between no load and full load operation.

Q.5 A separately excited dc generator has no load voltage of 120 V at a field current of 2 A, when driven at 1500 rpm. It is operating on the straight line portion of its saturation curve. Calculate the generated voltage when

(i) the field current is increased to 2.5 A.

(ii) the field current is increased to 2.84 A and the speed is reduced to 1400 rpm.

Q.6 A separately excited generator, when running at 1000 rpm supplies 200 A at 125 V. The armature resistance is $0.04\ \Omega$ and brush drop is 2 V. If field current is unchanged and torque is proportional to speed and the speed drops to 800 rpm, the load current is _______ Amp.

Explanation of NAT Question (Based on Basic of Construction)

Sol.1

Given : Number of pole $P = 4$,

Armature conductor $Z = 440$,

Flux per pole $\phi = 0.07$ Wb,

Speed $N = 900$ r.p.m.

Generatored emf, $E = \dfrac{\phi ZNP}{60A}$

(i) For lap wound, $A = P = 4$

Generated emf, $E = \dfrac{\phi ZNP}{60A}$

$$E = \frac{0.07 \times 440 \times 900 \times 4}{60 \times 4} = 462\ \text{V}$$ **Ans.**

(ii) For wave wound $A = 2$

Generated emf, $E = \dfrac{\phi ZNP}{60A}$

$$E = \frac{0.07 \times 440 \times 900 \times 4}{60 \times 2} = 924\ \text{V}$$ **Ans.**

Sol.2

Given : Induced emf $E_1 = 100\ \text{V}$,

Flux per pole $\phi_1 = 20 \times 10^{-3}$ Wb,

Speed $N_1 = 800$.

(i) With the same flux and a speed of 1000 rpm i.e., $\phi_2 = 20 \times 10^{-3}$, $N_2 = 1000$ rpm

We know, $E \propto \phi N$

$$\frac{E_1}{E_2} = \frac{N_1 \times \phi_1}{N_2 \times \phi_2}$$

$$\frac{100}{E_2} = \frac{800 \times 20 \times 10^{-3}}{1000 \times 20 \times 10^{-3}} = 0.8$$

Generated e.m.f., $E_2 = \dfrac{100}{0.8} = 125\ \text{V}$

Ans.

(ii) With a flux per pole of 24 mWb and a speed of 900 rpm i.e.,

$\phi_2 = 24 \times 10^{-3}$ Wb, $N_2 = 900$ rpm.

$$\frac{E_1}{E_2} = \frac{N_1 \times \phi_1}{N_2 \times \phi_2}$$

$$\frac{100}{E_2} = \frac{800 \times 20 \times 10^{-3}}{900 \times 24 \times 10^{-3}} = 0.7407$$

Generated e.m.f., $E_2 = 135\ \text{V}$ **Ans.**

Sol.3

Number of pole $P = 4$,

Number of slot $= 48$,

Conductor per slot $= 8$,

Flux per pole $= 30$ mWb,

Speed $N = 800$ rpm,

Total number of conductor $Z = 48 \times 8 = 384$,

For lap winding $A = P = 4$.

Generated emf, $E_1 = \dfrac{\phi ZNP}{60\ \text{A}}$

$$E_1 = \frac{30 \times 10^{-3} \times 384 \times 800 \times 4}{60 \times 4} = 153.6\ \text{V}$$

Ans.

For wave winding, $A = 2$

Generated emf, $E_2 = \frac{\phi ZNP}{60\,A}$

$$E_2 = \frac{30\times10^{-3}\times384\times800\times4}{60\times2} = 307.2\,\text{V}$$

Ans.

Sol.4

Given : Number of Pole $= 8$,

Lap winding $A = P = 8$,

Speed, $N = 350$ rpm,

Induced voltage $E_g = 260\,\text{V}$,

Flux per pole $= 0.05\,\text{Wb}$,

Number of slot $= 120$.

Generated emf, $E_g = \frac{\phi ZNP}{60\,A}$

∴ Total number of armature conductor

$$Z = \frac{E_g\times60\times A}{\phi\times N\times P}$$

$$Z = \frac{260\times60\times8}{0.05\times350\times8} = 891.42$$ **Ans.**

Number of conductor per slot,

$$\frac{Z}{\text{Slots}} = \frac{891.42}{120} = 7.428 \cong 8$$

Actual value of flux required,

$$\phi = \frac{E_g\times60\times A}{Z\times N\times P}$$

$$\phi = \frac{260\times60\times8}{8\times120\times350\times8} = 0.0464\,\text{Wb}$$ **Ans.**

Scan for Video Solution

Explanation of NAT Question (Based on EMF & Torque Equation of DC Machine)

Sol.1

Given : Output $P_L = 10\,\text{kW}$,

Number of pole $P = 6$,

Generated emf $E_g = 200\,\text{V}$

Speed $N = 1500$ rpm,

Lap connection $A = P = 6$,

Flux density $B = 0.9T$

Length of diameter of armature $l = 0.25\,\text{m}$,

Diameter of armature $D = 0.2\,\text{m}$

Armature current $I_a = 50\,\text{A}$.

(i) Flux per pole,

$$\phi = \frac{\pi\times D\times l\times B}{P}$$

$$\phi = \frac{\pi\times0.25\times0.2\times0.9}{6} = 0.02356\,\text{Wb}$$

$$\phi = 23.56\text{ mWb}$$ **Ans.**

(ii) Generated emf, $E_g = \frac{\phi ZNP}{60\,A}$

∴ Total number of active conductor

$$Z = \frac{E_g\times60\times A}{\phi\times N\times P}$$

$$Z = \frac{200\times60\times6}{23.56\times10^{-3}\times1500\times6}$$

$$Z = 339.53 \cong 340$$ **Ans.**

(iii) Torque developed,

$$T = \frac{E_g I_a}{\omega_n} = \frac{200\times50\times60}{2\pi\times1500} = 63.66\text{ Nm}$$

Ans.

Sol.2

Given : Number of pole $P = 8$,

Lap connection $A = P = 8$,

Number of armature conductor $Z = 500$,

Flux per pole $\phi = 0.05$ Wb,

Speed $N = 1203$ rpm.

Generated emf, $E_g = \frac{\phi ZNP}{60A}$

$$E_g = \frac{0.05\times500\times1203\times8}{60\times8} = 501.25\text{ V}$$

Wave connected winding $A = 2$

Speed, $N = \dfrac{E_g \times 60 \times A}{\phi \times Z \times P}$

$$N = \frac{501.25 \times 60 \times 2}{0.05 \times 500 \times 8} = 300.75 \text{ A} \quad \textbf{Ans.}$$

Sol.3

Given : Armature current at case 1 : $I_{a_1} = 15$ A

Armature current at case 2 : $I_{a_2} = 20$ A

Torque, $T \propto \phi I_a$

If torque is constant, $\phi \propto \dfrac{1}{I_a}$

$$\therefore \quad \frac{\phi_2}{\phi_1} = \frac{I_{a_1}}{I_{a_2}} = \frac{15}{20}$$

$$\phi_2 = 0.75\phi_1$$

Change in flux $= \dfrac{\phi_2 - \phi_1}{\phi_1} \times 100 = \left(\dfrac{\phi_2}{\phi_1} - 1\right) \times 100$

$$= (0.75 - 1) \times 100 = -25\%$$

So in case of 20 A armature current flux reduced by 25%. **Ans.**

Scan for Video Solution

Sol.4

Given : Number of pole, $P = 4$,

Lap connection $A = P = 4$,

Core length $l = 30 \text{ cm} = 30 \times 10^{-2}$ m,

Diameter $D = 40 \text{ cm} = 40 \times 10^{-2}$ m,

Total conductor $Z = 500$,

Speed $N = 1200$ rpm,

Armature current $I_a = 20$ A,

Flux density $B = 0.5$ T.

Flux per pole, $\phi = \dfrac{\pi \times D \times l \times B}{P}$

$$\phi = \frac{\pi \times 40 \times 10^{-2} \times 30 \times 10^{-2} \times 0.5}{4}$$

$$\phi = 0.0471 \text{ Wb}$$

Generated emf, $E_g = \dfrac{\phi Z N P}{60 A}$

$$E_g = \frac{0.0471 \times 500 \times 1200 \times 4}{60 \times 4} = 471 \text{ V}$$

Mechanical power developed

$$= E_g \times I_a = 471 \times 20 = 9420 \text{ W} \quad \textbf{Ans.}$$

Torque developed, $T = \dfrac{E_g I_a}{\omega_n} = \dfrac{9420}{2\pi N / 60}$

$$T = \frac{9420 \times 60}{2\pi \times 1200} = 74.96 \text{ Nm} \quad \textbf{Ans.}$$

Explanation of NAT Question (Based on Separately Excited DC Machines)

Sol.1

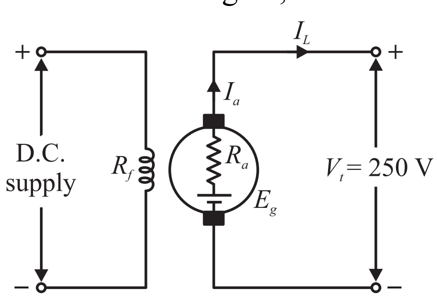
Given : Generated emf $E_g = 255$ V,

Terminal voltage $V_t = 250$ V,

Output power $P_L = 10$ kW,

Brush drop = 2V/brush .

Connection diagram of separately excited generator as shown in figure,



Note that 250 V, 10 kW generator means the full load capacity of generator is to supply 10 kW load at a terminal voltage $V_t = 250$ V.

Load current, $I_L = \dfrac{\text{Power consumed}}{\text{Terminal voltage}}$

$$I_L = \frac{P_L}{V_t} = \frac{10000}{250} = 40 \text{ A}$$

Armature current, $I_a = I_L = 40$ A

Generated emf, $E_g = V_t + I_a R_a +$ Brush drop

$$255 = 250 + 40 \times R_a + 2 \times 2$$

Armature resistance, $R_a = 0.025\ \Omega$ **Ans.**

Sol.2

Given : Speed $N_1 = 1200$ rpm ,

Armature current $I_{a_1} = 150\,\text{A}$,

Terminal voltage, $V_{t_1} = 400\,\text{V}$,

Armature resistance $R_a = 0.1252$.

Load resistance, $R_L = \dfrac{V_t}{I_{a_1}} = \dfrac{400}{150} = 2.67\,\Omega$

Case 1 :

Generated emf, $E_{g_1} = V_{t_1} + I_{a_1} R_a$

$$E_{g_1} = 400 + 150 \times 0.12 = 418\,\text{V}$$

Case 2 : When load current 100 A,

Terminal voltage,

$$V_{t_2} = I_{a_2} R_a = 100 \times 2.67 = 267\,\text{V}$$

Generated emf, $E_{g_2} = V_{t_2} + I_{a_2} R_a$

$$E_{g_2} = 267 + 100 \times 0.12 = 279\,\text{V}$$

$\because \quad E_g \propto N\phi \qquad (\because \phi = \text{Constant})$

$\therefore \quad \dfrac{E_{g_2}}{E_{g_1}} = \dfrac{N_2}{N_1}$

$\therefore \quad$ Speed, $N_2 = N_1 \times \dfrac{E_{g_2}}{E_{g_1}}$

$$N_2 = 1200 \times \frac{279}{418} = 667.5 \text{ rpm}$$ **Ans.**

Sol.3

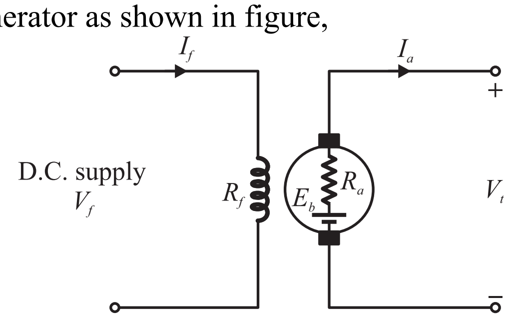
Case 1 : Terminal voltage $V_{t_1} = 100\,\text{V}$,

Current $I_{a_1} = 8\,\text{A}$, Speed $N_1 = 500$ rpm .

Case 2 : Speed $N_2 = 750$ rpm,

Armature resistance $R_a = 1\ \Omega$.

Connection diagram of separately excited generator as shown in figure,



From the figure,

Terminal voltage, $V_{t_1} = E_{b_1} + I_{a_1} R_a$

$$100 = E_{b_1} + 8 \times 1$$

Back emf, $E_{b_1} = 92\,\text{V}$

$\because \quad E_b \propto N\phi \qquad (\because \phi = \text{Constant})$

$\therefore \quad \dfrac{E_{b_2}}{E_{b_1}} = \dfrac{N_2}{N_1}$

Back emf, $E_{b_2} = 92 \times \dfrac{750}{500} = 138\,\text{V}$

$\therefore \quad E_{b_1} = K\phi\omega_1$

$$92 = K\phi \times \frac{2\pi N_1}{60}$$

$\therefore \quad$ Constant, $K\phi = \dfrac{92 \times 60}{2\pi \times 500} = 1.757$

Torque, $T_1 = K\phi I_{a_1}$

$$T_1 = 1.757 \times 8 = 14.056 \text{ Nm}$$

$\because \quad T \propto N^2$ (given)

$\therefore \quad \dfrac{T_2}{T_1} = \left(\dfrac{N_2}{N_1}\right)^2 = \dfrac{750^2}{500^2}$

Torque, $T_2 = 14.056 \times \dfrac{750^2}{500^2} = 31.62$

$\because \quad T_2 = K\phi I_{a_2}$

$\therefore \quad$ Terminal current, $I_{a_2} = \dfrac{31.62}{1.757} = 18\,\text{A}$

Ans.

Terminal voltage,

$$V_{t_2} = E_{b_2} + I_{a_2} R_a = 138 + 18 \times 1 = 156 \text{ V}$$

Ans.

Scan for Video Solution

Sol.4

Given :

Case 1 : Terminal voltage $V_{t_1} = 220\,\text{V}$,

Output power $P_L = 1.5\,\text{kW}$,

Speed $N_1 = 859$ rpm

Armature resistance $R_a = 2.5\,\Omega$, Armature current $I_{a_1} = 8\text{ A}$

At rated load condition, terminal voltage,

$$V_{t_1} = E_b + I_{a_1} R_a$$

$$220 = E_{b_1} + 8 \times 2.5$$

$$E_{b_1} = 200\text{ V}$$

Rated torque, $T = \dfrac{P_L}{\omega_n} = \dfrac{1.5\times 10^3}{2\pi N/60}$

$$T = \frac{1.5\times 10^3 \times 60}{2\pi \times 859} = 16.575\text{ Nm} \quad \textbf{Ans.}$$

Case 2 :

At no load condition, $V_{t_2} = E_{b_2} = 220\text{ V}$

$\because \quad E_b \propto N\phi \qquad (\because\ \phi = \text{Constant})$

$$\therefore \quad \frac{E_{b_2}}{E_{b_1}} = \frac{N_2}{N_1}$$

Speed at no load, $N_2 = 859 \times \dfrac{220}{200} = 944.9\text{ rpm}$

Ans.

Sol.5

Given : No load voltage $E_{g_1} = 120\text{ V}$,

Field current $I_{f_1} = 2\text{ A}$,

Speed $N_1 = 1500\text{ rpm}$.

Field current is directing proportional to flux i.e.,

$$I_f \propto \phi$$

(i) $I_{f_2} = 2.5\text{ A}$

$$\therefore \quad \frac{I_{f_2}}{I_{f_1}} = \frac{\phi_2}{\phi_1}$$

$$\text{or} \quad \frac{\phi_2}{\phi_1} = \frac{2.5}{2}$$

and $E \propto N\phi$ (If $N = \text{Constant}$)

$$\therefore \quad \frac{E_{g_2}}{E_{g_1}} = \frac{\phi_2}{\phi_1}$$

Generated emf, $E_{g_2} = 120 \times \dfrac{2.5}{2} = 150\text{ V}$

Ans.

(ii) $I_{f_2} = 2.84,\ N_2 = 1400\text{ rpm}$

$$\frac{I_{f_2}}{I_{f_1}} = \frac{\phi_2}{\phi_1}$$

$$\text{or} \quad \frac{\phi_2}{\phi_1} = \frac{2.84}{2}$$

and $E \propto N\phi$

$$\frac{E_{g_2}}{E_{g_1}} = \frac{N_2\phi_2}{N_1\phi_1}$$

Generated emf,

$$E_{g_2} = 120 \times \frac{1400}{1500} \times \frac{2.84}{2} = 159.04\text{ V}$$

Ans.

Sol.6

Given :

Case 1 : Speed $N_1 = 1000\text{ rpm}$,

Armature current $I_{a_1} = 200\text{ A}$,

Terminal voltage $V_{t_1} = 125\text{ V}$

Armature resistance $R_a = 0.04\,\Omega$ and

Brush drop $= 2\text{ V}$.

Case 2 :

Field current constant i.e., $\phi = \text{Constant}$,

Speed $N_2 = 800\text{ rpm}$

For separatly excited generator :

Generated emf, $E_{g_1} = V_{t_1} + I_{a_1} R_a + \text{Brush drop}$

$$E_{g_1} = 125 + 200 \times 0.04 + 2 = 135\text{ V}$$

Generated emf, $E_{g_1} = K\phi\omega_1$

$$\therefore \quad K\phi = \frac{135\times 60}{2\pi \times 1000} = 1.289$$

Torque, $T_1 = K\phi I_{a_1} = 1.289 \times 200 = 257.83\text{ Nm}$

$\because \quad T \propto N$

$$\frac{T_2}{T_1} = \frac{N_2}{N_1}$$

Torque, $T_2 = 257.83 \times \dfrac{800}{1000} = 206.26\text{ Nm}$

$$T_2 = K\phi I_{a_2}$$

$\therefore$ Armature current,

$$I_{a_2} = \frac{206.26}{1.289} = 160.01\text{ A} \quad \textbf{Ans.}$$

180+ Video Solutions along with QR Codes

35 YEARS GATE SOLVED PAPERS

Best Book for GATE Exam

GATE

SAKSHI DHANDE
UMESH DHANDE

2022

Exclusively With Synopsis

ELECTRICAL ENGINEERING

Topic - Wise Previous 35 Years GATE Questions With Detailed Solutions

Volume - I

Diligent Solutions of GATE Previous Year Questions(1987-2021)
Multi Method Approach for a Single problem to Develop Crystal clear Concept
Video Solutions for Conspicuous Questions to Enhance Problem Solving Skills
This book is also useful for EC and IN Branch Students because of their common subjects.
This book is also a value additions for ESE/PSUs/ISRO/DRDO/BARC/DMRC/State-AE Exams

GATE ACADEMY
steps to success...

211+ Video Solutions along with QR Codes

35 YEARS GATE SOLVED PAPERS

Best Book for GATE Exam

GATE

SAKSHI DHANDE
UMESH DHANDE

2022

Exclusively With Synopsis

ELECTRICAL ENGINEERING

Topic - Wise Previous 35 Years GATE Questions With Detailed Solutions

Volume - II

Diligent Solutions of GATE Previous Year Questions(1987-2021)
Multi Method Approach for a Single problem to Develop Crystal clear Concept
Video Solutions for Conspicuous Questions to Enhance Problem Solving Skills
This book is also a value additions for ESE/PSUs/ISRO/DRDO/BARC/DMRC/State-AE Exams

GATE ACADEMY®
steps to success...