4 Electrical Machines

Important Points to Remember

- This chapter includes various electrical machines which include,

1. Transformers (Single phase and Three phase)
2. D.C. Machines (D.C. Generators and D.C. Motors)
3. Three phase induction motors
4. Synchronous Generators

Part A : Transformers

4.1 : Definition of Transformer

Q.1 Define transformer and state its use.

[JNTU : Part A, May-07, Marks 2]

Ans. : • The transformer is a static piece of apparatus by means of which an electrical power is transformed from one alternating current circuit to another with the desired change in voltage and current, without any change in the frequency.

- Its use is to raise or lower the alternating voltages as per the requirements in the different stages of electrical network as generation, transmission, distribution and utilization.

4.2 : Working Principle of Transformer

Q.2 Explain the working principle of transformer.

[JNTU : Part B, Dec.-11, May-09,12, Aug.-8, Marks 5]

Ans. : • The transformer works on the principle of **mutual induction which states that when two coils are inductively coupled and if current in one coil is changed uniformly then an e.m.f. gets induced in the other coil.**

- In its elementary form, it consists of two inductive coils which are electrically separated but linked through a common magnetic circuit. The two coils have high mutual inductance. The basic transformer is shown in the Fig. Q.2.1.

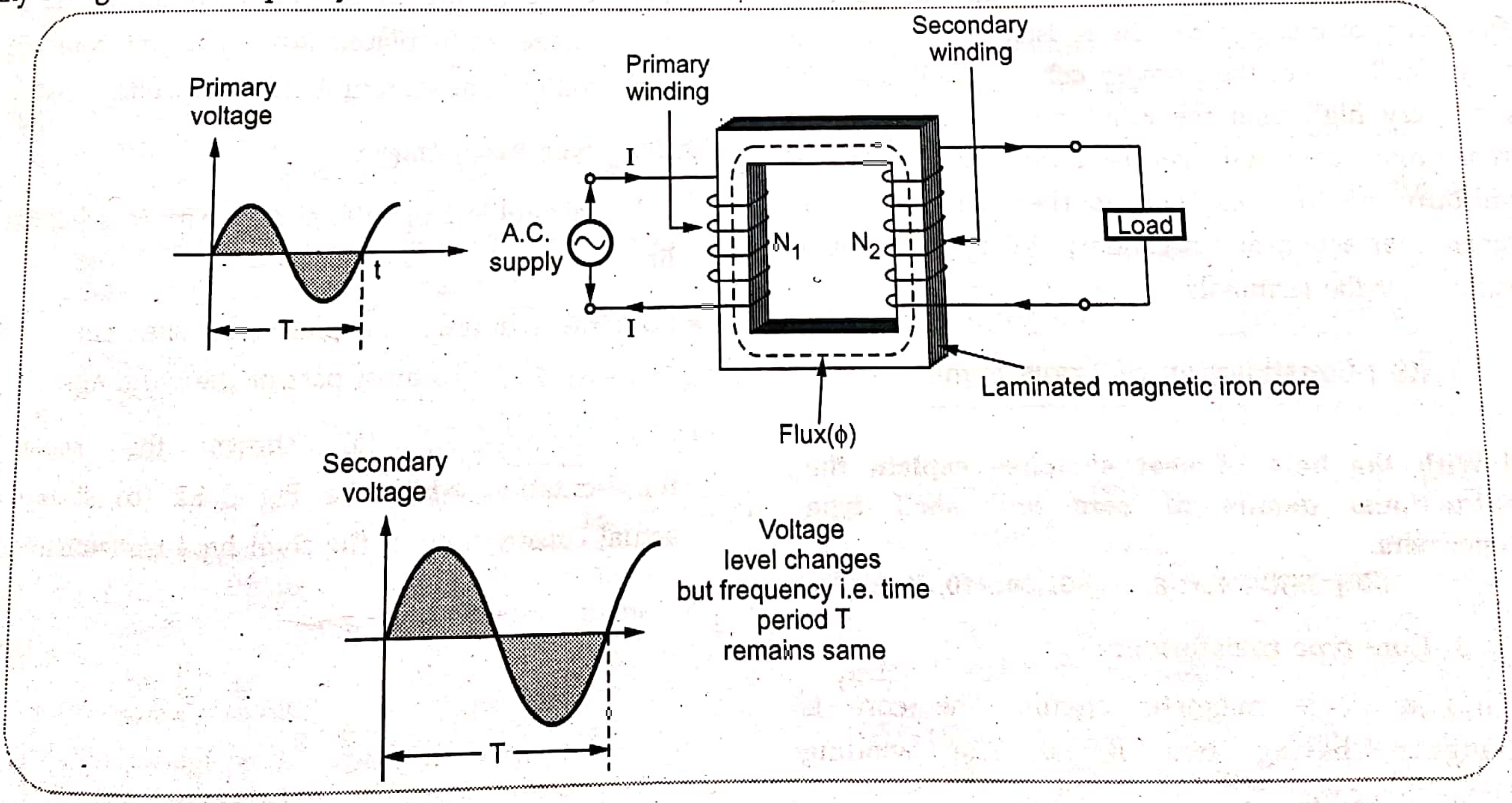


Fig. Q.2.1 Basic transformer

Scanned with CamScanner

- The coil to which supply is given is called primary winding having N_1 number of turns and the other winding connected to the load is called secondary winding having N_2 number of turns.
- When primary winding is excited by an alternating voltage, it circulates an alternating current.
- This current produces an alternating flux (ϕ) which completes its path through common magnetic core as shown dotted in the Fig. Q.2.1. Thus an alternating flux links with the secondary winding.
- As the flux is alternating, according to Faraday's law of an electromagnetic induction, mutually induced e.m.f. gets developed in the secondary winding.
- This secondary induced e.m.f. drives the load.
- Thus though there is no electrical contact between the two windings, an electrical energy gets transferred from primary to the secondary.

Q.3 What will happen if transformer primary is excited by d.c. voltage ?

☞[JNTU : Part A, Marks 2]

Ans. : • If the primary is excited by d.c., then the leakage reactance of primary winding is zero as frequency of d.c. is zero. The resistance of primary is very small. Hence the primary current (V_1/R_1) will be very very high than the rated primary current. The transformer core will get saturated or transformer will burn due to excessive heat. There will not be any transformer action and secondary voltage will not be available at the terminals.

4.3 : Construction of Transformer

Q.4 With the help of neat sketches explain the constructional details of core and shell type transformers.

☞[JNTU : Part B, May-09,Dec.-10, Marks 5]

Ans. : 1. Core type transformer :

- It has a single magnetic circuit. The core is rectangular having two limbs. The winding encircles the core.
- The Fig. Q.4.1 (a) shows the schematic representation of the core type transformer while the Fig. Q.4.1 (b) shows the view of actual construction of the core type transformer.

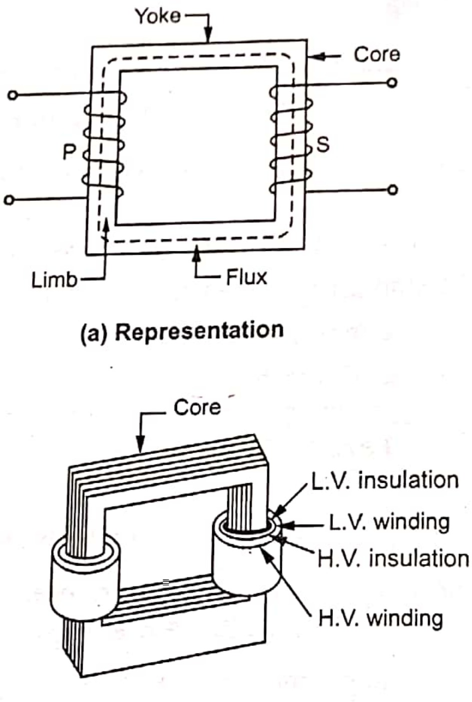


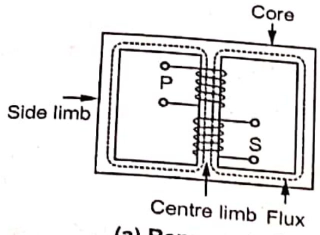
Fig. Q.4.1 Core type transformer

- Both the coils are placed on both the limbs. The low voltage coil is placed inside near the core while high voltage coil surrounds the low voltage coil.

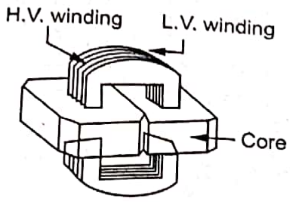
2. Shell type transformer :

- It has a double magnetic circuit. The core has three limbs.
- Both the windings are placed on the central limb. The core encircles most part of the windings.
- The Fig. Q.4.2 (a) shows the schematic representation while the Fig. Q.4.2 (b) shows the actual construction of the shell type transformer.

Scanned with CamScanner



(a) Representation



(b) Construction

Fig. Q.4.2 Shell type transformer

Q.5 Compare core type and shell type transformers.

☞[JNTU : Part B, Dec.-08, 09, Marks 5]

Ans. :

Sr. No.	Core type	Shell type
1.	The winding encircles the core.	The core encircles most part of the windings.
2.	The cylindrical type of coils are used.	Generally, multilayer disc type or sandwich coils are used.
3.	As windings are distributed, the natural cooling is more effective.	As windings are surrounded by the core, the natural cooling does not exist.
4.	The coils can be easily removed from maintenance point of view.	For removing any winding for the maintenance, large number of laminations are required to be removed. This is difficult.
5.	The construction is preferred for low voltage transformers.	The construction is used for very high voltage transformers.
6.	It has a single magnetic circuit.	It has a double magnetic circuit.
7.	In a single phase type, the core has two limbs.	In a single phase type, the core has three limbs

4.4 : E.M.F. Equation of Transformer

Q.6 Derive the e.m.f. equation of a transformer.

☞[JNTU : Part B, May-06,09, Aug.-06,08, Dec.-11, Marks 5]

Ans. : • When the primary winding is excited by an alternating voltage V_1, it circulates alternating current, producing an alternating flux ϕ.

• The maximum value of this flux is ϕ_m as shown in the Fig. Q.6.1.

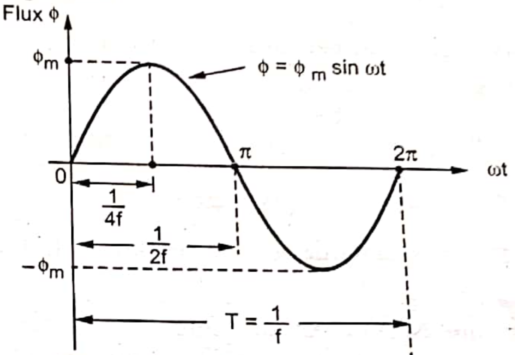


Fig. Q.6.1 Sinusoidal flux

• The alternating flux ϕ linking with the primary winding itself induces an e.m.f. in it denoted as E_1.

• The flux links with secondary winding through the common magnetic core. It produces induced e.m.f. E_2 in the secondary winding. This is mutually induced e.m.f.

• The various quantities which affect the magnitude of the induced e.m.f. are :

ϕ = Flux and ϕ_m = Maximum value of flux

N_1 = Number of primary winding turns

N_2 = Number of secondary winding turns

f = Frequency of the supply voltage

E_1 = R.M.S. value of the primary induced e.m.f.

E_2 = R.M.S. value of the secondary induced e.m.f.

• From Faraday's law of electromagnetic induction the average e.m.f. induced in each turn is proportional to the average rate of change of flux.

$\therefore$ Average e.m.f. per turn = Average rate of change of flux = $\dfrac{d\phi}{dt}$

Scanned with CamScanner

Now, $\frac{d\phi}{dt} = \frac{\text{Change in flux}}{\text{Time required for change in flux}}$

- Consider the 1/4th cycle of the flux as shown in the Fig. Q.6.1. Complete cycle gets completed in 1/f seconds. In 1/4th time period, the change in flux is from 0 to ϕ_m.

$$\therefore \quad \frac{d\phi}{dt} = \frac{\phi_m - 0}{\left(\frac{1}{4f}\right)} = 4\, f\, \phi_m \text{ Wb/sec}$$

... as dt for 1/4th time period is 1/4f seconds

$\therefore$ **Average e.m.f. per turn** $= 4\, f\, \phi_m$ volts

- For sinusoidal quantity,

$$\text{Form Factor} = \frac{\text{R.M.S. value}}{\text{Average value}} = 1.11$$

$\therefore$ R.M.S. value = 1.11 × Average value

$\therefore$ R.M.S. value of induced e.m.f. per turn = $1.11 \times 4\, f\, \phi_m = 4.44\, f\, \phi_m$

- There are N_1 number of primary turns hence the R.M.S. value of induced e.m.f. of primary denoted as E_1 is $E_1 = N_1 \times 4.44\, f\, \phi_m$ volts.
- While as there are N_2 number of secondary turns the R.M.S. value of induced e.m.f. of secondary denoted E_2 is

$E_2 = N_2 \times 4.44\, f\, \phi_m$ volts.

- The expressions of E_1 and E_2 are called e.m.f. equations of a transformer.

$$E_1 = 4.44\, f\, \phi_m N_1 \text{ volts}$$
$$\text{and} \quad E_2 = 4.44\, f\, \phi_m N_2 \text{ volts}$$

Important Points to Remember

- The ratio of secondary induced e.m.f. to primary induced e.m.f. is known as **voltage transformation ratio** denoted as K.

Thus, $\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$ and $E_2 = K\, E_1$

- **The currents are in the inverse ratio of the voltage transformation ratio** as the product of primary voltage V_1 and primary current I_1, is same as the product of secondary voltage V_2 and the secondary current I_2. Thus $V_1 I_1 = V_2 I_2$.

$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = K = \frac{N_2}{N_1}$$

- On both sides primary and secondary VA rating remains same. This rating is generally expressed in kVA (kilo volt amperes rating).

$$\text{kVA rating of a transformer} = \frac{V_1 I_1}{1000} = \frac{V_2 I_2}{1000}$$

...1000 to express in kVA

- The full load primary and secondary currents indicate the safe maximum values of currents which transformer windings can carry. The full load currents can be obtained from the kVA rating as,

$$I_1(FL) = \frac{\text{kVA rating} \times 1000}{V_1},$$

$$I_2(FL) = \frac{\text{kVA rating} \times 1000}{V_2}$$

Q.7 Why transformers are rated in kVA instead of kW ? [JNTU : Part A, Marks 3]

Ans. : • The copper loss (I^2R) in the transformer depends on the current 'I' through the winding while the iron or core loss depends on the voltage 'V' as frequency of operation is constant. None of these losses depend on the power factor (cos ϕ) of the load. Hence losses decide the temperature rise and hence the rating of the transformer. As losses depend on V and I only, the rating of the transformer is specified as a product of these two parameters V×I. Thus the transformer rating is in kVA and not in kW.

Q.8 The maximum flux density in the core of 250/3000 volts, 50 Hz single phase transformer is 1.2 webers per square meter. If the e.m.f. per turn is 8 volts determine primary and secondary turns and area of the core. [JNTU : Part B, Marks 5]

Ans. : $B_m = 1.2$ T, $E_1 = 250$ V, $E_2 = 3000$ V, $f = 50$ Hz

$$\text{e.m.f./turn} = \frac{E_1}{N_1} = \frac{E_2}{N_2} = 8 \quad \text{i.e.} \quad \frac{250}{N_1} = 8 = \frac{3000}{N_2}$$

$$\therefore \quad N_1 = 31 \quad \text{and} \quad N_2 = 375$$

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

$$\text{i.e.} \quad \frac{E_1}{N_1} = 4.44 \times 50 \times \phi_m$$

Scanned with CamScanner

$$\therefore \quad \phi_m = \frac{\left(\frac{E_1}{N_1}\right)}{4.44 \times 50} = \frac{8}{4.44 \times 50} = 0.036 \text{ Wb}$$

$$B = \frac{\phi_m}{a} \quad \text{i.e.} \quad a = \frac{\phi_m}{B_m} = \frac{0.03603}{1.2}$$

$$= 0.03003 \text{ m}^2$$

Q.9 The number of turns on the primary and secondary windings of a single phase transformer are 350 and 35 respectively. If the primary is connected to a 2.2 kV, 50 Hz supply, determine the secondary voltage. ☞[JNTU : Part B, Marks 5]

Ans. : $N_1 = 350$, $N_2 = 35$, $E_1 = 2.2$ kV, $f = 50$ Hz

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

$$\therefore \quad E_2 = \frac{N_2}{N_1} \times E_1 = \frac{35}{350} \times 2.2 \times 10^3 = 220 \text{ V}$$

Q.10 Differentiate between ideal and practical transformer. ☞[JNTU : Part A, May-19, Marks 3]

Ans. :

Sr. No.	Ideal	Practical
1)	It has no losses.	It has iron losses as well as copper losses.
2)	The winding resistances are zero.	The windings have finite resistances.
3)	The winding leakage reactances are zero.	The windings have finite reactances.
4)	The leakage flux is zero and all flux produced by primary links with the secondary.	The leakage flux exists hence all the flux produced by primary does not link with secondary.
5)	Zero current is required to establish the flux in the core.	The finite magnetising current is required to establish the flux.
6)	The voltage drops are zero hence primary applied voltage V_1 is same as induced e.m.f. E_1.	The V_1 and E_1 are different due to various drops present.
7)	The secondary induced e.m.f. E_2 is same as load voltage V_2.	Due to secondary voltage drops E_2 is not same as V_2.

Q.11 What is an ideal transformer ? ☞[JNTU : Part A, Marks 2]

Ans. : • A transformer is said to be ideal if it satisfies following properties :

i) It has no losses.

ii) Its windings have zero resistance.

iii) Leakage flux is zero i.e. 100 % flux produced by primary links with the secondary.

iv) Permeability of core is so high that negligible current is required to establish the flux in it.

4.5 : Practical Transformer on No Load

Q.12 Draw and explain no load phasor diagram of transformer. ☞[JNTU : Aug.-06, May-08, Jan.-10, Marks 5]

Ans. : • When transformer is on no load, its secondary current is zero. But the primary current under no load condition has to supply the iron losses i.e. hysteresis loss and eddy current loss and a small amount of primary copper loss. This current is denoted as I_0.

• The no load input current I_0 has two components :

1. A purely reactive component I_m called magnetizing component of no load current required to produce the flux. This is also called **wattless component**.
2. An active component I_c which supplies total losses under no load condition called **power component** of no load current. This is also called **wattful component** or **core loss component** of I_0.

• The total no load current I_0 is the vector addition of I_m and I_c.

$$I_0 = I_m + I_c \quad \text{...phasor addition}$$

• The phasor diagram is shown in the Fig. Q.12.1.

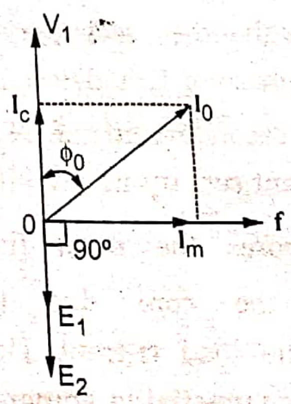


Fig. Q.12.1 Practical transformer on no load

Scanned with CamScanner

- In practical transformer, due to winding resistance, no load current I_0 is no longer at 90° with respect to V_1. But it lags V_1 by angle ϕ_0 which is less than 90°. Thus $\cos \phi_0$ is called **no load power factor** of practical transformer.
- It can be seen that the two components of I_0 are,

$$I_m = I_0 \sin \phi_0, \text{ magnetizing component lagging } V_1 \text{ exactly by } 90° \quad \text{... (Q.12.1)}$$

$$I_c = I_0 \cos \phi_0, \text{ core loss component which is in phase with } V_1 \quad \text{... (Q.12.2)}$$

- The magnitude of the no load current is given by,

$$I_0 = \sqrt{I_m^2 + I_c^2} \quad \text{... (Q.12.3)}$$

- The total power input on no load is denoted as W_0 and is given by,

$$W_0 = V_1 I_0 \cos \phi_0 = V_1 I_c = P_i \text{ (Iron losses)}$$

- It may be noted that the current I_0 is very small, hence the primary copper loss is negligibly small.
- Hence power input W_0 on no load always represents the iron losses, as copper loss is negligibly small. **The iron losses are denoted as P_i and are constant for all load conditions.**

4.6 : Transformer on Load

Q.13 Why there is inrush of primary current when the transformer is loaded ? Why transformer is called constant flux machine ?

[JNTU : Part B, Marks 5]

Ans. : • When the transformer is loaded, the current I_2 flows through the secondary winding. The magnitude and phase of I_2 is determined by the load.

- There exists a secondary m.m.f. N_2I_2 due to which secondary current sets up its own flux ϕ_2.
- This flux opposes the main flux ϕ which is produced in the core due to magnetizing component of no load current. Hence the m.m.f. N_2I_2 is called **demagnetizing ampere-turns.**
- The flux ϕ_2 momentarily reduces the main flux ϕ, due to which the primary induced e.m.f. E_1 also reduces. Hence the vector difference $\bar{V}_1 - \bar{E}_1$ increases due to which **primary draws more current from the supply.**
- This additional current drawn by primary is due to the load hence called load component of primary current denoted as I_2'. This current I_2' is in antiphase with I_2.
- The current I_2' sets up its own flux ϕ_2' which opposes the flux ϕ_2 and neutralizes the flux ϕ_2 produced by I_2. Hence the net flux in the core is again maintained at constant level.
- Thus for any load condition, no load to full load the flux in the core is practically constant. Hence the transformer is called constant flux machine.
- As the ampere turns are balanced we can write,

$$N_2 I_2 = N_1 I_2' \qquad \text{i.e.} \qquad I_2' = \frac{N_2}{N_1} I_2 = K I_2$$

- Thus when a transformer is loaded, the primary current I_1 has two components :

1. The no load current I_0 having two components I_m and I_c.
2. The load component I_2' which is in antiphase with I_2. And phase of I_2 is decided by the load.

- Hence primary current I_1 is vector sum of I_0 and I_2'.

$$\therefore \quad \bar{I}_1 = \bar{I}_0 + \bar{I}_2'$$

4.7 : Equivalent Resistance, Inductance and Impedance

Q.14 What is meant by equivalent resistance referred to primary and secondary ?

[JNTU : Part A, Dec.-18, Marks 2]

Ans. : The resistances, reactances and impedances of the two windings can be transferred to any one side either primary or secondary without affecting the performance of the transformer.

- The **total resistance referred to primary** is addition of R_1 and R_2' called equivalent resistance of transformer referred to primary and denoted R_{1e} and given by,

Scanned with CamScanner

$$R_{1e} = R_1 + R_2' = R_1 + \frac{R_2}{K^2} \quad \text{where } K = \frac{N_2}{N_1}$$

- The total resistance referred to secondary is the addition of R_2 and R_1' called **equivalent resistance of transformer referred to secondary** and denoted as R_{2e} given by,

$$R_{2e} = R_2 + R_1' = R_2 + K^2 R_1 \quad \text{where } K = \frac{N_2}{N_1}$$

Important Points to Remember

High voltage side → Low current side → High resistance side

Low voltage side → High current side → Low resistance side

- Similarly the reactances can be transferred as,

$$X_{1e} = X_1 + X_2' = X_1 + \frac{X_2}{K^2}$$

$$\text{and } X_{2e} = X_2 + X_1' = X_2 + K^2 X_1$$

- The total impedance of primary winding is $Z_1 = R_1 + j X_1 \ \Omega$
- The total impedance of the secondary winding is $Z_2 = R_2 + j X_2 \ \Omega$
- $Z_{1e} = R_{1e} + j X_{1e}$ = Total equivalent impedance referred to primary
- $Z_{2e} = R_{2e} + j X_{2e}$ = Total equivalent impedance referred to secondary

$$Z_{1e} = Z_1 + Z_2' = Z_1 + \frac{Z_2}{K^2}$$

$$\text{and } Z_{2e} = Z_2 + Z_1' = Z_2 + K^2 Z_1$$

Magnitudes, $Z_{1e} = \sqrt{R_{1e}^2 + X_{1e}^2}$ and $Z_{2e} = \sqrt{R_{2e}^2 + X_{2e}^2}$

4.8 : Phasor Diagram of Transformer on Load

Q.15 Draw and explain the full load phasor diagrams of a single phase transformer for lagging, leading and unity power factor loads.

[JNTU : Part B, May-19, Marks 5]

Ans. : Steps to draw the phasor diagram are,

1. Consider flux ϕ as reference
2. E_1 lags ϕ by 90°. Reverse E_1 to get $-E_1$.
3. E_1 and E_2 are in phase.
4. Assume V_2 in a particular direction.
5. Draw I_2 depending on the 'aod factor. For unity power factor it is in phase with V_2, for lagging it lags V_2 and for leading it leads V_2.
6. Add $I_2 R_2$ and $I_2 X_2$ to V_2 to get E_2.
7. Reverse I_2 to get I_2'.
8. Add I_0 and I_2' to get I_1.
9. Add $I_1 R_1$ and $I_1 X_1$ to $-E_1$ to get V_1.

$$\bar{I}_1 = \bar{I}_0 + \bar{I}_2', \quad \bar{V}_1 = -\bar{E}_1 + \overline{I_1 R_1} + \overline{I_1 X_1},$$

$$\bar{V}_2 = \bar{E}_2 - \bar{I}_2 (R_2 + j X_2)$$

1. Unity power factor :

- The phasor diagram is shown in the Fig. Q.15.1.
- Angle between V_1 and I_1 is ϕ_1 and $\cos \phi_1$ is primary power factor. Remember that I_1X_1 leads I_1 direction by 90° and I_2X_2 leads I_2 by 90° as current through inductance lags voltage across inductance by 90°.

2. Lagging power factor :

- The phasor diagram is shown in the Fig. Q.15.2.
- As load power factor is lagging $\cos \phi_2$, the current I_2 lags V_2 by angle ϕ_2.
- Accordingly directions of I_2R_2, I_2X_2, I_2', I_1, I_1R_1 and I_1X_1 will change. Remember that whatever may be the power factor of load, I_2X_2 leads I_2 by 90° and I_1X_1 leads I_1 by 90°.

3. Leading power factor :

- The phasor diagram is shown in the Fig. Q.15.3.
- As load power factor is leading, the current I_2 leads V_2 by angle ϕ_2. Accordingly change the directions of I_2R_2, I_2X_2, I_2', I_1, I_1R_1 and I_1X_1 . All other steps remain same as before.

Scanned with CamScanner

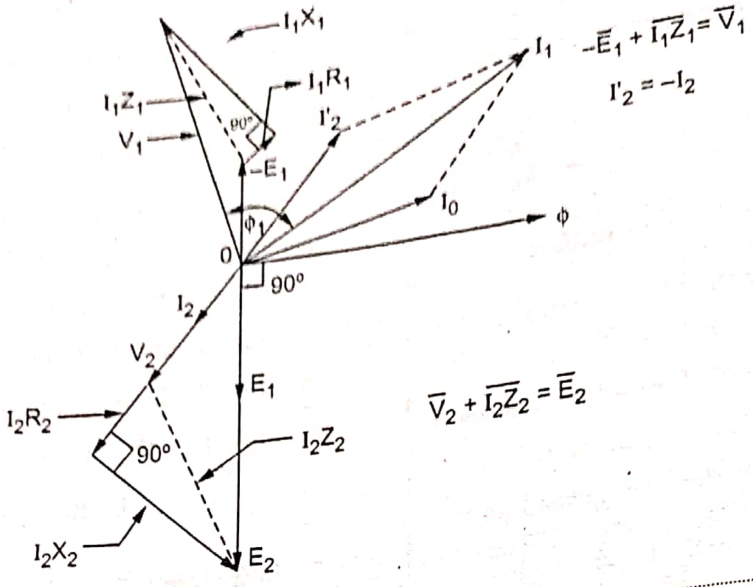


Fig. Q.15.1 Phasor diagram for unity power factor load

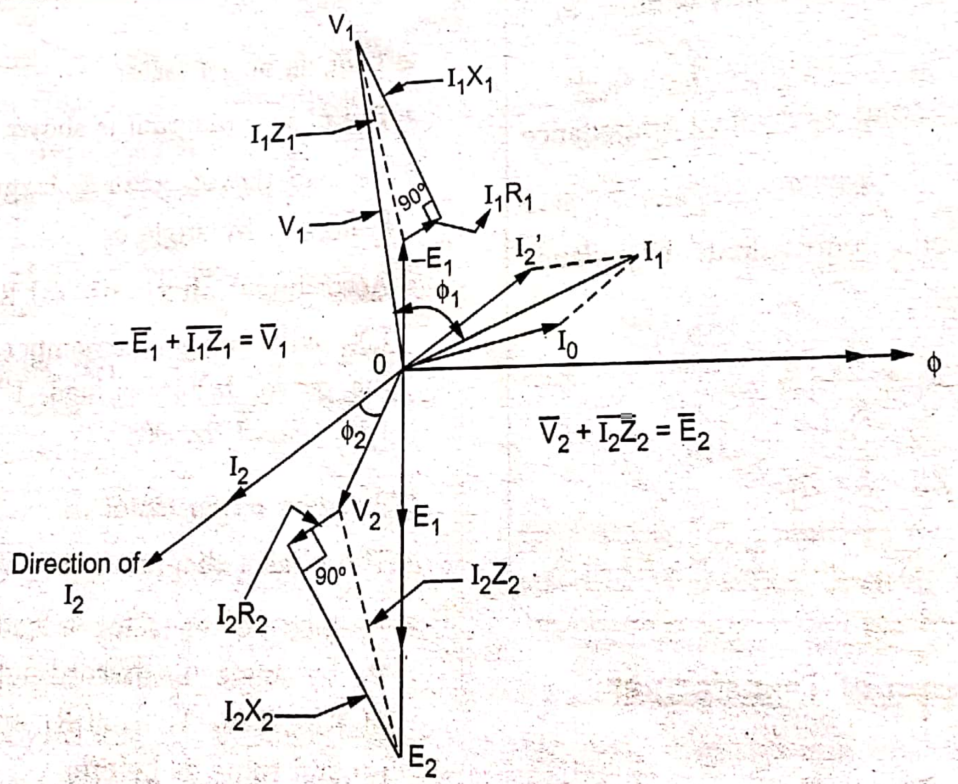


Fig. Q.15.2 Phasor diagram for lagging power factor load

Scanned with CamScanner

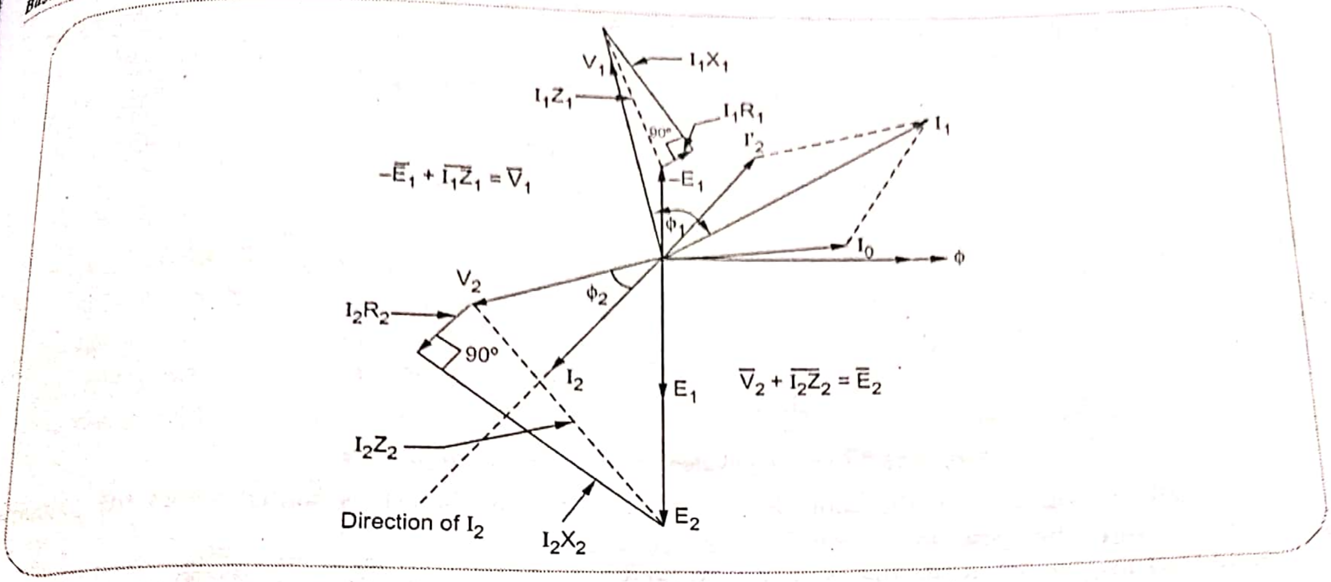


Fig. Q.15.3 Phasor diagram for leading power factor load

4.9 : Equivalent Circuit of Transformer

Q.16 Derive the equivalent circuit of a single phase two winding transformer.

[JNTU : Part B, May-08, 11, Jan.-10, Marks 5]

Ans. : • For a single phase transformer, no load primary current I_0 has two components, the manetising component I_m and coreloss component I_c The current I_m is assumed to flow through reactance X_0 called no load reactance. The current I_c is assumed to flow through the resistance R_0.

- The equivalent circuit of no load barnch is the parallel combination of R_0 and X_0, which is also called exciting circuit.
- When the load is connected to the transformer then secondary current I_2 flows. This causes voltage drop across R_2 and X_2. Due to I_2, primary draws an additional current $I'_2 = I_2 / K$.
- The current I_1 is the phasor addition of I_0 and I'_2. This I_1 causes the voltage drop across primary resistance R_1 and reactance X_1.
- Hence the equivalent circuit can be shown as in the Fig. Q.16.1.

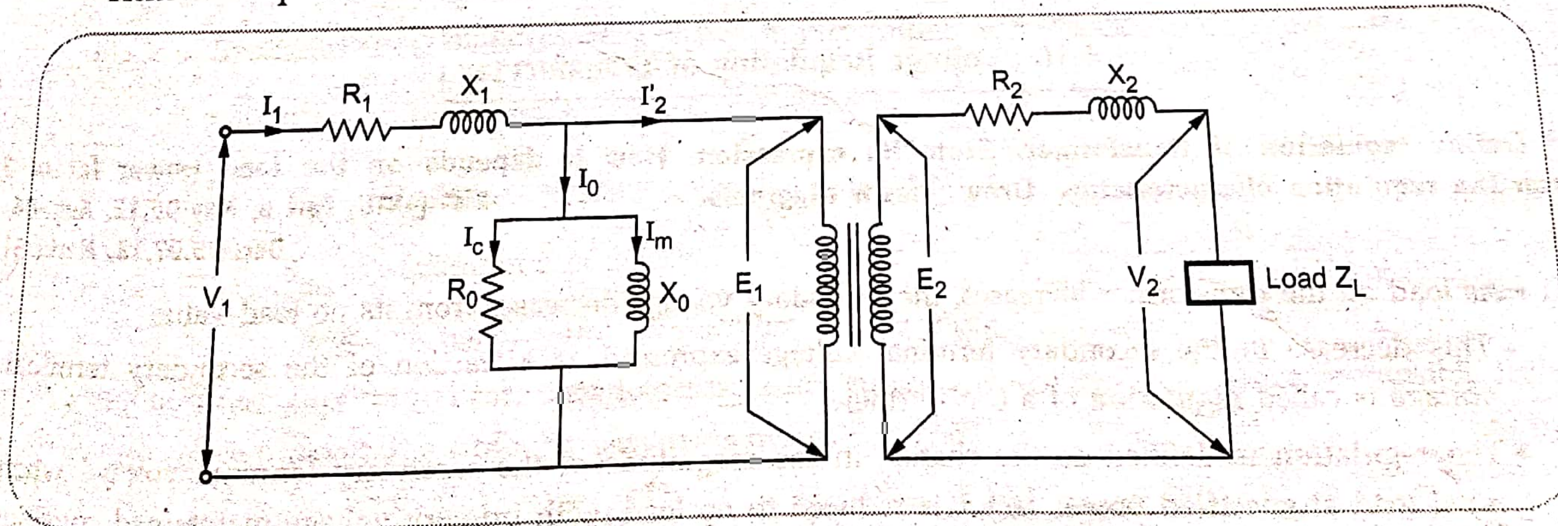


Fig. Q.16.1

Scanned with CamScanner

- But in the equivalent circuit, windings are not shown and it is further simplified by transferring all the values to the primary or secondary.
- Thus the exact equivalent circuit referred to primary is as shown in the Fig. Q.16.2.

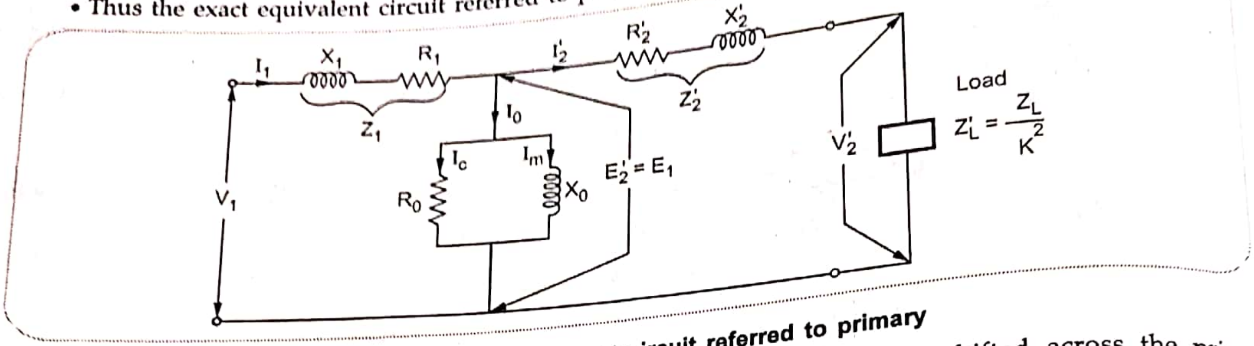


Fig. Q.16.2 Exact equivalent circuit referred to primary

- Practically for simplifying the equivalent circuit, the no load branch is shifted across the primary voltage and the resistances R_1 and R_2' are combined to give R_{1e} while the reactances X_1 and X_2' are combined to give X_{1e}.
- Such an equivalent circuit is called approximate equivalent circuit as in this circuit the drop arross R_1 and X_1 due to I_0 is neglected. The Fig. Q.16.3 shows an approximate equivalent circuit refferred to primary.
- Referring all the quantities to the secondary side, an approximate equivalent circuit referred to secondary can be obtained.

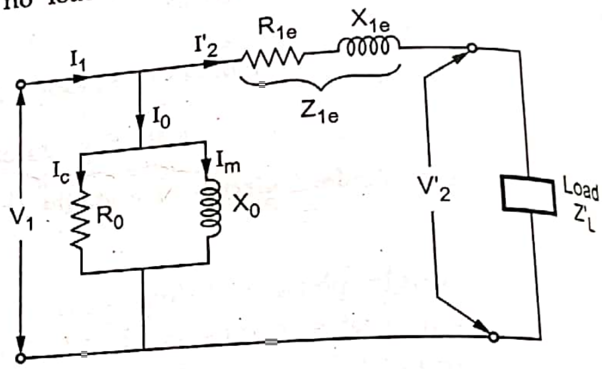


Fig. Q.16.3 Approximate equivalent circuit referred to primary

Q.17 What is an approximate equivalent circuit ? What is an error because of approixmate equivalent circuit ? **[JNTU : Part A, Dec.-11, Marks 2]**

Ans. : Refer Q.16.

- To get approximate equivalent circuit, the no load branch containing R_0 and X_0 is shifted to the left of R_1 and X_1. By doing this we are creating an error that the drop across R_1 and X_1 due to I_0 is neglected.

4.10 : Voltage Regulation of Transformer

Q.18 Define regulation of transformer. State its expression. How it depends on the load power factor ? Sketch the regulation characteristics. Draw phasor diagrams. **[JNTU, Part B, May-06,12, Aug.-06, Dec.-05,07,18, Marks 5]**

Ans. :
- As load on the transformer increases, the secondary voltage decreases from its no load value.
- This decrease in the secondary terminal voltage expressed as a fraction of the secondary terminal voltage is called **regulation** of a transformer.
- The **regulation** is defined as the change in the magnitude of the secondary terminal voltage when rated load at **specified** power factor is reduced to no load, with primary voltage maintained constant expressed as the percentage of the rated terminal voltage.

DECODE
Scanned with CamScanner

- Let E_2 = Secondary terminal voltage on no load
  V_2 = Secondary terminal voltage on given load

then mathematically voltage regulation at given load can be expressed as,

$$\% \text{ Voltage regulation} = \frac{E_2 - V_2}{V_2} \times 100$$

- The ratio $((E_2 - V_2)/V_2)$ is called **per unit regulation.**
- The secondary terminal voltage does not depend only on the magnitude of the load current but also on the nature of the power factor of the load.
- In case of lagging power factor $V_2 < E_2$ and we get positive voltage regulation, while for leading power factor $E_2 < V_2$ and we get negative voltage regulation.
- The Fig. Q.18.1 shows the regulation characteristics of transformer at different load power factors.

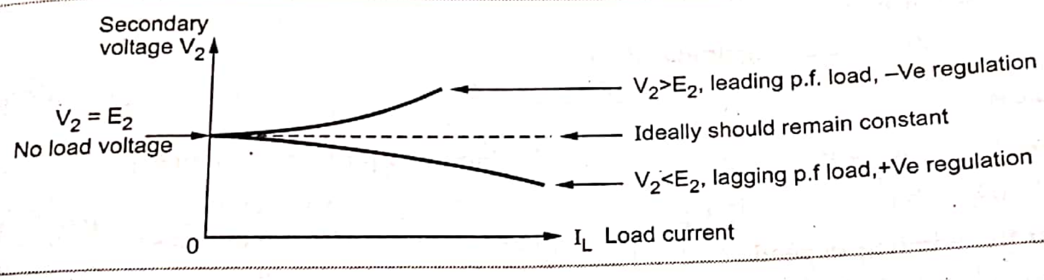


Fig. Q.18.1 Regulation characteristics at different power factors

4.11 : Losses in Transformer

Q.19 Explain the various losses in a transformer. In which part these losses occur ? How to minimize them ? On which factors they depend ? [JNTU : Part B, May-08, 12, Jan-10, Dec.-06, 18, Marks 5]

Ans. : • In a transformer, there exists two types of losses,

i) Core losses or iron losses and ii) Copper losses.

1. Core or Iron losses

- Due to alternating flux set up in the magnetic core of the transformer, it undergoes a cycle of magnetisation and demagnetisation.
- Due to hysteresis effect there is loss of energy in this process which is called hysteresis loss.

It is given by, $\boxed{\text{Hysteresis loss} = K_h\, B_m^{1.67}\, f\, v \text{ Watts}}$

K_h = Hysteresis constant depends on material and

B_m = Maximum flux density

f = Frequency and v = Volume of the core.

- The induced e.m.f. in the core tries to set up eddy currents in the core and hence responsible for the eddy current losses. The eddy current loss is given by,

$$\boxed{\text{Eddy current loss} = K_e\, B_m^2\, f^2 t^2 \text{ Watts/unit volume}}$$

Scanned with CamScanner

where K_e = Eddy current constant

and t = Thickness of the core.

- The flux in the core is constant as supply voltage V_1 at rated frequency f is always constant. Hence, the flux density B_m in the core and hence both hysteresis and eddy current losses are constant losses at all the loads.
- The iron losses are minimized by using high grade core material like silicon steel having very low hysteresis loop and by manufacturing the core in the form of laminations.

2. Copper losses

- The copper losses are due to the power wasted in the form of I^2R loss due to the resistances of the primary and secondary windings.
- The copper loss depends on the magnitude of the currents flowing through the windings and the winding resistances.
- Total Cu loss $= I_1^2 R_1 + I_2^2 R_2 = I_1^2 (R_1 + R_2')$
  $= I_2^2 (R_2 + R_1') = I_1^2 R_{1e} = I_2^2 R_{2e}$.
- As the current in the winding depends on the load, the copper losses also vary with the load. Thus copper losses are called **variable losses.**
- Thus for a transformer,

Total losses = Iron losses + Copper losses

- The copper losses are kept minimum by designing the windings with low resistance values.

Q.20 Why the copper losses are more in a transformer ? ☞[JNTU : Part A, May-19, Marks 2]

Ans. : The iron losses in a transformer are constant losses and kept to minimum by proper design and use of high grade material. The eddy currents are also small causing low eddy current losses. But copper losses are proportional to the square of the currents in the windings. The winding currents are decided by the load and are high. Hence the copper losses are more in a transformer.

4.12 : Efficiency of Transformer

Q.21 Define efficiency of a transformer. How to obtain it at different loads ? ☞[JNTU : Part B, Marks 5]

Ans. : • The efficiency of a transformer is defined as the ratio of the power output to power input.

$$\eta = \frac{\text{Power output}}{\text{Power input}} = \frac{\text{Power output}}{\text{Power output} + \text{Total losses}}$$

$$= \frac{\text{Power output}}{\text{Power output} + P_i + P_{Cu}}$$

where P_i = Iron losses and P_{Cu} = Copper losses

- If transformer is supplying full load then full load power output is,

Full load power output $= V_2 I_2[FL] \cos\phi$

where $\cos\phi$ is load power factor

$$P_{Cu} = \text{Copper losses on full load}$$
$$= I_2^2 R_{2e} \text{ or } = I_1^2 R_{1e}$$

$$\therefore \quad \eta = \frac{V_2 I_2[FL] \cos\phi_2}{V_2 I_2[FL]\cos\phi_2 + P_i + P_{Cu}}$$

but $V_2 I_2[FL] = [\text{ VA rating }]$

$$\therefore \quad \boxed{\% \eta = \frac{(\text{VA rating}) \times \cos\phi}{(\text{VA rating}) \times \cos\phi + P_i + P_{Cu}} \times 100} \quad \text{... Full load efficiency}$$

- If the transformer is subjected to fractional load then using the appropriate values of various quantities, the efficiency can be obtained.
- Let n = Fraction by which load is different than full load

$$= \frac{\text{Actual load}}{\text{Full load}}$$

- For example, if transformer is subjected to half load then,

$$n = \frac{\text{Half load}}{\text{Full load}} = \frac{(1/2)}{1} = 0.5$$

- When load changes, the load current changes by same proportion.

$$\therefore \quad \text{New } I_2 = n\,(I_2)\text{F.L.}$$

- Similarly the output $V_2 I_2 \cos\phi$ also reduces by the same fraction. Thus fraction of VA rating is available at the output i.e. $n \times [\text{VA rating}] \cos\phi$.
- Similarly as copper losses are proportional to square of current then,

$$\therefore \quad \boxed{\text{New } P_{Cu} = n^2 (P_{Cu}) \text{ F.L.}} \quad \text{... Copper losses on new load}$$

- The copper losses get reduced by n^2 while iron losses remain same.
- In general for any fractional load the efficiency is given by,

$$\therefore \quad \% \eta = \frac{n \text{ (VA rating) } \cos\phi}{n \text{ (VA rating) } \cos\phi + P_i + n^2 (P_{Cu})_{F.L.}} \times 100$$

where n = Fraction by which load is less than full load

Q.22 Derive the condition for the maximum efficiency for a transformer.

[JNTU : Part B, Dec.-04,08,18, May-09, Marks 5]

Ans. : • The load current at which the efficiency attains maximum value is denoted as I_{2m} and maximum efficiency is denoted as η_{max}.

- The efficiency is a function of load i.e. load current I_2 assuming $\cos\phi_2$ constant. The secondary terminal voltage V_2 is also assumed constant.
- So for maximum efficiency,

$$\frac{d\eta}{dI_2} = 0 \quad \text{while} \quad \eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e}}$$

$$\therefore \quad \frac{d\eta}{dI_2} = \frac{d}{dI_2}\left[\frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e}}\right] = 0$$

$$\therefore \quad (V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e})(V_2 \cos\phi_2) - (V_2 I_2 \cos\phi_2)(V_2 \cos\phi_2 + 2I_2 R_{2e}) = 0$$

- Cancelling $(V_2 \cos\phi_2)$ from both the terms we get,

$$V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e} - V_2 I_2 \cos\phi_2 - 2 I_2^2 R_{2e} = 0$$

i.e. $P_i - I_2^2 R_{2e} = 0$

$$\therefore \quad \boxed{P_i = I_2^2 R_{2e} = P_{Cu}}$$

So condition to achieve maximum efficiency is that,

$$\boxed{\text{Copper losses} = \text{Iron losses i.e. } P_i = P_{Cu}}$$

Important Points to Remember

- **Load current I_{2m} at maximum efficiency is given by,**

$$I_{2m} = (I_2)_{F.L.} \sqrt{\frac{P_i}{(P_{Cu})_{F.L.}}} \quad \text{i.e. n for } \eta_{max} = \sqrt{\frac{P_i}{(P_{Cu})_{F.L.}}}$$

- kVA supplied at maximum efficiency is given by,

$$\text{kVA at } \eta_{max} = (\text{kVA rating}) \times \sqrt{\frac{P_i}{(P_{Cu})_{F.L.}}}$$

- Substituting condition for η_{max} in the expression of efficiency, we can write expression for η_{max} as,

$$\% \eta_{max} = \frac{V_2 I_{2m} \cos\phi}{V_2 I_{2m} \cos\phi + 2P_i} \times 100 \quad \text{as } P_{Cu} = P_i$$

Scanned with CamScanner

Q.23 In a 25 kVA, 2000/200 V transformer, the iron and copper losses are 200 W and 400 W respectively at full load. Calculate : i) Efficiency at half load and 0.8 p.f. lagging ii) kVA for maximum efficiency iii) Maximum efficiency at 0.8 p.f.

[JNTU : Part B, Aug.-08, Marks 5]

Ans. : P_i = 200 W, $P_{cu\,(FL)}$ = 400 W, 25 kVA

i) $\cos\phi = 0.8$, half load i.e. n = 0.5

$$\%\eta_{HL} = \frac{n\ VA\cos\phi}{n\ VA\cos\phi + P_i + [n^2\ P_{cu}\ (FL)]}\times 100$$

$$= \frac{0.5\times 25\times 10^3\times 0.8}{0.5\times 25\times 10^3\times 0.8 + 200 + [0.5^2\times 400]}\times 100 = \mathbf{97.08\ \%}$$

ii) $$\text{kVA at } \eta_{max} = \text{kVA}\times\sqrt{\frac{P_i}{P_{cu}\ (FL)}} = 25\times\sqrt{\frac{200}{400}} = \mathbf{17.677\ kVA} \qquad \ldots P_{cu} = P_i \text{ for } \eta_{max}$$

iii) $$\%\eta_{max} = \frac{VA\ for\ \eta_{max}\times\cos\phi}{VA\ for\ \eta_{max}\times\cos\phi + 2P_i}\times 100$$

$$= \frac{17.677\times 10^3\times 0.8}{17.677\times 10^3\times 0.8 + [2\times 200]}\times 100 = \mathbf{97.25\ \%}$$

Q.24 The efficiency of a 400 kVA, single phase transformer is 98.77 % at full load 0.8 power factor and 99.13 % at half full load unity power factor. Find : i) Iron losses ii) Cu losses at full and half full loads.

[JNTU : Part B, Dec.-4, May-08, Marks 5]

Ans. : 400 kVA, η_{FL} = 98.77 %, $\cos\phi = 0.8$,

η_{HL} = 99.13 %, $\cos\phi = 1$

$$\%\ \eta_{FL} = \frac{VA\cos\phi}{VA\cos\phi + P_i + P_{cu}\,(F.L.)}\times 100$$

$$\therefore\quad 0.9877 = \frac{400\times 10^3\times 0.8}{400\times 10^3\times 0.8 + P_i + P_{cu}\,(F.L.)}$$

$$\therefore\quad P_i + P_{cu}(F.L.) = 3985.01569 \qquad \ldots(1)$$

$$\%\ \eta_{HL} = \frac{n\ VA\cos\phi}{n\ VA\cos\phi + P_i + n^2\ P_{cu}\,(F.L.)}\times 100$$

$$\therefore\quad 0.9913 = \frac{0.5\times 400\times 10^3\times 1}{0.5\times 400\times 10^3\times 1 + P_i + (0.5)^2\ P_{cu}\,(F.L.)} \qquad \text{where } n = 0.5$$

$$\therefore\ P_i + 0.25\ P_{cu}\ (F.L.) = 1755.27085 \qquad \ldots(2)$$

Subtracting equation (Q.24.2) from (Q.24.1)

$$0.75\ P_{cu}\ (F.L.) = 2229.74483 \quad \text{i.e. } P_{cu}\ (F.L.) = 2972.9931\ W$$

$$\therefore\quad P_i = 1012.0225\ W$$

i) Iron losses remain same on full load and half load which are P_i = **1012.0225 W**

ii) Copper losses on full load = P_{cu} (F.L.) = **2972.9931 W**

iii) Copper losses on half load = $(0.5)^2$ P_{cu} (F.L.) = **743.2482 W**

Scanned with CamScanner

Q.25 The maximum efficiency of a 100 kVA transformer is 98.40 % and operates at 90 % full load unity power factor. Calculate the efficiency of a transformer at unity power factor at full load.

[JNTU : Dec.-10, Marks 5]

Ans. : 100 kVA, η_{max} = 98.4 %, kVA for η_{max} = 90 % of full load while $\cos\phi = 1$

$$\%\eta_{max} = \frac{(VA)\text{ for }\eta_{max}\times\cos\phi}{(VA)\text{ for }\eta_{max}+2P_i}\times 100 \text{ i.e. } 0.984$$

$$= \frac{0.9\times 100\times 10^3\times 1}{0.9\times 100\times 10^3\times 1+2P_i}$$

$$\therefore \quad P_i = 731.7073 \text{ W}$$

At η_{max}, Copper losses = Iron losses

$\therefore$ P_{cu} = 731.7073 W at 0.9 of full load i.e. n = 0.9.

Now $P_{cu} \propto I^2 \propto (VA)^2$

$$\text{i.e.} \quad \frac{(P_{cu})_{FL}}{P_{cu}} = \left[\frac{(VA)_{FL}}{0.9\,(VA)_{FL}}\right]^2$$

$$\therefore \quad (P_{cu})_{FL} = 731.7073\times\left(\frac{1}{0.9}\right)^2 = 903.3423 \text{ W}$$

$$\%\eta_{FL} = \frac{(VA)\cos\phi}{(VA)\cos\phi+P_i+(P_{cu})_{FL}}\times 100$$

$$= \frac{100\times 10^3\times 1}{100\times 10^3\times 1+731.7073+903.3423}\times 100$$

$$= 98.3912 \text{ \%}$$

Q.26 A 50 kVA, 1000/10000 V, 50 Hz single phase transformer has iron loss of 1200 W. The copper loss with 5 A in the high voltage winding is 500 W. Calculate the efficiency at i) 25 % ii) 50 % iii) 100 % of normal load at power factor of 0.8. **[JNTU : May-19, Marks5]**

Ans. : 50 kVA, P_i = 1200 W, P_{cu} = 500 W with

I_2 = 5 A

$$\therefore \quad I_2(FL) = \frac{VA}{V_2} = \frac{50\times 10^3}{10000} = 5 \text{ A}$$

- As $I_2 = 5 \text{ A} = I_2(FL)$, given copper losses represent full load copper loss.

$$\therefore \quad P_{cu}\ (FL) = 500 \text{ W}$$

$$\%\ \eta = \frac{n\,VA\cos\phi}{n\,VA\cos\phi+P_i+n^2 P_{cu}\,(FL)}\times 100$$

i) 25 % load, n = 0.25, $\cos\phi$ = 0.8

$$\therefore \%\ \eta = \frac{0.25\times 50\times 10^3\times 0.8}{0.25\times 50\times 10^3\times 0.8+1200+[0.25^2\times 500]}\times 100$$

$$= 89.037 \text{ \%}$$

ii) 50 % load, n = 0.5, $\cos\phi$ = 0.8

$$\therefore \%\ \eta = \frac{0.5\times 50\times 10^3\times 0.8}{0.5\times 50\times 10^3\times 0.8+1200+[0.5^2\times 500]}\times 100$$

$$= 93.797\%$$

iii) 100 % load, n = 1, $\cos\phi$ = 0.8

$$\therefore \%\ \eta = \frac{50\times 10^3\times 0.8}{50\times 10^3\times 0.8+1200+[1^2\times 500]}\times 100$$

$$= 95.923 \text{ \%}$$

4.13 : Three Phase Transformer Connections

Q.27 What are the advantages of 3-phase transformers ? **[JNTU : Part B, Dec.-18, Marks 5]**

Ans. :

1. A three phase transformer occupies less space for same rating, compared to a bank of three single phase transformers.
2. It weighs 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 busbar structure, switchgear and installation of single three phase unit is simpler.

Q.28 What are the possible connections of three phase transformers ? State where they are used.

[JNTU : Part B, Marks 5]

Ans. : • The various possible connections of three phase transformers are,

1. Star-Star connection

- In this, both the primary and secondary windings are connected in star as shown in the Fig. Q.28.1.

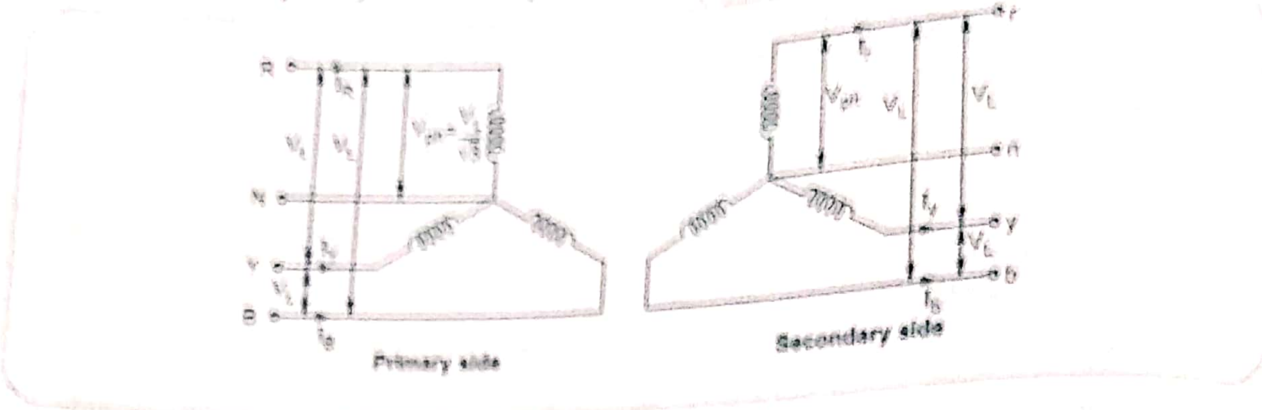


Fig. Q.28.1 Star-Star connection

- This particular connection is used for small high voltage transformers as phase voltage is $1/\sqrt{3}$ times that of line voltage, the number of turns per phase and the quantity of insulation required is minimum.

2. Delta-Delta connection

- In this, both the primary and secondary windings are connected in delta as shown in the Fig. Q.28.2.

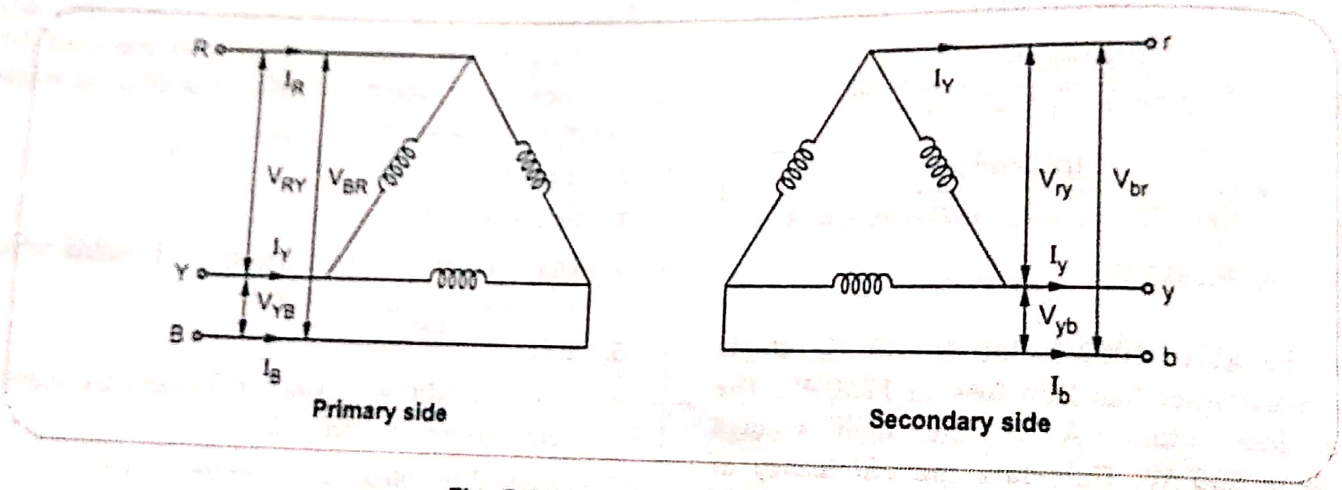


Fig. Q.28.2 Delta-Delta connection

- There is no phase shift between primary and secondary voltages. It is used for large low voltage transformers.

3. Star-Delta connection :

- In this, the primary is connected in star fashion while the secondary is connected in delta fashion as shown in the Fig. Q.28.3.
- It can be seen that there is phase difference of 30° between primary and secondary line voltages. This is used for large high voltage step down transformers.

Scanned with CamScanner

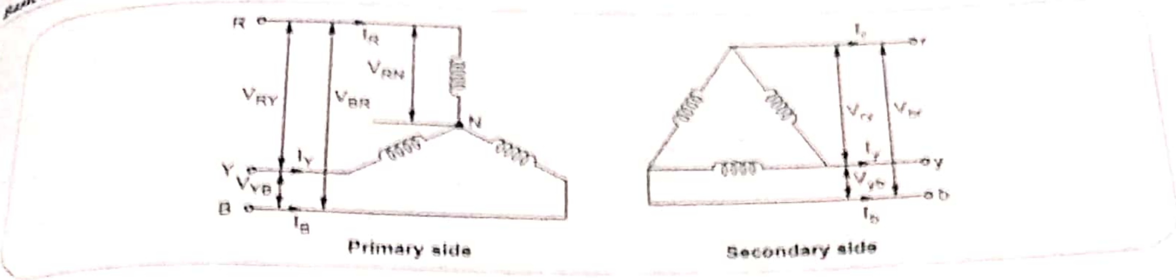


Fig. Q.28.3

4. **Delta-Star connection :**

- In this, the primary is connected in delta fashion while the secondary is connected in star fashion as shown in the Fig. Q.28.4.
- On secondary side, neutral is available, due to which it can be used for 3 phase, 4 wire supply system. Large unbalanced loads can be handled without any difficulty.

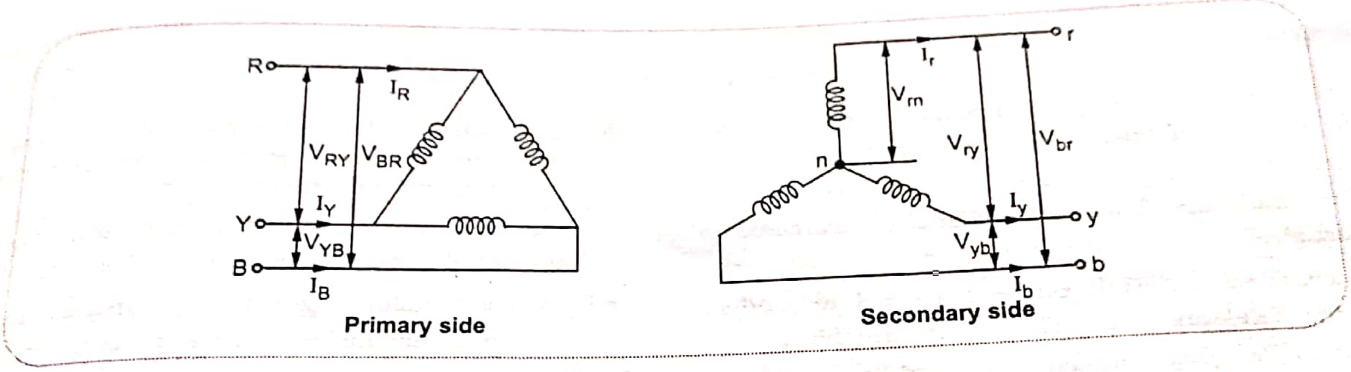


Fig. Q.28.4

Part B : D.C. Machines

4.14 : Construction of D.C. Machine

Q.29 With suitable diagram, explain the constructional features of a d.c. machine.

[JNTU : Part B, Aug.-06, 08, May-06, 09, Dec.-07, Marks 10]

Ans. : • The construction of a d.c. machine is shown in the Fig. Q.29.1.

- It consists of the following parts :

1. **Yoke :** It is outermost cover of a d.c. machine. It provides the mechanical support to the poles and forms a part of magnetic circuit. It protects the insulating material from harmful atmosperic elements like moisture, dust etc.

2. **Poles :** Each pole is divided into two parts namely,

   I) Pole core and II) Pole shoe.

- The pole core carries the field winding. It directs the flux through the air gap to the armature core.

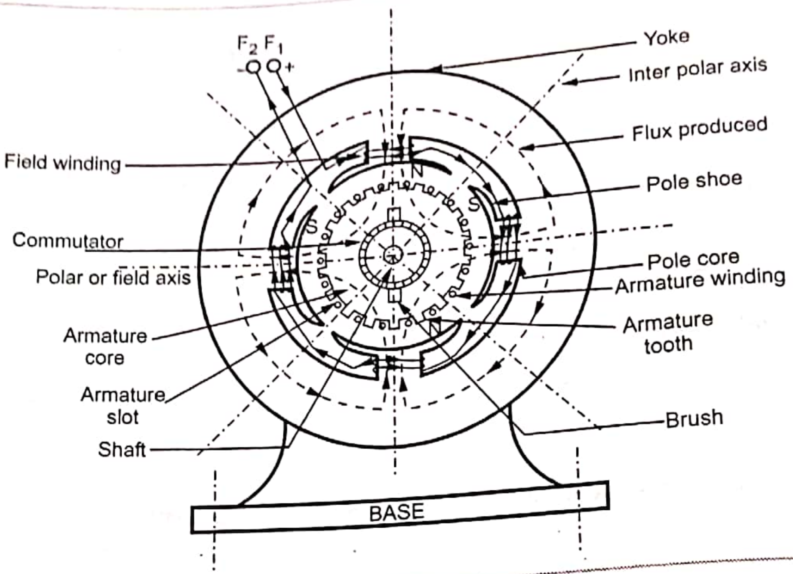


Fig. Q.29.1 A cross-section of typical d.c. machine

- Pole shoe has been given a particular shape so that it enlarges the area of armature core to come across the flux.
- It is made up of magnetic material like cast iron or cast steel.

3. **Field winding :** It carries a current to produce the necessary flux.

- It is made up of conducting material like copper.
- The field winding is wound around the pole core in such a direction such that alternate 'N'. and 'S' poles are formed.

4. **Armature :** It is further divided into two parts namely,
   I) Armature core and II) Armature winding

- Armature core provides house for armature winding. It also provides a path of low reluctance to the magnetic flux produced by the field winding. It is made up of magnetic material like cast iron or cast steel. It is made up of laminated construction.
- Armature winding is nothing but the interconnection of the armature conductors, placed in the slots provided on the armature core periphery. It is made up of conducting material like copper.

5. **Commutator :** It is cylindrical in shape and is made up of wedge shaped segments of hard drawn, high conductivity copper.

- These segments are insulated from each other by thin layer of mica.
- Each commutator segment is connected to the armature conductor by means of copper lug or strip.
- It converts internally developed alternating e.m.f. to unidirectional (d.c.) e.m.f.

6. **Brushes and brush gear :** Brushes are stationary and resting on the surface of the commutator.

- Brushes are normally made up of soft material like carbon.
- Brushes are rectangular in shape. They are housed in brush holders, which are usually of box type.
- The brushes are made to press on the commutator surface by means of a spring, whose tension can be adjusted with the help of lever.
- Brushes collect current from commutator and make it available to the stationary external circuit.

7. **Bearings :** Ball-bearings are usually used as they are more reliable. For heavy duty machines, roller bearings are preferred.

Q.30 Why pole shoe has been given a specific shape ? [JNTU : Part A, Marks 2]

Ans. : It is necessary that maximum area of the armature comes across the flux produced by the field winding. Pole shoe enlarges the area of armature core to come across the flux, which is necessary to produce larger induced e.m.f. To achieve this, pole shoe has been given a particular shape.

Q.31 What is the function of brushes ? Why brushes are made up of soft material ? [JNTU : Part A, Marks 2]

Ans. : The function of brushes is to collect current from commutator and make it available to the stationary external circuit. It connects the stationary external circuit to the rotating commutator. Brushes are stationary and resting on the surface of the commutator just making a contact with it. Thus as commutator rotates there is friction between brushes and commutator. To avoid wear and tear of commutator which is costly, the brushes are made up of soft material like carbon.

4.15 : Working Principle of D.C. Generator

Q.32 Explain the working principle of a d.c. generator. [JNTU : Part B, May-06,09, Dec.-11, Aug.-08, Marks 5]

Ans. : • All generators work on the principle of dynamically induced e.m.f. It states that, 'whenever the number of magnetic lines of force i.e. flux linking with a conductor or a coil changes, an electromotive force is set up in that conductor or coil.'

- The magnitude of induced e.m.f. in a conductor is proportional to the rate of change of flux associated with the conductor. This is mathematically given by, e (magnitude) $\propto \frac{d\phi}{dt}$.
- The relative motion can be achieved by rotating conductor with respect to flux or by rotating flux with respect to a conductor.
- So a voltage gets generated in a conductor, as long as there exists a relative motion between conductor and the flux.
- Such an induced e.m.f. which is due to physical movement of coil or conductor with respect to flux or movement of flux with respect to coil or conductor is called **dynamically induced e.m.f.**
- So a generating action requires following basic components to exist, i) The conductor or a coil ii) The flux iii) The relative motion between conductor and flux.
- To have a large voltage as the output, the number of conductors are connected together in a specific manner, to form a winding. This winding is called **armature winding** and the part on which this winding is kept is called **armature** of a d.c. machine.
- To have the rotation of conductors, the conductors placed on the armature are rotated with the help of some external device. Such an external device is called a **prime mover**. The commonly used prime movers are diesel engines, steam engines, steam turbines, water turbines etc.
- The necessary magnetic flux is produced by current carrying winding which is called **field winding.**
- The direction of the induced e.m.f. can be obtained by using Fleming's right hand rule.
- If angle between the plane of rotation and the plane of the flux is ' θ ' as measured from the axis of the plane of flux then the induced e.m.f. is given by,

$$E = B\,l\,(v \sin\theta) \text{ volts}$$

where $v \sin\theta$ is the component of velocity which is perpendicular to the plane of flux and hence responsible for the induced e.m.f.

- As seen from the equation of induced e.m.f. E, it is sinusoidal in nature. Thus to convert it to d.c., commutator is used in d.c. generator. Hence finally the output voltage of generator is d.c. in nature.

4.16 : Types of Armature Winding

Important Points to Remember

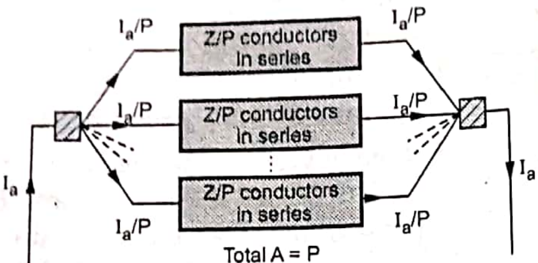
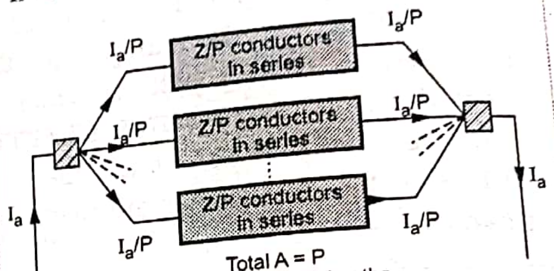
- The two types of armature windings used in d.c. machines are,

  a) Lap winding b) Wave winding

- Number of parallel paths are denoted as A hence A = P for lap winding and A = 2 for wave winding.
- The two conductors placed in different slots when connected together forms a turn. Hence number of conductors Z = 2 × number of turns.
- The distance between the two adjacent poles is called a **pole pitch. It is defined as total slots along the periphery of armature divided by the total number of poles.**

Q.33 Compare lap and wave type of windings used in d.c. machines. [JNTU : Part B, Jan.-10, Marks 5]

Ans. :

Sr. No.	Lap winding	Wave winding
1.	Number of parallel paths (A) = Poles (P)	Number of parallel paths (A) = 2 (always)
2.	Number of brush sets required is equal to number of poles.	Number of brush sets required is always equal to two.
3.	Preferable for high current, low voltage capacity generators.	Preferable for high voltage, low current capacity generators.
4.	Normally used for generators of capacity more than 500 A.	Preferred for generators of capacity less than 500 A.
5.	If Z = Total number of conductors then,  Total A = P number of parallel paths	If Z = Total number of conductors then,  Total A = P number of parallel paths

4.17 : E.M.F. Equation of D.C. Generator

Q.34 Derive the e.m.f. equation of a d.c. generator. [JNTU : Part B, Dec.-04, 05, 07, 08, 11, 12, May-06, 12, Aug.-08, Marks 5]

Ans. : Let P = Number of poles,

ϕ = Flux per pole in webers (Wb)

N = Speed of armature in r.p.m., Z = Total number of armature conductors

A = Number of parallel paths, N = Speed in r.p.m.

- So A = P for lap type of winding and A = 2 for wave type of winding
- Now e.m.f. gets induced in the conductor according to Faraday's law of electromagnetic inducti Hence average value of e.m.f. induced in each armature conductor is,

$$e = \text{Rate of cutting the flux} = \frac{d\phi}{dt}$$

- Consider one revolution of conductor. In one revolution, conductor will cut total flux produced b the poles i.e. $\phi \times P$. While time required to complete one revolution is $\frac{60}{N}$ seconds as speed is N r.

$$\therefore \quad e = \frac{\phi P}{\frac{60}{N}} = \phi P \frac{N}{60}$$

...This is the e.m.f. induced in one cond

Scanned with CamScanner

- The conductors in one parallel path are always in series. There are total Z conductors with A parallel paths, hence $\frac{Z}{A}$ number of conductors are always in series and e.m.f. remains same across all the parallel paths.

$\therefore$ Total e.m.f. can be expressed as, $E = \phi P \frac{N}{60} \times \frac{Z}{A}$ volts

- This is nothing but the e.m.f. equation of a d.c. generator.

So, $$E = \frac{\phi PNZ}{60A} \quad \text{... e.m.f. equation}$$

with A = P for Lap and A = 2 for Wave

Important Points to Remember

Turn : The two conductors placed in different slots when connected together, forms a turn hence $Z = 2 \times$ Number of turns.

Coil : The turns are grouped together to form a coil. If coil contains only one turn it is called single turn coil while coil more than one turn is called multiturn coil.

Coilside : Two coilsides form one coil. These coilsides are placed in different slots having a distance of around one pole pitch between them.

Single layer winding : Each slot contains only one coil side of a coil.

Double layer winding : There are two coilsides per slot, one in the top half of the slot and other in the bottom half of the slot.

Q.35 A 4-pole d.c. generator has a lap wound armature having 400 conducors. It generates an e.m.f. of 300 V when the flux per pole is 0.02 Wb. Find the speed of rotation of its armature.

[JNTU : Part B, Marks 5]

Ans. : P = 4, lap i.e. A = P, Z = 400, ϕ = 0.02 Wb, E_g = 300 V.

$$\therefore \quad E_g = \frac{\phi PNZ}{60\,A} \quad \text{i.e.} \quad N = \frac{300 \times 60 \times 4}{0.02 \times 4 \times 400} = \mathbf{2250\ r.p.m.}$$

Q.36 A 4 pole wave wound d.c. generator has 50 slots and 24 conductors per slot. The flux per pole is 10 mWb. Determine the induced e.m.f. in the armature if it is rotating at a speed of 700 r.p.m.

[JNTU : Part B, Marks 5]

Ans. : P = 4, Wave i.e. A = 2, 50 slots, 20 conductors/slot, ϕ = 10 mWb, N = 700 r.p.m.

$$Z = \text{slots} \times \text{conductors/slot} = 50 \times 20 = 1000$$

$$E_g = \frac{\phi PNZ}{60\,A} = \frac{10 \times 10^{-3} \times 4 \times 700 \times 1000}{60 \times 2} = \mathbf{233.333\ V}$$

Scanned with CamScanner

4.18 : Types of D.C. Generators

Q.37 State the various types of d.c. generators. Draw their connection diagrams and state their voltage and current relationships.

[JNTU : Part B, May-08,11,19, Dec.-06,09,11, Marks 10]

Ans. : The field winding of a d.c. generator is called exciting winding.

- Supplying current to the field winding is called excitation and the way of supplying the exciting current (field current) is called **method of excitation.**
- The d.c. generators are classified depending on type of excitation used. The two types of excitation are,

  a) Separate excitation and b) Self excitation.

a) Separately excited generator

- In this type, a separate external d.c. supply is used to provide exciting current through the field winding.
- The Fig. Q.37.1 shows the circuit of separately excited generator

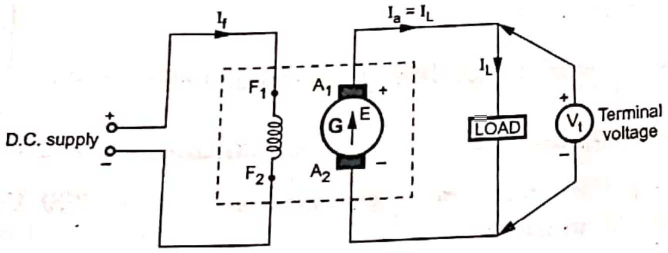


Fig. Q.37.1 Separately excited generator

- The induced e.m.f. E has three components namely, i) Terminal voltage V_t ii) Armature resistance drop $I_a R_a$ iii) Brush contact drop V_{brush}.

$$I_a = I_L \text{ and } E_g = V_t + I_a R_a + V_{brush}$$

b) Self excited generator

- The d.c. generator produces d.c. voltage. If this generated voltage itself is used to excite the field winding of the same d.c. generator, it is called **self excited generator.**
- Based on how field winding is connected to the armature to derive its excitation, self excited generators are further divided into following three types : i) Shunt ii) Series and iii) Compound generator.

1. **Shunt generator :** In this type, the field winding is connected in parallel with the armature and the combination across the load.

- From the Fig. Q.37.2,

$$I_a = I_L + I_{sh}, \quad I_{sh} = \frac{V_t}{R_{sh}}$$

$$E_g = V_t + I_a R_a + V_{brush}$$

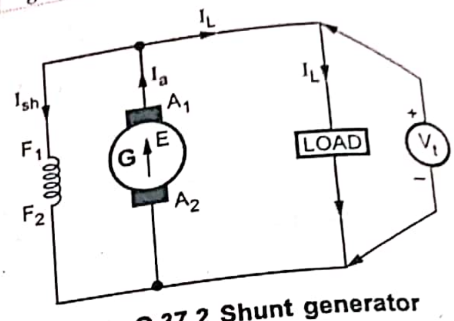


Fig. Q.37.2 Shunt generator

2. **Series generator :** In this type the field winding is connected in series with the armature winding while supplying the load.

- From the Fig. Q.37.3.

$$I_a = I_{se} = I_L \text{ and}$$

$$E_g = V_t + I_a R_a + I_a R_{se} + V_{brush}$$

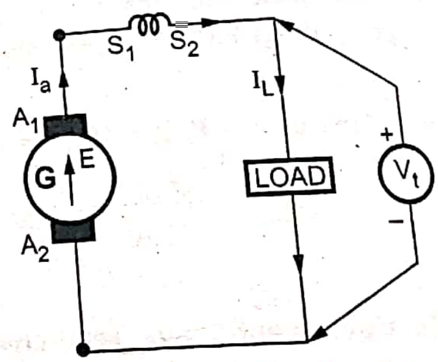


Fig. Q.37.3 Series generator

3. **Compound generator :** In this type, the part of the field winding is connected in parallel with the armature and part in series with the armature.

- Depending upon the connection of shunt and series field winding, compound generator is further classified as : i) Long shunt compound generator ii) Short shunt compound generator.

Scanned with CamScanner

ii) **Long shunt compound generator :**

- In this type, shunt field winding is connected across the series combination of armature and series field winding as shown in the Fig. Q.37.4.

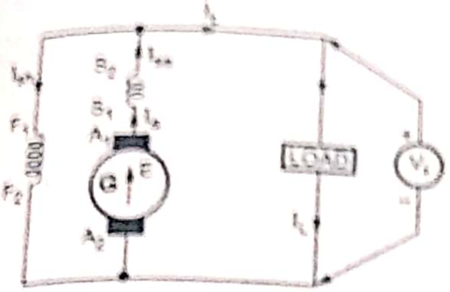


Fig. Q.37.4 Long shunt compound generator

$$I_a = I_{sh} + I_L$$

$$I_{sh} = \frac{V_t}{R_{sh}}$$

$$E_g = V_t + I_a R_a + I_a R_{se} + V_{brush}$$

iii) **Short Shunt Compound Generator :** In this type, shunt field winding is connected, only across the armature, excluding series field winding as shown in the Fig. Q.37.5.

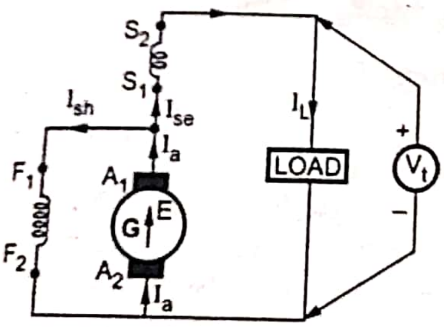


Fig. Q.37.5 Short shunt compound generator

$$I_a = I_L + I_{sh},$$

$$I_{sh} = \frac{E_g - I_a R_a}{R_{sh}} = \frac{V_t + I_L R_{se}}{R_{sh}}, \quad I_{se} = I_L$$

$$E_g = V_t + I_a R_a + I_L R_{se} + V_{brush}$$

4.19 : Applications of D.C. Generators

Q.38 State the applications of various types of d.c. generators.

[JNTU : Part A, Aug.-08, 09, May-08, 09, 12, 13, Dec.-08, Marks 3]

Ans. : Separately excited generators :

- As a separate supply is required to excite field, the use is restricted to some special applications like electro-plating, electro-refining of materials etc.

Shunt generators :

- Commonly used in battery charging and ordinary lighting purposes.

Series generators :

- Commonly used as boosters on d.c. feeders, as a constant current generators for welding generator and arc lamps.

Cumulatively compound generators :

- These are used for domestic lighting purposes and to transmit energy over long distance.

Differential compound generator :

The use of this type of generators is very rare and it is used for special application like electric arc welding.

4.20 : Working Principle of D.C. Motors

Important Points To Remember

- An electrical machine which converts electrical energy into mechanical energy is called an electric motor.
- The d.c. motors convert d.c. electrical energy into mechanical energy.

Q.39 Explain the working principle of a d.c. motor.

[JNTU : Part B, May-04, 08, Dec.-07, 12, Marks 5]

Ans. : The principle of operation of a d.c. motor can be stated as 'when a current carrying conductor is placed in a magnetic field; it experiences a mechanical force'.

- Consider a single conductor placed in a magnetic flux. In a practical d.c. motor magnetic flux is produced by the field winding when it carries a current.
- This conductor is excited by a separate supply so that it carries a current in a particular direction.

- Any current carrying conductor produces its own magnetic field around it, hence this conductor also produces its own flux, around it.
- Thus there are two fluxes present,

1. The flux produced by the field winding called main flux.
2. The flux produced by the current carrying conductor.

- Both the fluxes interact with each other such that on one side of the conductor, both the fluxes are in the same direction and assist each other. As against this, on the other side of the conductor, the two fluxes are in opposite direction and hence try to cancel each other.
- Due to this, there exists low high flux density area on one side of the conductor and low flux density area on the other side of the conductor.
- This flux distribution around the conductor acts like a stretched rubber band under tension. This exerts a mechanical force on the conductor which acts from high flux density area towards low flux density area.
- All the armature conductors, mounted on the periphery of the armature drum, get subjected to such mechanical force.
- Due to this, overall armature experiences a twisting force called torque and armature of the motor starts rotating.

Q.40 How to reverse the direction of rotation of d.c. motor ? ☞[JNTU : Part A, May-09, Marks 2]

Ans. : To reverse direction of rotation of d.c. motor, either direction of main field produced by the field winding is reversed or direction of the current passing through the armature is reversed.

The direction of the main field can be reversed by changing the direction of current passing through the field winding, which is possible by interchanging the polarities of supply which is given to the field winding.

4.21 : Back E.M.F. and its Significance

Q.41 What is back e.m.f. ? Explain the significance of a back e.m.f.
☞[JNTU : Part B, May-05, Aug.-06, 08, Dec.-10, Marks 5]

Ans. : • In a d.c. motor, when motor starts rotating, the armature conductors rotate in the flux produced by the field winding.

- Thus the armature conductors cut the flux and there is an induced e.m.f. in the rotating armature conductors according to Faraday's law of electromagnetic induction.
- According to Lenz's law this induced e.m.f. in the armature always acts in the opposite direction to the cause producing it which is the supply voltage.
- This e.m.f. tries to set up a current through the armature which is in the opposite direction to that, which supply voltage is forcing through the conductor.
- So as this e.m.f. always opposes the supply voltage, it is called **back e.m.f.** and denoted as E_b. Though it is denoted as E_b, basically it gets generated by the generating action hence its magnitude can be determined by the e.m.f. equation as,

$$E_b = \frac{\phi P N Z}{60 A} \text{ volts} \qquad \text{i.e. } E_b \propto N\phi$$

Significance of back e.m.f. :

- In case of a d.c. motor, supply voltage V has to overcome back e.m.f. E_b which is opposing V and also various drops as armature resistance drop $I_a R_a$, brush drop etc.
- Hence the voltage equation of a d.c. motor can be written as,

$$V = E_b + I_a R_a + \text{Brush drop and negelcting brush drop, } I_a = \frac{V - E_b}{R_a}$$

- When load is suddenly put onto the motor, motor tries to slow down. So speed of the motor reduces due to which back e.m.f. also decreases. So the net voltage across the armature $(V - E_b)$ increases and motor draws more armature current.
- Due to increased current, force experienced by the conductors increases and hence the torque on the armature increases. This satisfies increased load demand.
- When load on the motor is decreased, the speed of the motor tries to increase. Hence back e.m.f. increases. This causes $(V - E_b)$ to reduce which eventually reduces the current drawn by the armature. This produces the less torque required by the new load.

• Thus back e.m.f. regulates the flow of armature current and it automatically alters the armature current to meet the load requirement. This is the practical significance of the back e.m.f.

Important Points to Remember

Power equation of a d.c. motor :

• Multiplying both sides of the voltage equation by I_a we get power equation as,

$VI_a = E_b I_a + I_a^2 R_a$

• VI_a = Net electrical power input to the armature measured in watts.

• $I_a^2 R_a$ = Power loss due to the resistance of the armature called **armature copper loss.**

• $E_b I_a$ = Electrical equivalent of gross mechanical power developed by the armature. This is denoted as P_m.

Q.42 A 220 V, d.c. motor has an armature resistance of 0.75 Ω. It is drawing an armature current of 30 A, driving a certain load. Calculate the induced e.m.f. in the motor under this condition. **[JNTU : Aug.-08, Part A, Marks 2]**

Ans. : V = 200 V, I_a = 30 A, R_a = 0.75 Ω are the given values.

For a motor, $V = E_b + I_a R_a$

$$220 = E_b + 30 \times 0.75$$

$$\therefore \quad E_b = \mathbf{197.5 \text{ volts}}$$

This is the induced e.m.f. called back e.m.f. in a motor.

4.22 : Torque Equation

Q.43 Derive from the first principle an expression for the torque developed in a d.c. motor. **[JNTU : Part B, May- 08, 09, 10, Dec.-09, 11, Marks 5]**

Ans. : • Consider a wheel of radius R metres acted upon by a circumferential force F newtons as shown in the Fig. Q.43.1.

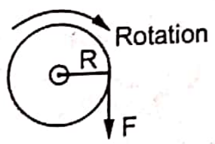


Fig. Q.43.1

• The wheel is rotating at a speed of N r.p.m.

• Then angular speed of the wheel is,

$$\omega = \frac{2\pi N}{60} \quad \text{rad/sec}$$

• So work done in one revolution is,

$$W = F \times \text{Distance travelled in one revolution}$$

$$= F \times 2\pi R \text{ joules}$$

And P = Power developed = $\frac{\text{Work done}}{\text{Time}}$

$$= \frac{F \times 2\pi R}{\text{Time for 1 rev}} = \frac{F \times 2\pi R}{\left(\frac{60}{N}\right)} = (F \times R) \times \left(\frac{2\pi N}{60}\right)$$

$$\therefore \quad P = T \times \omega \quad \text{watts}$$

where T = Torque in N · m and

ω = Angular speed in rad/sec.

• Let T_a be the gross torque developed by the armature of the motor. It is also called **armature torque.**

• The gross mechanical power developed in the armature is $E_b I_a$ from the power equation.

• So if speed of the motor is N r.p.m. then,

Power in armature = Armature torque × ω i.e.

$$E_b I_a = T_a \times \frac{2\pi N}{60}$$

• But E_b in a motor is given by, $E_b = \frac{\phi P N Z}{60 A}$

$$\therefore \quad \frac{\phi P N Z}{60 A} \times I_a = T_a \times \frac{2\pi N}{60}$$

$$\therefore \quad \boxed{T_a = \frac{1}{2\pi} \phi I_a \times \frac{PZ}{A} = 0.159\, \phi I_a \cdot \frac{PZ}{A} \text{ Nm}}$$

• This is the **torque equation** of a d.c. motor.

Important Points to Remember

• The total armature torque T_a is not available at the shaft to drive the load because of friction and windage losses.

• The torque required to overcome these losses is called **lost torque**, denoted as T_f.

• The torque which is available at the shaft for doing the useful work is known as **load torque or shaft torque** denoted as T_{sh}. So $T_a = T_f + T_{sh}$.

• The product of shaft torque T_{sh} and the angular speed ω rad/sec is called power available at the shaft i.e. net output of the motor.

• Net output of motor = $P_{out} = T_{sh} \times \omega$ ... Rating of motor

Q.44 The armature of a 6 pole, d.c. shunt motor takes 300 A at the speed of 400 revolutions per minute. The flux per pole is 75 mWb. The number of armature turns is 500. The torque lost in windage, friction and iron losses can be assumed a 2.5 %. Calculate :

i) Torque developed by the armature

ii) Shaft torque iii) Shaft power in kW.

[JNTU : Part B, May-08, Aug.-08, June-09, Jan.-10, Marks 5]

Scanned with CamScanner

Ans. : $P = 6$, $I_a = 300$ A, $N = 400$ r.p.m., $\phi = 75$ mWb

Turns = 500, $T_{lost} = 2.5$ % of T_a

Two conductors constitute one turn hence $Z = 2 \times$ Turns $= 2 \times 500 = 1000$

Assume lap connected armature i.e. A = P.

i) $\frac{1}{2\pi}\phi I_a \times \frac{PZ}{A} = \frac{1}{2\pi} \times 75 \times 10^{-3} \times 300 \times \frac{6 \times 1000}{6}$

$= \mathbf{3580.986\ Nm}$

ii) $T_{lost} = 2.5$ % of $T_a = \frac{2.5}{100} \times 3580.986 = 89.5246$ Nm

$\therefore \quad T_{sh} = T_a - T_{lost} = \mathbf{3491.461\ Nm}$

iii) $P_{out} = T_{sh} \times \omega = T_{sh} \times \frac{2\pi N}{60} = \frac{3491.461 \times 2\pi \times 400}{60}$

$= \mathbf{146.25\ kW}$

4.23 : Types of D.C. Motors

Q.45 State the various types of d.c. motors alongwith their voltage and current relationships.

☞ [JNTU : Part B, May-05, 07, Dec. -04, 08, Marks 5]

Ans. : The various types of d.c. motors are,

1. D.C. shunt motor : The field winding is connected across the armature winding and the combination is connected across the supply, as shown in the Fig. Q.45.1.

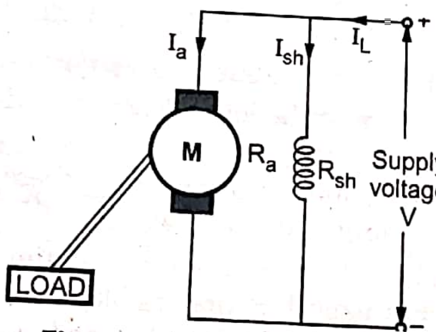


Fig. Q.45.1 D.C. shunt motor

$$I_L = I_a + I_{sh}$$

$$I_{sh} = \frac{V}{R_{sh}}$$

$$V = E_b + I_a R_a + V_{brush} \quad \text{... Voltage equation}$$

- Flux produced by the field winding is proportional to the current passing through it i.e. I_{sh}.

$$\phi \propto I_{sh}$$

2. D.C. Series motor : The series field winding is connected in series with the armature and the supply, as shown in the Fig. Q.45.2.

$$I_L = I_{se} = I_a$$

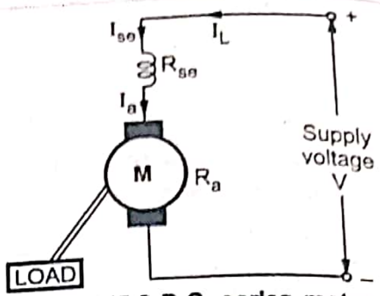


Fig. Q.45.2 D.C. series motor

- Supply voltage has to overcome the drop across series field winding in addition to E_b and drop across armature winding.

$$V = E_b + I_a (R_a + R_{se}) + V_{brush} \quad \text{... Voltage equation}$$

$$\phi \propto I_{se} \propto I_a \quad \text{for series motor}$$

3. Long shunt compound motor :

- The shunt field winding is connected across the combination of armature and the series field winding as shown in the Fig. Q.45.3.

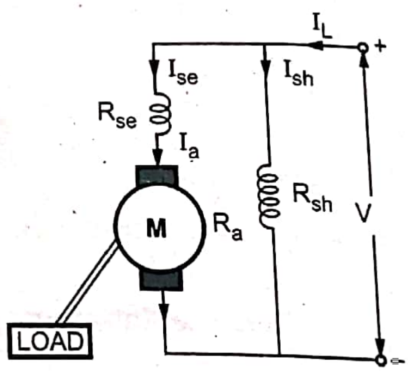


Fig. Q.45.3 Long shunt compound motor

$$I_L = I_{se} + I_{sh}$$

$$I_{se} = I_a$$

$$\therefore \quad I_L = I_a + I_{sh}$$

$$I_{sh} = \frac{V}{R_{sh}}$$

$$V = E_b + I_a (R_a + R_{se}) + V_{brush} \quad \text{... Voltage equatio}$$

4. Short shunt compound motor :

The shunt field is connected purely in parallel w armature and the series field is connected in se with this combination shown in the Fig. Q.45.4.

Scanned with CamScanner

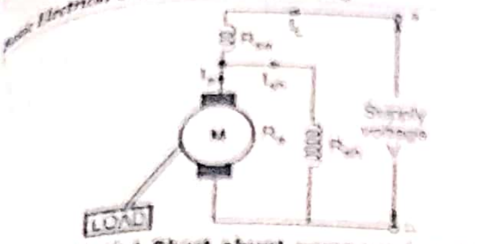


Fig. Q.45.4 Short shunt compound motor

$$I_L = I_{se}$$
$$I_L = I_a + I_{sh}$$

$$V = E_b + I_{se} R_{se} + I_a R_a + V_{brush} \quad \text{... Voltage equation}$$

$$I_{sh} = \frac{V - I_L R_{se}}{R_{sh}} = \frac{E_b + I_a R_a + V_{brush}}{R_{sh}}$$

Important Points to Remember

- Torque equation,
  $T \propto \phi I_a$ ... from torque equation.
  $\phi \propto I_{field}$ ... flux proportional to field current
- For d.c. shunt motor,
  $T \propto I_a$ ... ϕ is constant
- For d.c. series motor,
  $T \propto I_a \phi \propto I_a^2$ ... $\phi \propto I_a$
- Speed equation, $E_b \propto \phi N$ i.e. $N \propto \frac{E_b}{\phi}$

$$\% \text{ Speed regulation} = \frac{N_{no\ load} - N_{full\ load}}{N_{full\ load}} \times 100$$

Q.46 A 120 V dc shunt motor having an armature circuit resistance of 0.2 Ω and field circuit resitance of 60 Ω, draw a line current current of 40 A at full load. The brush voltage drop is 3 V and rated full load speed is 1800 rpm. Calculate : i) The speed at half load ii) The speed at 125 % of full load. ☞[JNTU : Part B, Jan.-10, Marks 5]

Ans. : $V = 120\ V$, $R_a = 0.2\,\Omega$, $R_{sh} = 60\,\Omega$

$$I_{FL} = 40\ A, \quad V_{brush} = 3\ V, \quad N_{FL} = 1800 \text{ r.p.m.}$$

$$I_{sh} = \frac{V}{R_{sh}} = 2\ A$$

$$I_{aFL} = I_{FL} - I_{sh} = 38\ A$$

$$E_{bFL} = V - I_{aFL} R_a - V_{brush} = 120 - 38 \times 0.2 - 3$$
$$= 109.4\ A$$

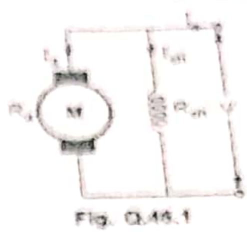


Fig. Q.46.1

$T \propto \phi I_a \propto I_a$ ... ϕ is constant

i) At half load, $T_2 = 0.5\ T_1$

$$\therefore \quad \frac{T_1}{T_2} = \frac{I_{a1}}{I_{a2}} \quad \text{i.e.} \quad \frac{1}{0.5} = \frac{38}{I_{a2}}$$

$$\therefore \quad I_{a2} = 19\ A$$

$$\therefore \quad E_{b2} = V - I_{a2} R_a - V_{brush} = 113.2\ V$$

$$N \propto \frac{E_b}{\phi} \propto E_b$$

$$\therefore \quad \frac{N_{FL}}{N_{HL}} = \frac{E_{bFL}}{E_{b2}} \quad \text{i.e.} \quad N_{HL} = \frac{1800 \times 113.2}{109.4}$$

$$= \mathbf{1862.52\ r.p.m.}$$

ii) At 125 % of full load i.e. $T_3 = 1.25\ T_1$

$$\therefore \quad \frac{T_3}{T_1} = \frac{I_{a3}}{I_{a1}} \quad \text{i.e.} \quad 1.25 = \frac{I_{a3}}{I_{aFL}}$$

$$\text{i.e.} \quad I_{a3} = 47.5\ A$$

$$\therefore \quad E_{b3} = V - I_{a3} R_a - V_{brush} = 107.5\ V$$

$$\therefore \quad \frac{N_{FL}}{N_3} = \frac{E_{bFL}}{E_{b3}} \quad \text{i.e.} \quad N_3 = \frac{1800 \times 107.5}{109.4}$$

$$\therefore \quad N_3 = \mathbf{1768.74\ r.p.m.} \quad \text{... Speed at 125 \% of FL}$$

4.24 : Characteristics of D.C. Shunt Motor

Q.47 Draw the torque-armature current, speed - torque and speed-armature current characteristics of d.c. shunt motor. ☞[JNTU : Part B, Aug.-06, May-09, Dec.-09, Marks 5]

Ans. : i) Torque-Armature current characteristics :

- For a d.c. motor,
  $T \propto \phi I_a$
- For a constant values of R_{sh} and supply voltage V, I_{sh} is also constant and hence flux is also constant.
  $T_a \propto I_a$
- The equation represents a straight line, passing through the origin, as shown in the Fig. Q.47.1.

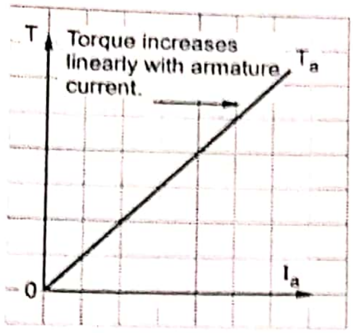


Fig. Q.47.1 T Vs I_a for shunt motor

- Torque increases linearly with armature current.

ii) Speed-Armature current characteristics :

- From the speed equation we get,

$$N \propto \frac{V - I_a R_a}{\phi} \propto V - I_a R_a \qquad \text{...as } \phi \text{ is constant.}$$

- So as load increases, the armature current increases and hence drop $I_a R_a$ also increases.
- Hence for constant supply voltage, $V - I_a R_a$ decreases and hence speed reduces. But as R_a is very small, for change in I_a from no load to full load, drop $I_a R_a$ is very small and hence drop in speed is also not significant from no load to full load.
- So the characteristics is slightly droping as shown in the Fig. Q.47.2.

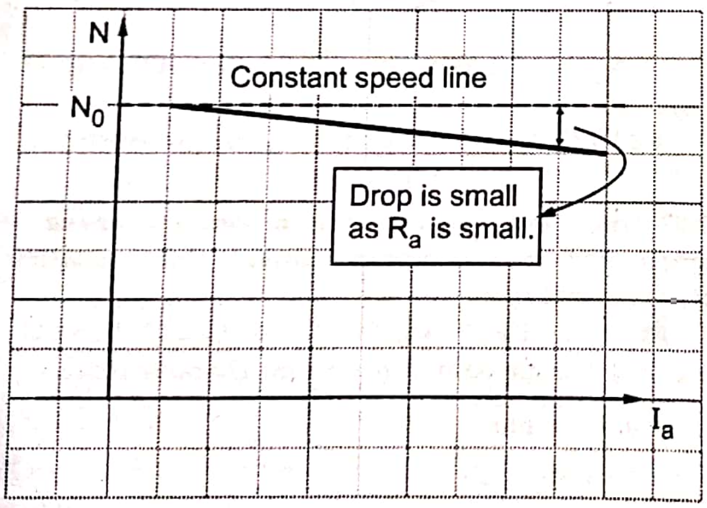


Fig. Q.47.2 N Vs I_a for shunt motor

iii) Speed-Torque characteristics :

- The graph is similar to speed-armature current characteristics as torque is proportional to the armature current.

- This curve shows that the speed almost remains constant though torque changes from no load to full load conditions. This is shown in the Fig. Q.47.3.

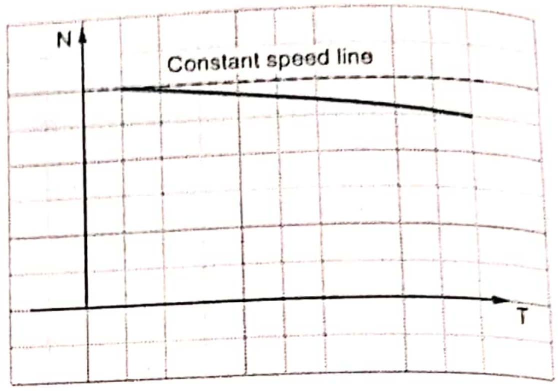


Fig. Q.47.3 N Vs T for shunt motor

4.25 : Characteristics of D.C. Series Motor

Q.48 Draw the torque-armature current, speed - torque and speed-armature current characteristics of d.c. series motor.

☞ [JNTU : Part B, May-07, Aug.-08, Dec.-10, Marks 5]

Ans. : i) Torque-Armature current characteristics :

- In case of series motor the series field winding is carrying the entire armature current. So flux produced is proportional to the armature current.

Hence $\quad T_a \propto \phi I_a \propto I_a^2 \quad \text{as } \phi \propto I_a$

- Thus torque in case of series motor is proportional to the square of the armature current. This relation is parabolic in nature as shown in the Fig. Q.48.1.
- As load increases, armature current increases and torque produced increases proportional to the square of the armature current upto a certain limit.

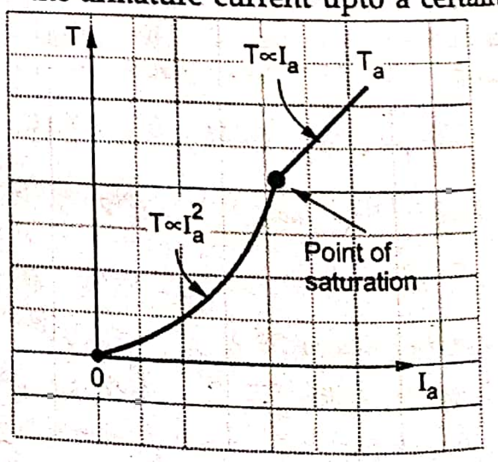


Fig. Q.48.1 T Vs I_a for series motor

- After saturation the flux remains constant. Hence after saturation the characteristics take the shape of straight line as flux becomes constant, as shown.

ii) **Speed-Armature current characteristics :**

- From the speed equation we get,

$$N \propto \frac{E_b}{\phi} \propto \frac{V - I_a R_a - I_a R_{se}}{I_a} \qquad \text{as } \phi \propto I_a$$

- The values of R_a and R_{se} are so small that the effect of change in I_a on speed overrides the effect of change in $V - I_a R_a - I_a R_{se}$ on the speed.
- Hence in the speed equation, $E_b \cong V$ and can be assumed constant. So speed equation reduces to,

$$\boxed{N \propto \frac{1}{I_a}}$$

- So speed-armature current characteristics is rectangular hyperbola type as shown in the Fig. Q.48.2.

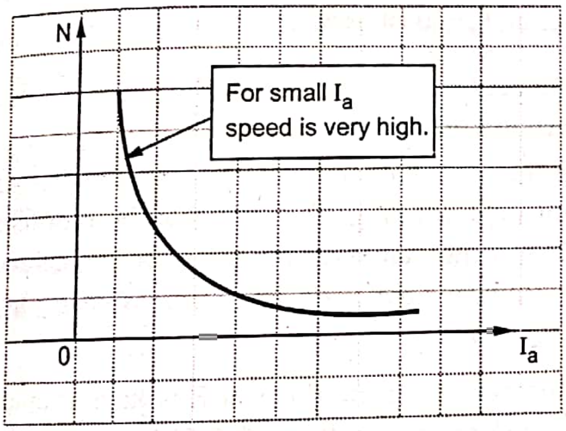


Fig. Q.48.2 N Vs I_a for series motor

iii) **Speed-Torque characteristics :**

- In case of series motors, $T \propto I_a^2$ and $N \propto \frac{1}{I_a}$

Hence we can write, $\boxed{N \propto \frac{1}{\sqrt{T}}}$

Thus as torque increases when load increases, the speed decreases.

On no load, torque is very less and hence speed increases to dangerously high value.

- Thus the nature of the speed-torque characteristics is similar to the nature of the speed-armature current characteristics as shown in the Fig. Q.48.3.

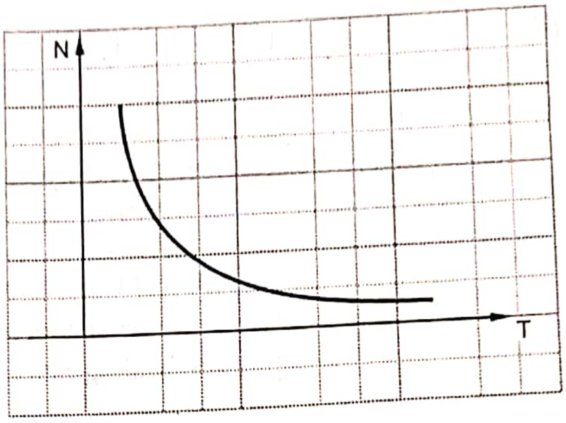


Fig. Q.48.3 N Vs T for series motor

Q.49 Why d.c. series motor is never started on no load ?

[JNTU : Part A, May-08, Marks 3]

Ans. : • The armature current of a d.c. motor is decided by the load.

- On light load or no load, the armature current drawn by the motor is very small.
- In case of a d.c. series motor, $\phi \propto I_a$ and on no load as I_a is small hence flux produced is also very small.
- According to speed equation,

$$N \propto \frac{1}{\phi} \qquad \text{as } E_b \text{ is almost constant}$$

- So on very light load or no load as flux is very small, the motor tries to run at dangerously high speed which may damage the motor mechanically.
- On low armature current and low torque condition motor shows a tendency to rotate with dangerously high speed. Hence d.c. series motor is never started on light load or no load.

Scanned with CamScanner

4.26 : Applications of D.C. Motors

Q.50 State the applications of d.c. motors.

[JNTU : Part A, Jan.-10, May-12, Marks 3]

Ans. :

Types of motor	Characteristics	Applications
Shunt	Speed is fairly constant and medium starting torque.	1) Blowers and fans 2) Centrifugal and reciprocating pumps 3) Lathe machines 4) Machine tools 5) Milling machines 6) Drilling machines
Series	High starting torque. No load condition is dangerous. Variable speed.	1) Cranes 2) Hoists, Elevators 3) Trolleys 4) Conveyors 5) Electric locomotives
Cumulative compound	High starting torque. No load condition is allowed.	1) Rolling mills 2) Punches 3) Shears 4) Heavy planers 5) Elevators
Differential compound	Speed increases as load increases.	Not suitable for any practical application.

4.27 : Speed Control of D.C. Motors

Q.51 Explain the speed control methods of d.c. shunt motors.

Ans.: The speed of d.c. shunt motor is controlled by two methods called, i) Armature voltage control ii) Flux control

i) Armature voltage control :

As the supply voltage is normally constant, the voltage across the armature can be controlled by adding a variable resistance in series with the armature as shown in the Fig. Q.51.1.

- The field winding is excited by the normal voltage hence I_{sh} is rated and constant in this method.

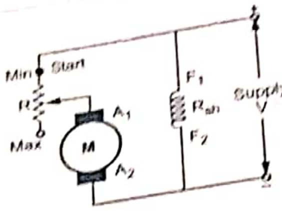


Fig. Q.51.1 Rheostatic control

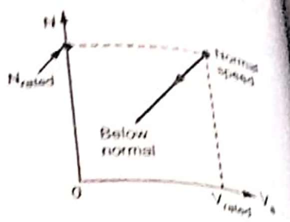


Fig. Q.51.2 N Vs voltage

- Initially the rheostat position is minimum and rated voltage gets applied across the armature. So speed is also rated.
- For a given load, armature current is fixed. So when extra resistance is added in the armature circuit, I_a remains same and there is voltage drop across the resistance added ($I_a R$).
- Hence voltage across the armature decreases, decreasing the speed below normal value.
- By varying this extra resistance, various speeds below rated value can be obtained.
- The relationship between speed and voltage across the armature is shown in the Fig. Q.51.1.

ii) Flux control : The speed is inversely proportional to the flux.

- The flux is dependent on the current through the shunt field winding. Thus flux can be controlled by adding a rheostat (variable resistance) in series with the shunt field winding, as shown in the Fig. Q.51.3.
- At the beginning the rheostat R is kept at minimum indicated as start in the Fig. Q.51.3.
- The supply voltage is at its rated value. So current through shunt field winding is also at its rated value. Hence the speed is also rated speed also called normal speed.

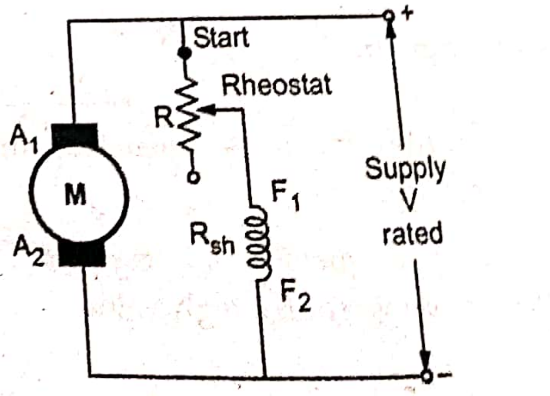


Fig. Q.51.3 Flux control of shunt motor

Scanned with CamScanner

- Then the resistance R is increased due to which shunt field current I_{sh} decreases, decreasing the flux produced.
- As $N \propto (1/\phi)$, the speed of the motor increases beyond its rated value.
- Thus by this method, the speed control above rated value is possible.
- This is shown in the Fig. Q.51.4, by speed against field current curve. The curve shows the inverse relation between N and ϕ as its nature is rectangular hyperbola.

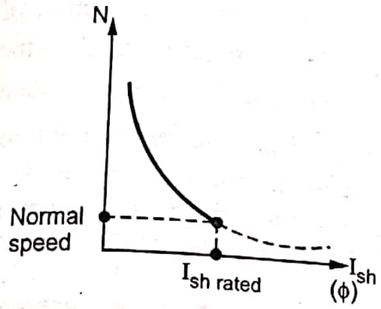


Fig. Q.51.4 N Vs I_{sh} (ϕ) for shunt motor

Q.52 Explain the speed control methods of d.c. series motors.

Ans.: The speed control methods of d.c. series motor are called,

i) Rheostatic control ii) Flux control

i) Rheostatic control :

- The arrangement is shown in the Fig. Q.52.1.

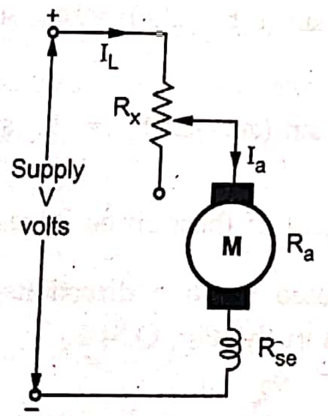


Fig. Q.52.1 Rheostatic control of series motor

- In this method, a variable resistance (R_x) is inserted in series with the motor circuit. As this resistance is inserted, the voltage drop across this resistance ($I_a R_x$) occurs. This reduces the voltage across the armature.
- As speed is directly proportional to the voltage across the armature, the speed reduces. By varying the resistance the various speeds can be obtained.

ii) Flux control :

- In this method the various techniques are used to control the flux. These techniques are,

a) Field Divertor Method :

- In this method the series field winding is shunted by a variable resistance (R_x) known as **field divertor**. The arrangement is shown in the Fig. Q.52.2.

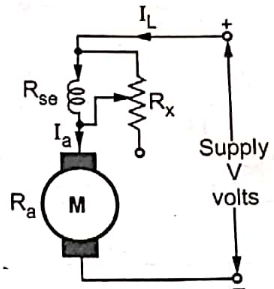


Fig. Q.52.2 Field divertor method

- Due to the parallel path of R_x, by adjusting the value of R_x, any amount of current can be diverted through the divertor. Hence current through the field winding can be adjusted as per the requirement. Due to this, the flux gets controlled and hence the speed of the motor gets controlled.

b) Armature Divertor Method :

- An armature of the motor is shunted with an external variable resistance (R_x) as shown in the Fig. Q.52.3. This resistance R_x is called **armature divertor.**

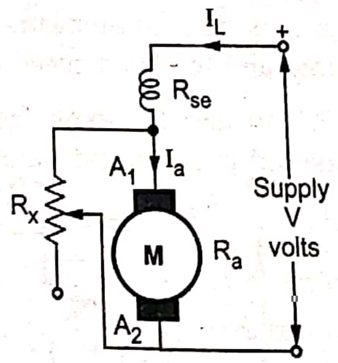


Fig. Q.52.3 Armature divertor

- Any amount of armature current can be diverted through the divertor. Due to this, armature current reduces.

- But as $T \propto \phi I_a$ and load torque is constant, the flux is to be increased. So motor reacts by drawing more current from the supply. So current through field winding increases, so flux increases and speed of the motor reduces.

c) Tapped Field Method :

- In this method, flux change is achieved by changing the number of turns of the field winding.
- The field winding is provided with the taps as shown in the Fig. Q.52.4.

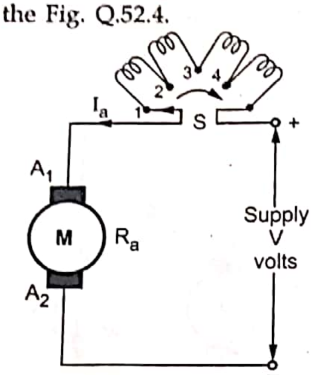


Fig. Q.52.4 Tapped field

- The selector switch 'S' is provided to select the number of turns (taps) as per the requirement.
- When the switch 'S' is in position 1 the entire field winding is in the circuit and motor runs with normal speed. As switch is moved from position 1 to 2 and onwards, the number of turns of the field winding in the circuit decreases. Due to this m.m.f. required to produce the flux, decreases. Due to this flux produced decreases, increasing the speed of the motor above rated value.

d) Series-Parallel Connection of Field :

- In this method, the field coil is divided into various parts. These parts can then be connected in series or parallel as per the requirement to change the m.m.f. produced and to obtain speed control.
- The Fig. Q.52.5 (a) and (b) show the two parts of field coil connected in series and parallel.

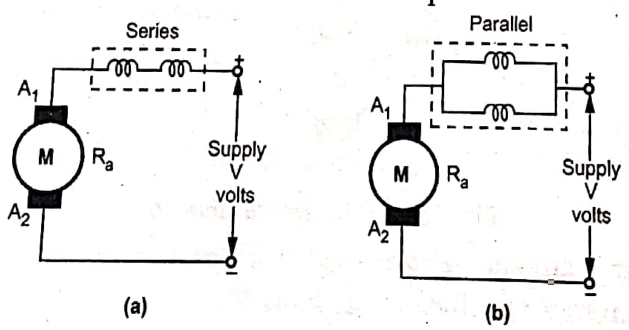


Fig. Q.52.5 Series-Parallel grouping of field coils

Part C : Three Phase Induction Motor

4.28 : Concept of Rotating Magnetic Field

Q.53 What is necessity of rotating magnetic field in the induction motor ?
[JNTU : Part A, May-19, Marks 2]

Ans. : In induction motor, rotor is stationary at start. To have induced e.m.f. in the rotor by induction principle, rotor must cut the magnetic flux. But as rotor is stationary, the magnetic flux must be rotating so as to have cutting of flux. This causes induced e.m.f. in rotor. Hence there is rotor current, rotor flux and the moter starts due to interaction of stator flux and rotor flux. Thus for starting of induction motor, there is necessity of rotating magnetic field.

Q.54 Prove that the resultant field in case of 3 phase induction motor is given by $\phi_T = 1.5\,\phi_{max}$ where ϕ_{max} is the maximum flux in any one phase.
[JNTU : Part B, Aug.-06, 08, May-06, Marks 5]

OR Explain the production of rotating magnetic field in a 3 phase induction motor.
[JNTU : Part B, Aug.-06, 08, Dec.-18, Marks 5]

Ans. : • When 3 phase stator winding is excited by 3 phase a.c. supply then three fluxes are produced namely ϕ_R, ϕ_Y and ϕ_B. There is phase difference of 120° in between these three fluxes. The equations of these fluxes are,

$$\phi_R = \phi_m \sin(\omega t) = \phi_m \sin\theta \quad \text{... (1)}$$

$$\phi_Y = \phi_m \sin(\omega t - 120°) = \phi_m \sin(\theta - 120°) \quad \text{... (2)}$$

$$\phi_B = \phi_m \sin(\omega t - 240°) = \phi_m \sin(\theta - 240°) \quad \text{... (3)}$$

- Let the resultant of these three fluxes is ϕ_T.
- Let the assumed positive directions of these fluxes are as shown in the Fig. Q.54.1.

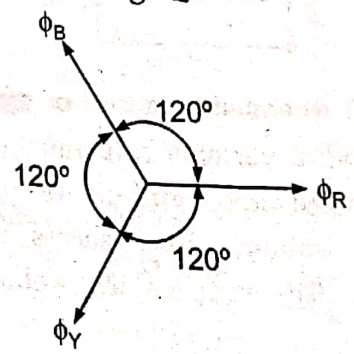


Fig. Q.54.1

Case 1 : $\theta = 0°$

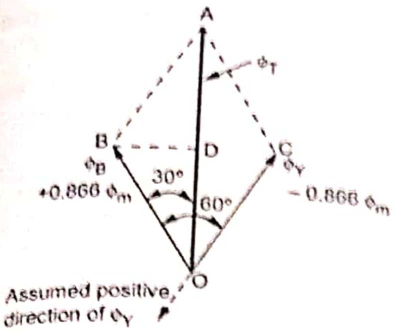


Fig. Q.54.2 Vector diagram for $\theta = 0°$

- Substituting in the equations (1), (2) and (3) we get,

$\phi_R = 0, \; \phi_Y = -0.866\,\phi_m, \quad \phi_B = +0.866\,\phi_m$

- The phasor addition of all these fluxes is shown in the Fig. Q.54.2.
- The positive values are shown in assumed positive directions while negative values are shown in opposite direction to the assumed positive directions of the respective fluxes.
- BD is drawn perpendicular from B on ϕ_T. It bisects ϕ_T.

$$\therefore \quad OD = DA = \frac{\phi_T}{2}$$

- In triangle OBD, $\angle BOD = 30°$

$$\therefore \quad \cos 30° = \frac{OD}{OB} = \frac{\phi_T/2}{0.866\phi_m}$$

$$\therefore \quad \phi_T = 2 \times 0.866\,\phi_m \times \cos 30° = 1.5\,\phi_m$$

- **So magnitude of ϕ_T is 1.5 ϕ_m and its position is vertically upwards at $\theta = 0°$.**

Case 2 : $\theta = 60°$

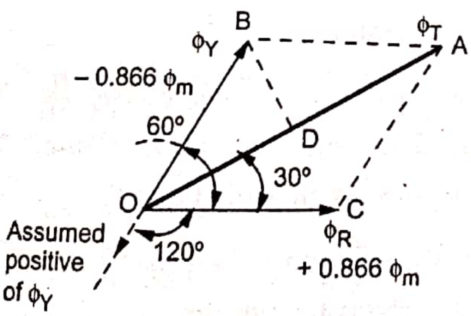


Fig. Q.54.3 Vector diagram for $\theta = 60°$

- Equations (1), (2) and (3) give us,

$\phi_R = +0.866\,\phi_m, \quad \phi_Y = -0.866\,\phi_m, \quad \phi_B = 0$

- So ϕ_R is positive and ϕ_Y is negative and hence drawing in appropriate directions we get phasor diagram as shown in the Fig. Q.54.3.
- Doing the same construction, drawing perpendicular from B on ϕ_T at D we get the same result as,

$$\phi_T = 1.5\,\phi_m$$

- **But it can be seen that though its magnitude is 1.5 ϕ_m it has rotated through 60° in space, in clockwise direction, from its previous position.**
- For various values of θ, it can be seen that the magnitude of the resultant flux ϕ_T remains constant equal to 1.5 ϕ_m and it rotates in space.
- Such a magnetic field having constant magnitude and rotating in space is called **rotating magnetic field.**

Important Points to Remember

- Speed of rotating magnetic field is synchronous speed denoted as N_s and given by,

$$\therefore \quad N_s = \frac{120\,f}{P} = \textbf{Speed of R.M.F.}$$

where f is supply frequency and P is number of stator poles.

- The direction of rotating magnetic field can be reversed by interchanging any two terminals of the three phase windings while connecting to the three phase supply.

Q.55 For a machine having 4 poles, find the speed of rotating magnetic field if it is excited by 50 Hz supply. ☞ [JNTU : Part A, Marks 3]

Ans. : $P = 4, \; f = 50$ Hz

$$N_s = \frac{120\,f}{P} = \frac{120 \times 50}{4} = 1500 \text{ r.p.m.}$$

... speed of rotating magnetic field

Q.56 How to reverse the direction of rotation of 3 phase induction motor ? ☞ [JNTU : Part A, Marks 3]

Ans. : By interchanging any two terminals of three phase winding while connecting it to three phase a.c. supply, direction of rotation of rotating magnetic field gets reversed. Due to this direction of rotation of 3 phase induction motor gets reversed.

4.29 : Construction of Three Phase Induction Motor

Q.57 Explain the construction of three phase induction motor. [JNTU : Part B, May-09, Marks 5]

OR Describe the constructional details of three phase slip ring induction motor. [JNTU : Part B, May-19, Marks 5]

Ans. : • The three phase induction motor consists of two main parts, namely

1. The part carrying three phase windings, which is stationary called **stator.**
2. The part which rotates and is connected to the mechanical load through shaft called **rotor.**

1. Stator : The stator has a laminated type of construction made up of stampings which are 0.4 to 0.5 mm thick.

- The stampings are slotted on its periphery to carry the stator winding. The stampings are insulated from each other. Such a construction essentially keeps the iron losses to a minimum value.
- The number of stampings are stamped together to build the stator core.
- The slots on the periphery of the stator core carries a **three phase winding,** connected either in star or delta. This three phase winding is called **stator winding.** It is wound for definite number of poles.
- The radial ducts are provided for the cooling purpose. The Fig. Q.57.1 shows a stator lamination.

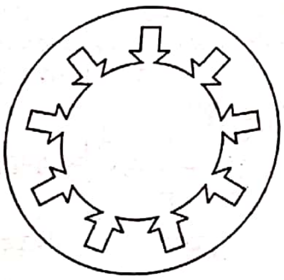


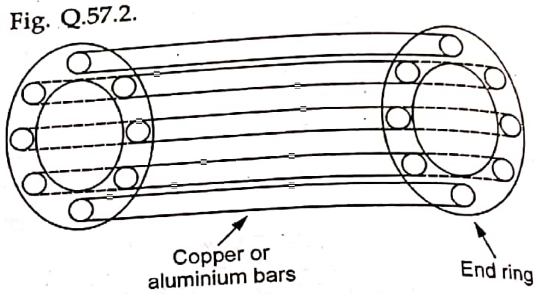
Fig. Q.57.1 Stator lamination

2. Rotor : The rotor is placed inside the stator.

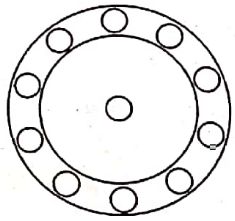
- The air gap between stator and the rotor is 0.4 mm to 4 mm.
- The two types of rotor constructions which are used for induction motors are, a. Squirrel cage rotor and b. Slip ring or phase wound rotor

a) Squirrel cage rotor :

- The rotor core is cylindrical and slotted on its periphery.
- The rotor consists of uninsulated copper or aluminium bars called rotor conductors. The bars are placed in the slots.
- These bars are permanently shorted at each end with the help of conducting copper ring called end ring. The bars are usually brazed to the end rings to provide good mechanical strength.
- The entire structure looks like a cage, forming a closed electrical circuit. So the rotor is called squirrel cage rotor. The construction is shown in the Fig. Q.57.2.



(a) Cage type structure of rotor



(b) Symbolic representation

Fig. Q.57.2 Squirrel cage rotor

b) Slip Ring Rotor or Phase Wound Rotor :

- In this type of construction, rotor winding is exactly similar to the stator.
- The rotor carries a three phase star or delta connected, distributed winding, wound for same number of poles as that of stator.
- The rotor construction is laminated and slotted. The slots contain the rotor winding.
- The three ends of three phase winding, available after connecting the winding in star or delta, are permanently connected to the slip rings.

Scanned with CamScanner

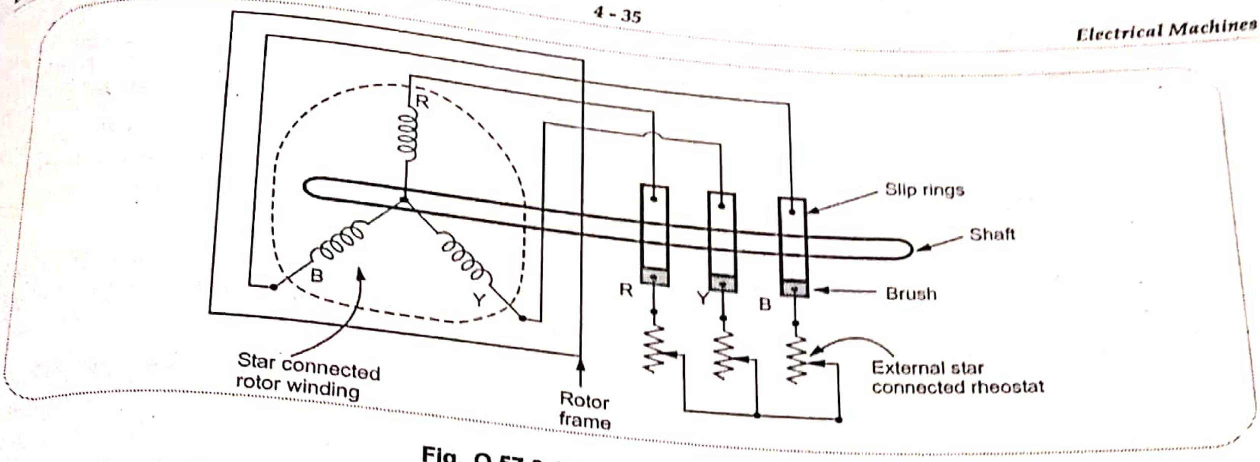


Fig. Q.57.3 Slip rings or wound rotor

- With the help of slip rings, the external resistances can be added in series with each phase of the rotor winding. This arrangement is shown in the Fig. Q.57.3.
- In the running condition, the slip rings are shorted.

Q.58 Compare squirrel cage and wound type rotors.

Ans. :

Sr. No.	Wound or slip ring rotor	Squirrel cage rotor
1.	Rotor consists of a three phase winding similar to the stator winding.	Rotor consists of bars which are shorted at the ends with the help of end rings.
2.	Construction is complicated.	Construction is very simple.
3.	Resistance can be added externally.	As permanently shorted, external resistance cannot be added.
4.	Slip rings and brushes are present to add external resistance.	Slip rings and brushes are absent.
5.	The construction is delicate and due to brushes, frequent maintenance is necessary.	The construction is robust and maintenance free.
6.	The rotors are very costly.	Due to simple construction, the rotors are cheap.
7.	Only 5 % of induction motors in industry use slip ring rotor.	Very common and almost 95 % induction motors use this type of rotor.
8.	High starting torque can be obtained.	Moderate starting torque which cannot be controlled.
9.	Rotor resistance starter can be used.	Rotor resistance starter cannot be used.
10.	Rotor must be wound for the same number of poles as that of stator.	The rotor automatically adjusts itself for the same number of poles as that of stator.
11.	Speed control by rotor resistance is possible.	Speed control by rotor resistance is not possible.
12.	Rotor copper losses are high hence efficiency is less.	Rotor copper losses are less hence have higher efficiency.
13.	Used for lifts, hoists, cranes, elevators, compressors etc.	Used for lathes, drilling machines, fans, blowers, water pumps, grinders, printing machines etc.

Q.59 Write the merits and demerits of slip-ring induction motor. [JNTU : Part A, Dec.-18, Marks 2]

Ans. : Merits of slip ring induction motor,

1. External resistance can be added.
2. Starting torque can be controlled.
3. Rotor resistance starter can be used.
4. Speed control from rotor side is possible.
5. Smooth acceleration on heavy loads.
6. High over loading capacity.

Scanned with CamScanner

Demerits of slip ring induction motor,

1. Initial cost is high.
2. Due to slip rings and brushes, maintenance cost is high.
3. Speed regulation is poor.
4. Efficiency and power factor is low.
5. Sensitive to supply voltage fluctuations.

4.30 : Working Principle of Three Phase Induction Motor

Q.60 Explain the working principle of three phase induction motor.

[JNTU : Part B, May-06,08,09,Dec.-09,10,Aug.-06,Marks 5]

Ans. : • Induction motor works on the principle of electromagnetic induction.

- When a three phase supply is given to the three phase stator winding, a rotating magnetic field of constant magnitude is produced. The speed of this rotating magnetic field is synchronous speed, N_s r.p.m.

$$N_s = \frac{120 f}{P} = \text{Speed of rotating magnetic field.}$$

- This rotating field produces an effect of rotating poles around a rotor.
- At this instant rotor is **stationary** and stator flux R.M.F. is **rotating**. So its obvious that there exists a relative motion between the R.M.F. and rotor conductors.
- Whenever conductor cuts the flux, e.m.f. gets induced in it. So e.m.f. gets induced in the rotor conductors called **rotor induced e.m.f.**
- As rotor forms closed circuit, induced e.m.f. circulates current through rotor called **rotor current.**
- Any current carrying conductor produces its own flux. So rotor produces its flux called **rotor flux.**
- The two fluxes, stator flux and the rotor flux interact with each other such that on one side of rotor conductor, two fluxes are in same direction hence add up to get high flux area while on other side, two fluxes cancel each other to produce low flux area.
- As flux lines act as stretched rubber band, high flux density area exerts a push on rotor conductor towards low flux density area. So rotor conductor experiences a force due to interaction of the two **fluxes.**
- As all the rotor conductors experience a force, the overall rotor experiences a torque and starts rotating.
- According to Lenz's law the direction of induced current in the rotor is so as to oppose the cause producing it.
- The cause of rotor current is the induced e.m.f. which is induced because of relative motion present between the rotating magnetic field and the rotor conductors.
- Hence to oppose the relative motion i.e. to reduce the relative speed, the rotor experiences a torque in the same direction as that of R.M.F. and tries to catch up the speed of rotating magnetic field.

Q.61 Why induction motor can not run at synchronous speed ?

[JNTU : Part B, May-07, Dec.-11, Dec.-10, Marks 5]

Ans. : • The rotor starts rotating in the same direction as that of rotating magnetic field so as to reduce the relative speed between the rotating magnetic field and the rotor. Thus rotor tries to catch the rotating magnetic field.

- But if it catches the speed of the rotating magnetic field, the relative motion between rotor and the rotating magnetic field will vanish ($N_s - N = 0$).
- In fact the relative motion is the main cause for the induced e.m.f. in the rotor. So induced e.m.f. will vanish and hence there cannot be rotor current and the rotor flux which is essential to produce the torque on the rotor.
- Eventually motor will stop. But immediately there will exist a relative motion between rotor and rotating magnetic field and it will start.
- But due to inertia of rotor, this does not happen in practice and rotor continues to rotate with a speed slightly less than the synchronous speed of the rotating magnetic field in the steady state.

Scanned with CamScanner

- Thus the induction motor never rotates at synchronous speed.
- The speed at which it rotates is hence called subsynchronous speed and motor sometimes called asynchronous motor
- i.e. $N < N_s$
- So it can be said that rotor slips behind the rotating magnetic field produced by stator.
- The difference between the two is called slip speed of the motor.

$N_s - N$ = Slip speed of the motor in r.p.m.

Q.62 Define slip of induction motor. [JNTU : Part A, Marks 2]

Ans. : • The difference between the speed of rotating magnetic field and the actual rotor speed is called slip speed i.e. $N_s - N$ = Slip speed of the motor.

$$\boxed{\text{Slip speed} = N_s - N}$$

- Slip of the induction motor is defined as the difference between the synchronous speed (N_s) and actual speed of rotor i.e. motor (N) expressed as a fraction of the synchronous speed (N_s). This is also called **absolute slip or fractional slip** and is denoted as 's'.

Thus,
$$\boxed{\text{Slip, } s = \frac{N_s - N}{N_s} \quad \text{and} \quad \% s = \frac{N_s - N}{N_s} \times 100}$$

Important Points to Remember

- In terms of slip, the actual speed of motor (N) can be expressed as,

$$N = N_s (1 - s) \quad \text{... (From the expression of slip)}$$

- At start, motor is at rest and hence its speed N is zero.

$$s = 1 \text{ at start}$$

- This is maximum value of slip s possible for induction motor which occurs at start.
- The slip of induction motor cannot be zero under any circumstances.
- Practically motor operates in the slip range of 0.01 to 0.05 i.e. 1 % to 5 %. The slip corresponding to full load speed of the motor is called **full load slip.**

Q.63 A 3 phase, 4 pole, 50 Hz, induction motor runs at 1460 r.p.m. Determine its percentage slip. [JNTU : Part A, May-11, March - 06, Marks 3]

Ans. : P = 4, N = 1460 r.p.m., f = 50 Hz

$$N_s = \frac{120 f}{P} = \frac{120 \times 50}{4} = 1500 \text{ r.p.m.}$$

$$s = \frac{N_s - N}{N_s} \times 100 = \frac{1500 - 1460}{1500} \times 100$$

$$= 2.667 \%$$

4.31 : Torque Equation of Three Phase Induction Motor

Q.64 State the torque equation of three phase induction motor stating meaning of each term in it. On which factors the torque depends ? Hence write the expression for the starting torque. [JNTU : Part B, May-05, Aug.-08, Marks 5]

Ans. : • The torque of a three phase induction motor is given by,

$$\boxed{T = \frac{k s E_2^2 R_2}{R_2^2 + (s X_2)^2} \text{ N.m where } k = \frac{3}{2\pi n_s}}$$

n_s = Synchronous speed in r.p.s.,

s = Slip, R_2 = Standstill resistance,

X_2 = Standstill reactance

and E_2 = Standstill rotor induced e.m.f.

- The torque produced in the induction motor depends on the following factors :

1. The part of rotating magnetic field which reacts with rotor and is responsible to produce induced e.m.f. in rotor.
2. The magnitude of rotor current in running condition.
3. The power factor of the rotor circuit in running condition.

The expression for the starting torque T_{st} is,

$$\boxed{T_{st} = \frac{3}{2\pi n_s} \cdot \frac{E_2^2 R_2}{(R_2^2 + X_2^2)} \quad \text{...s = 1 at start}}$$

Scanned with CamScanner

Q.65 Derive the condition for maximum torque under running condition of 3-phase induction motor.
[JNTU : Part B, Dec.-18, Marks 5]

Ans. : The only parameter which controls the torque is slip s.

- Mathematically for the maximum torque we can write, $\frac{dT}{ds} = 0$ where $T = \frac{k s E_2^2 R_2}{R_2^2 + (sX_2)^2}$.
- While carrying out differentiation remember that E_2, R_2, X_2 and k are constants. The only variable is slip s.
- As load on motor changes, its speed changes and hence slip changes. This slip decides the torque produced corresponding to the load demand.

$$T = \frac{k s E_2^2 R_2}{R_2^2 + s^2 X_2^2} \quad \text{... Writing } (sX_2^2) = s^2 X_2^2$$

- As both numerator and denominator contains s terms, differentiate T with respect to s using the rule of differentiation for u/v.

$$\therefore \quad \frac{dT}{ds} = \frac{(k s E_2^2 R_2)\frac{d}{ds}(R_2^2 + s^2 X_2^2) - (R_2^2 + s^2 X_2^2)\frac{d}{ds}(k s E_2^2 R_2)}{(R_2^2 + s^2 X_2^2)^2} = 0$$

$$\therefore \quad k s E_2^2 R_2 [2sX_2^2] - (R_2^2 + s^2 X_2^2)(k E_2^2 R_2) = 0$$

$$\therefore \quad k s^2 X_2^2 E_2^2 R_2 - R_2^2 k E_2^2 R_2 = 0$$

$$\therefore \quad s^2 X_2^2 - R_2^2 = 0 \quad (\text{Taking } k E_2^2 R_2 \text{ common}) \quad \text{i.e.} \quad s^2 = \frac{R_2^2}{X_2^2}$$

$$\therefore \quad \boxed{s_m = \frac{R_2}{X_2} = \text{slip condition at maximum torque}}$$

- This is the slip at which the torque is maximum and is denoted as s_m. It is the ratio of standstill per phase values of resistance and reactance of rotor, when the torque produced by the induction motor is at its maximum.

4.32 : Torque-Slip Characteristics of Three Phase Induction Motor

Q.66 Draw the torque-slip characteristics of a three phase induction motor and explain its various regions.
[JNTU : Part B, May-05, 11, Aug.-06, Dec.-18, Marks 5]

Ans. : • The graph obtained by plotting the torque developed against the slip values from s = 1 (at start) to s = 0 (at synchronous speed) is called **torque-slip characteristics** of the induction motor.

- For a constant supply voltage, E_2 is also constant. So we can write torque equation as,

$$\therefore \quad \boxed{T \propto \frac{s R_2}{R_2^2 + (sX_2)^2}}$$

i) Low slip region : In low slip region, 's' is very very small. Due to this, the term $(s X_2)^2$ is so small as compared to R_2^2 that it can be neglected.

- Hence $T \propto \frac{s R_2}{R_2^2} \propto s$ as R_2 is constant.

- Hence in **low slip region torque is directly proportional to slip**. Hence the graph is straight line in nature. The torque increases linearly in this low slip region hence this is called **stable region** of operation.

ii) **High slip region :** In this region, slip is high i.e. slip value is approaching to 1. Here it can be assumed that the term R_2^2 is very very small as compared to $(s\,X_2)^2$.

- Hence neglecting R_2^2 from the denominator, we get $T \propto \dfrac{s\,R_2}{(sX_2)^2} \propto \dfrac{1}{s}$.
- So in high slip region torque is inversely proportional to the slip. Hence its nature is like rectangular hyperbola.
- When load increases, load demand increases but speed decreases. As speed decreases, slip increases. In high slip region as $T \propto 1/s$, torque decreases as slip increases. But torque must increase to satisfy the load demand. As torque decreases, due to extra loading effect, speed further decreases and slip further increases. Again torque decreases as $T \propto 1/s$ hence same load acts as an extra load due to reduction in torque produced. Hence speed further drops. Eventually motor comes to standstill condition.
- Thus the **motor cannot continue to rotate at any point in this high slip region.** Hence this region is called **unstable region** of operation.
- Every motor has its own limit to produce a torque. The maximum torque, the motor can produce as load increases is T_m which occurs at $s = s_m$. So linear behaviour continues till $s = s_m$.
- If load is increased beyond this limit, motor slip acts dominantly pushing motor into high slip region. Due to unstable conditions, motor comes to standstill condition at such a load. Hence T_m i.e. maximum torque which motor can produce is also called **breakdown torque** or **pull out torque.**
- So range $s = 0$ to $s = s_m$ is called low slip region, known as stable region of operation. Motor always operates at a point in this region.
- At $s = 1$, $N = 0$ i.e. at start, motor produces a torque called **starting torque** denoted as T_{st}.

The entire torque-slip characteristics is shown in the Fig. Q.66.1.

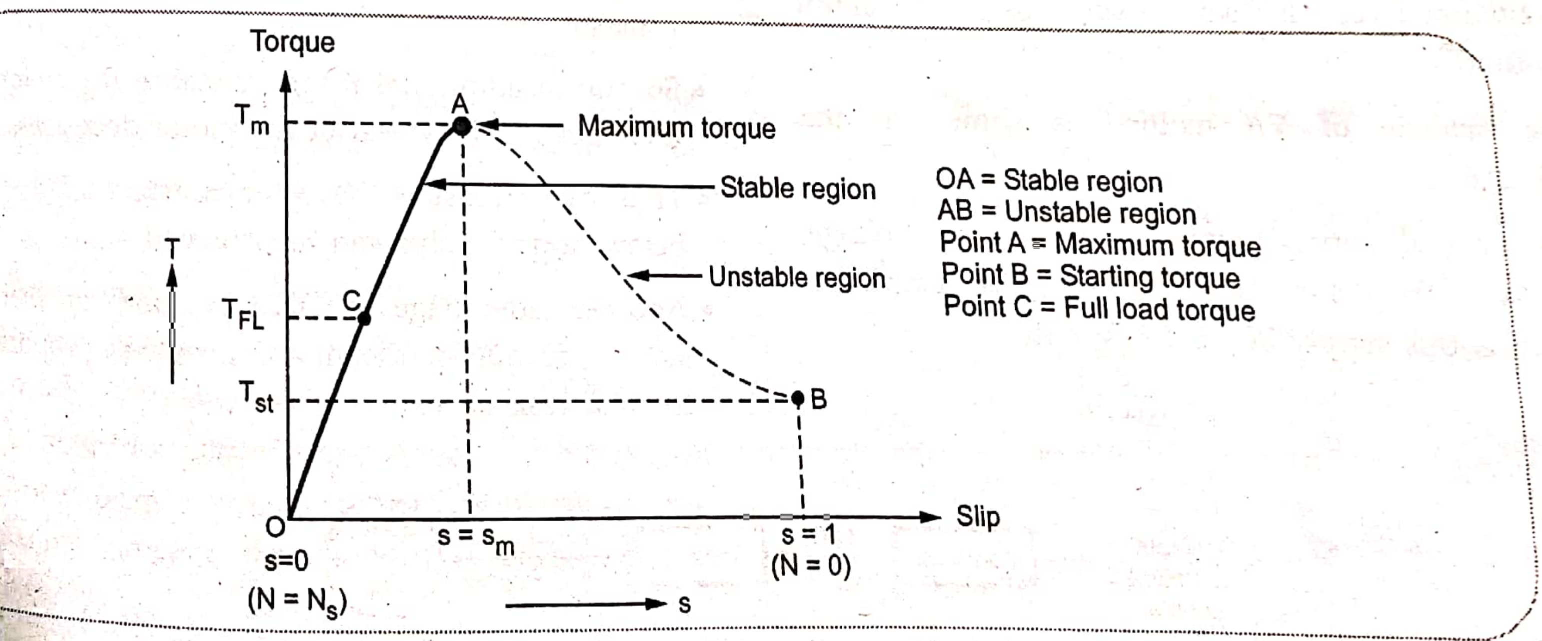


Fig. Q.66.1 Torque-slip characteristics

Scanned with CamScanner

4.33 : Speed Control of Three Phase Induction Motor

Important Points to Remember

- The speed control of three phase induction motor is not easy. The speed of three phase induction motor can be changed by changing its synchronous speed. To change the synchronous speed, it is necessary to change the supply frequency or to change the number of poles for which stator winding is wound. This is difficult in practice.

Q.67 Explain the V/f control method for controlling speed of three phase induction motor. [JNTU : Part B, Marks 5]

Ans. : • When supply frequency changes, the synchronous speed changes hence the speed of the induction motor changes.

- But it is necessary to keep V/f ratio constant while changing the frequency by controlling the voltage also.
- If the supply frequency f is changed, the value of air gap flux also gets affected. This may result into saturation of stator and rotor cores.
- Such a saturation leads to the sharp increase in the (magnetization) no load current of the motor. Hence it is necessary to maintain air gap flux constant when supply frequency f is changed.
- Hence to keep air gap flux constant, the V/f ratio is maintained constant while using this speed control method.
- The scheme of V/f method is shown in the Fig. Q.67.1.
- The normal supply available is constant voltage constant frequency a.c. supply. The **converter** converts this supply into a d.c. supply.
- This d.c. supply is then given to the inverter. The **inverter** is a device which converts d.c. supply, to variable voltage variable frequency a.c. supply which is required to keep V/f ratio constant.
- By selecting the proper frequency and maintaining V/f constant, smooth speed control of the induction motor is possible.
- The main disadvantage of this method is that the supply obtained cannot be used to supply other devices which require constant voltage. Hence an individual scheme for a separate motor is required which makes it costly.

Q.68 Explain the speed control of 3-ϕ induction motor using rotor resistance control. [JNTU : Part B, Dec.-18, Marks 5]

Ans. :

- We know, $T \propto \dfrac{s E_2^2 R_2}{R_2^2 + (s X_2)^2}$
- For low slip region $(sX_2)^2 << R_2$ and can be neglected and for constant supply voltage E_2 is also constant.

$$\therefore \qquad T \propto \frac{s R_2}{(R_2)^2} \propto \frac{s}{R_2}$$

- Thus if the rotor resistance is increased, the torque produced decreases.
- But when the load on the motor is same, motor has to supply same torque as load demands. So motor reacts by increasing its slip to compensate decrease in T due to R_2 and maintains the load torque constant.
- So due to additional rotor resistance R_2, motor slip increases i.e. the speed of the motor decreases.
- Thus by increasing the rotor resistance R_2, speed below normal value can be achieved.
- Another advantage of this method is that the starting torque of the motor increases proportion to rotor resistance.

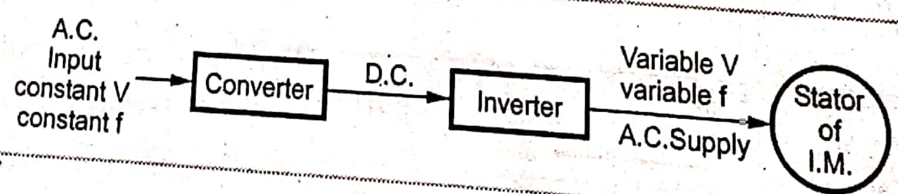


Fig. Q.67.1 Electronic scheme for V/f control

Scanned with CamScanner

4.34 : Applications of Three Phase Induction Motor

Q.69 State the applications of three phase induction motor. ☞[JNTU : Part A, May-08, Marks 3]

Ans. : i) Squirrel cage type of motors having moderate starting torque and constant speed characteristics preferred for driving fans, blowers, water pumps, grinders, lathe machines, printing machines, drilling machine.

ii) Slip ring induction motors can have high starting torque as high as maximum torque. Hence they are preferred for lifts, hoists, elevators, cranes, compressors.

Part D Three Phase Synchronous Generators

Important Points To Remember

- The machines generating a.c. e.m.f. are called alternators. The alternators work at a specific constant speed called synchronous speed to produce a.c. e.m.f. at rated frequency and are called synchronous generators.
- In d.c. generators, the armature is rotating while in synchronous generators field is rotating and armature is stationary.

4.35 : Advantages of Rotating Field Stationary Armature

Q.70 What are the advantages of armature winding placing in its stator ? ☞[JNTU : Part A, May-19, Marks 3]

Ans. : The advantages of stationary armature are,

1) For stationary armature large space can be provided to accommodate large number of conductors and the insulation.

2) It is always better to protect high voltage winding from the centrifugal forces caused due to the rotation. So high voltage armature is generally kept stationary.

3) It is easier to collect larger currents at very high voltages from a stationary member than from the rotating member through slip ring and brush assembly.

4) The problem of sparking at the slip rings can be avoided by keeping field rotating which is low voltage circuit and high voltage armature as stationary.

5) Due to low voltage level on the field side, the insulation required is less and hence field system has very low inertia. It is always better to rotate low inertia system than high inertia, as efforts required to rotate low inertia system are always less.

6) Rotating field makes the overall construction very simple.

7) The ventilation arrangement for high voltage side can be improved if it is kept stationary.

4.36 : Construction of Three Phase Synchronous Generator

Q.71 Explain the construction of synchronous generator. ☞[JNTU : Part B, May-19, Marks 5]

Ans. : • In synchronus generators i.e. alternators the stationary winding is called 'Stator' while the rotating winding is called 'Rotor'.

1. **Stator :** The stator is a stationary armature. This consists of a core and the slots to hold the armature winding.

- The stator core uses a laminated construction. It is built up of special steel stampings insulated from each other with varnish or paper. The laminated construction is basically to keep down eddy current losses.
- The entire core is fabricated in a frame made of steel plates. The core has slots on its periphery for housing the armature conductors.
- Ventilation is maintained with the help of holes casted in the frame.
- The section of an alternator stator is shown in the Fig. Q.71.1.

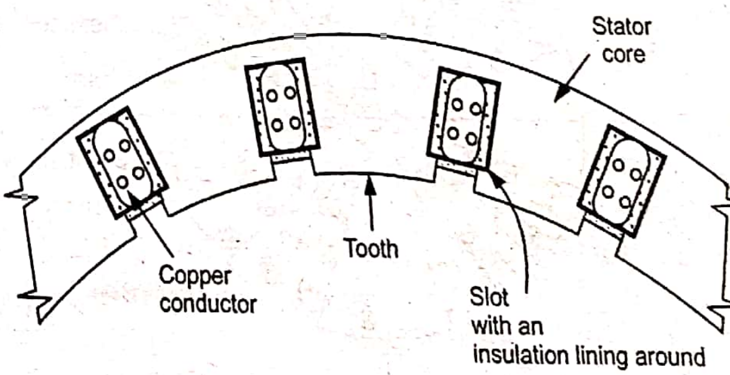


Fig. Q.71.1 Section of an alternator stator

Scanned with CamScanner

2. **Rotor :** There are two types of rotors used in alternators,

i) Salient pole or projected pole type :

This is also called **projected pole type as all the poles are projected out from the surface of the rotor.**

- The poles are built up of thick steel laminations. The poles are bolted to the rotor as shown in the Fig. Q.71.2.

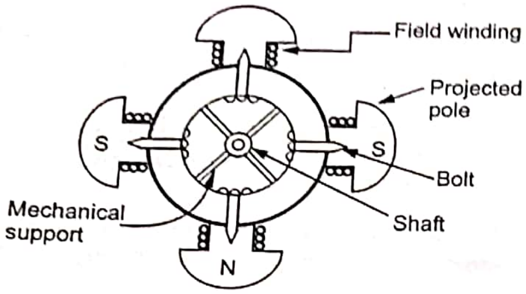


Fig. Q.71.2 Salient pole type rotor

- The pole face has been given a specific shape as discussed earlier in case of d.c. generators. The field winding is provided on the pole shoe.
- These rotors have large diameters and small axial lengths.
- As mechanical strength of salient pole type is less, this is preferred for low speed alternators ranging from 125 r.p.m. to 500 r.p.m..
- The prime movers used to drive such rotor are generally water turbines and I.C. engines.

ii) Smooth cylindrical or non salient type :

- *This is also called* ***non salient type*** *or* ***non-projected pole type of rotor.***
- *The Fig. Q.71.3 shows smooth cylindrical type of rotor.*

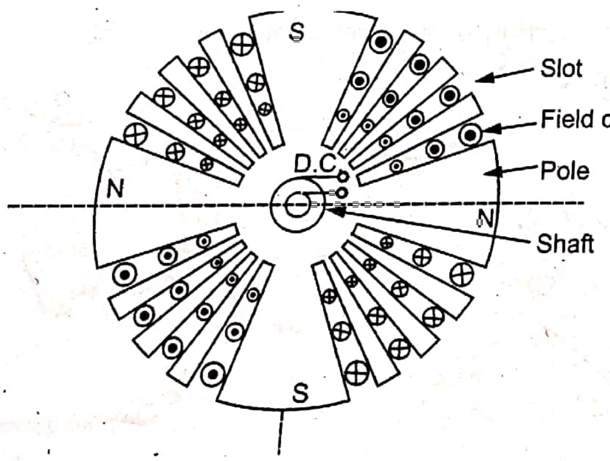


Fig. Q.71.3 Smooth cylindrical rotor

- The rotor consists of smooth solid steel cylinder, having number of slots to accommodate the field coil. The slots are covered at the top with the help of steel or manganese wedges.
- The unslotted portions of the cylinder itself act as the poles. The poles are not projecting out and the surface of the rotor is smooth which maintains uniform air gap between stator and the rotor.
- These rotors have small diameters and large axial lengths. This is to keep peripheral speed within limits.
- The main advantage of this type is that these are mechanically very strong and thus preferred for high speed alternators ranging between 1500 to 3000 r.p.m.. Such high speed alternators are called **'turboalternators'**.
- The prime movers used to drive such type of rotors are generally steam turbines, electric motors.

4.37 : Working Principle of Three Phase Synchronous Generators

Q.72 Explain the working principle of synchronous generator.

Ans. : • The alternators i.e. synchronous generator work on the principle of **electromagnetic induction.** When there is a relative motion between the conductors and the flux, e.m.f. gets induced in the conductors.

- Consider a relative motion of a single conductor under the magnetic field produced by two stationary poles. The magnetic axis of the two poles produced by field is vertical, shown dotted in the Fig. Q.72.1.
- Let conductor starts rotating from position 1. At this instant, the entire velocity component is **parallel** to the flux lines. Hence there is no cutting of flux lines by the conductor. Hence induced e.m.f. in the conductor is also zero.
- As the conductor moves from position 1 towards position 2, the part of the velocity component becomes perpendicular to the flux lines and proportional to that, e.m.f. gets induced in the conductor. The magnitude of such an induced e.m.f. increases as the conductor moves from position 1 towards 2.

Scanned with CamScanner

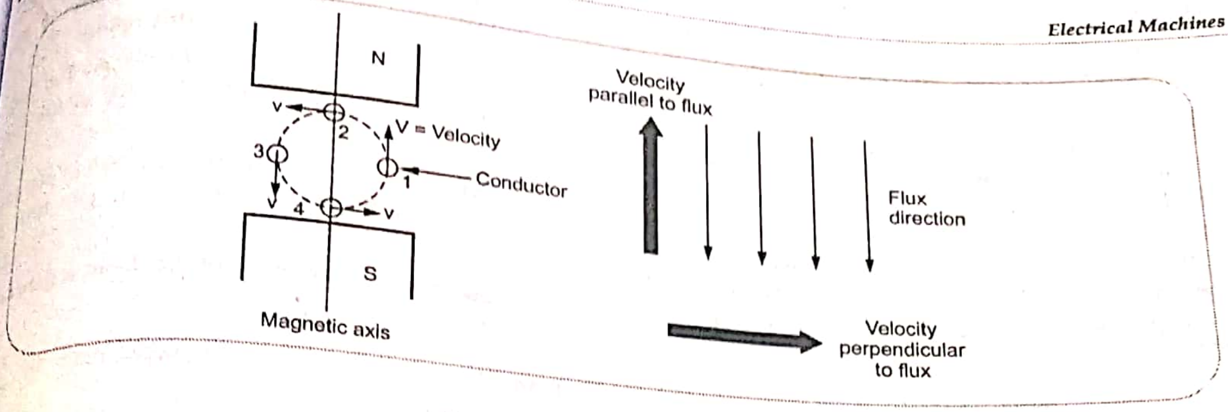


Fig. Q.72.1 Two pole alternator

- At position 2, the entire velocity component is perpendicular to the flux lines. Hence there exists maximum cutting of the flux lines. And at this instant, the induced e.m.f. in the conductor is at its maximum.
- As the position of conductor changes from 2 towards 3, the velocity component perpendicular to the flux starts decreasing and hence induced e.m.f. magnitude also starts decreasing. At position 3, again the entire velocity component is parallel to the flux lines and hence at this instant induced e.m.f. in the conductor is zero.
- As the conductor moves from position 3 towards 4, the velocity component perpendicular to the flux lines again starts increasing. But the direction of velocity component now is opposite to the direction of velocity component existing during the movement of the conductor from position 1 to 2. Hence an induced e.m.f. in the conductor increases but in the opposite direction.
- At position 4, it achieves maxima in the opposite direction, as the entire velocity component becomes perpendicular to the flux lines.
- Again from position 4 to 1, induced e.m.f. decreases and finally at position 1, again becomes zero. This cycle continues as conductor rotates at a certain speed.
- So if we plot the magnitudes of the induced e.m.f. against the time, we get an alternating nature of the induced e.m.f. as shown in the Fig. Q.72.2.

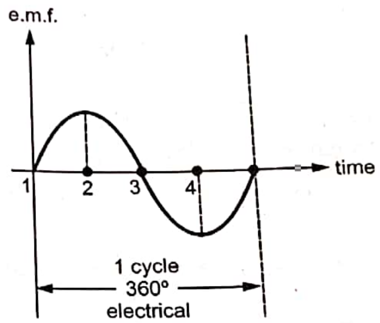


Fig. Q.72.2 Alternating nature of e.m.f.

Q.73 Why a.c. generators are called synchronous ?

Ans. : • For fixed number of poles, alternator has to be rotated at a particular speed to keep the frequency of the generated e.m.f. constant at the required value. Such a speed is called synchronous speed of the alternator denoted as N_s.

So
$$N_s = \frac{120 f}{P}$$
where f = Required rated frequency

- In our nation, the frequency of an alternating e.m.f. is standard equal to 50 Hz.

- Such a machine bearing a fixed relationship between P, N and f is called **synchronous machine** and hence alternators are also called **synchronous generators.**

Scanned with CamScanner

Q.74 What are the two types of synchronous generators ? Where are they used suitably ?

☞[JNTU : Part A, Dec.-12, Marks 2]

Ans. : Two types of synchronous generators are salient pole or projected pole type and smooth cylindrical or nonsalient pole type. Salient pole type are used for low speed alternators with speeds ranging from 125 to 500 r.p.m. The nonsalient pole type are used for high speed alternators called turboalternators with speeds ranging from 1500 to 3000 r.p.m.

Scanned with CamScanner