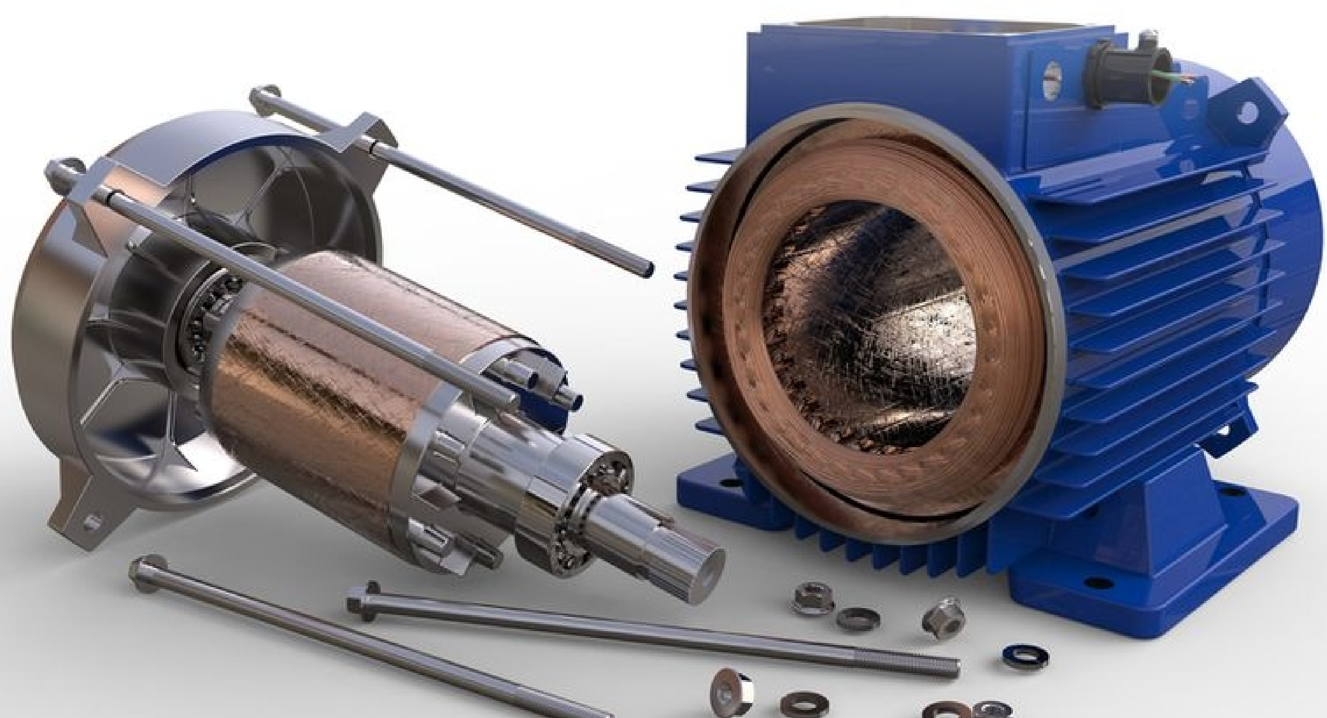
Electrical Machines



Published By:

Physics Wallah

ISBN: 978-93-94342-39-2

Mobile App: Physics Wallah (Available on Play Store)

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ELECTRICAL MACHINES

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1 TRANSFORMERS

1.1. Introduction

1.1.1 Transformer

- Transformer is a static device that transfers electrical energy from one electrical circuit to another circuit through magnetic fields without change in frequency.
- Faraday's Law of electromagnetic induction

$$E = \pm \frac{N d\phi}{dt}$$

- **Lenz's Law :** The polarity of induced e.m.f is such that , if it allows to cause a current then current so produced must oppose the cause.

- **Dot polarity :** In transformer, if current enters through dot then current of same instant must leave through dot in mutual (coupled coil.)

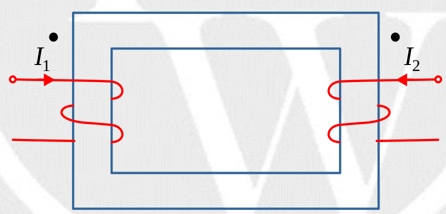


Fig.1.1: Polarity

Note : The dots have same instantaneous polarity.

M.M.F (Magneto-motive force) → Responsible for the motion of flux

$$\text{M.M.F} = NI = HL.$$

Where, L is mean core length.

1.1.2 Ideal Transformer

- No losses, No Leakage flux

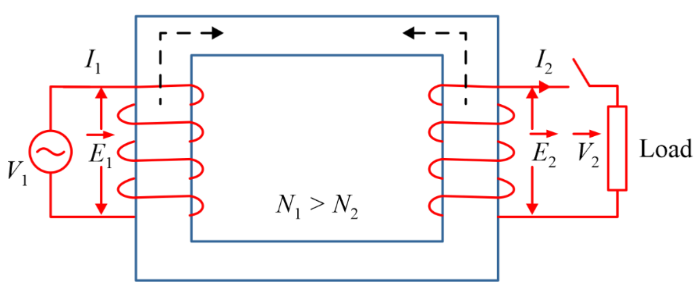


Fig.1.2. Ideal Transformer

E.M.F Equation of transformer

$$E_1 = \sqrt{2}\pi f\, \phi_m\, N_1$$
$$E_2 = \sqrt{2}\pi f\, \phi_m\, N_2$$
$$\frac{v_1}{v_2} = \frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{I_1}{I_2} = a$$

NOTE :

$$E = \sqrt{2}\pi f\, \phi_m . N$$

$\frac{E}{N} \propto \phi_m$ (ie for common flux between two winding e.m.f per turn must be constant)

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = \text{e.m.f turn.}$$

Induced e.m.f are always in phase however terminal voltages may or may not be in same phase.

1.1.3. Practical Transformer

- Windings and core are not loss less
- Magnetizing current is needed to setup flux in the core.
- Leakage flux is present.

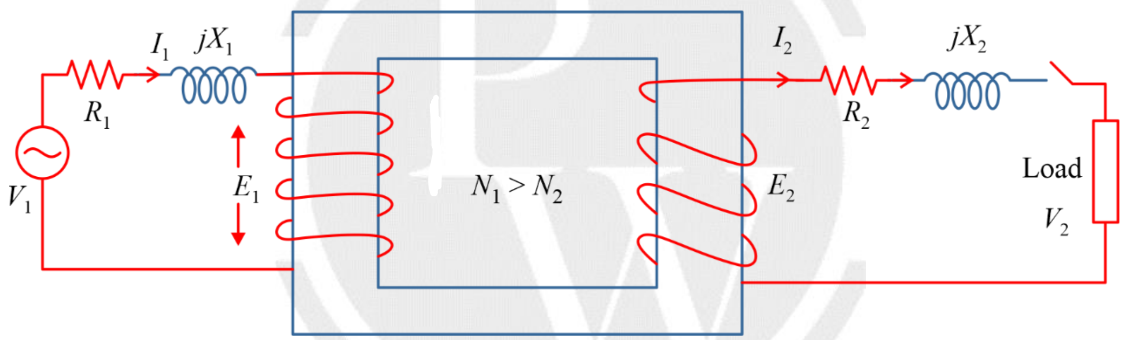


Fig. 1.3. Ideal Transformer

- Under no – load transformer draws small current called no – load current "Io" and is only 2 to 5 % of full load current and 80 – 85° logging.
- Electrical model of transformer referred to source side.

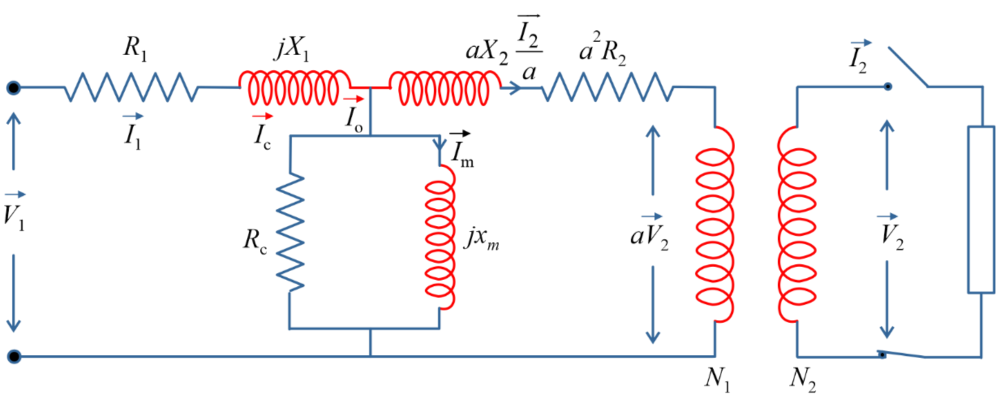


Fig.1.4: Ideal Transformer

- $a = \dfrac{N_1}{N_2}$
- $\vec{I}_1 = \left(\vec{I}_o + \dfrac{\vec{I}_2}{a}\right)$
- $\vec{I}_o = \vec{I}_c + \vec{I}_m$

I_C = core loss component of I_O

I_m = magnetizing component of I_O

1.1.4 Approximate model of Transformer Electrical Model

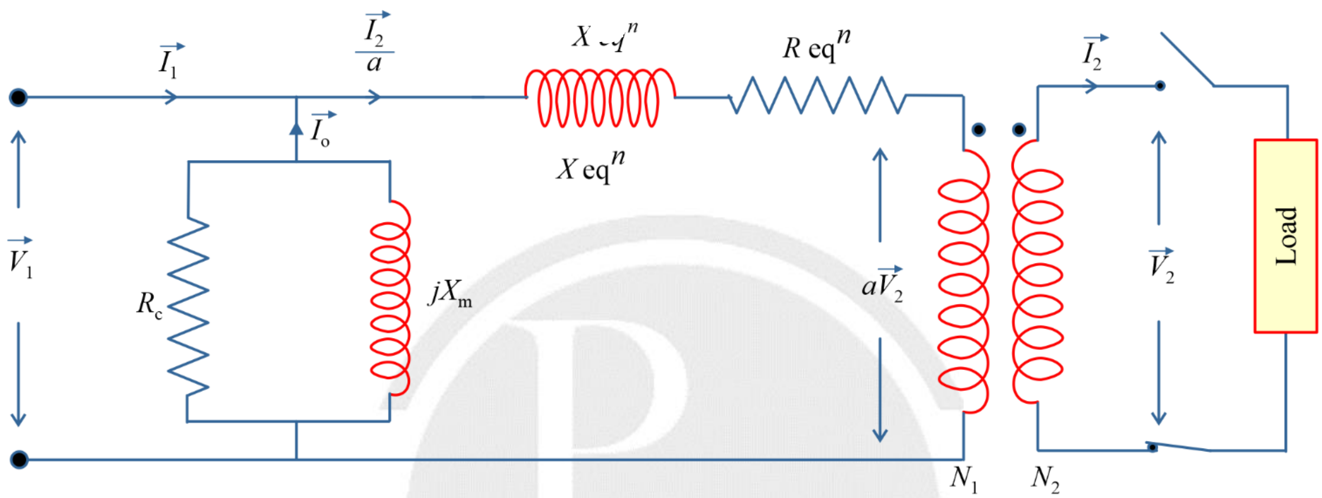


Fig.1.5. Transformer electrical model

$$Req^n = R_1 + a^2R_2$$

$$Xeq^n = X_1 + a^2X_2$$

R_C = Core loss equivalent resistance

X_m = magnetizing reactance

$a = (N_1 / N_2)$

Note : (i) No-Load Branch $R_c \parallel jx_m$ position is always such that rated voltage appeared across the Branch.
(ii) Irrespective of the type of loading, Flux in the core of transformer remains same (maximum flux).

1.1.5 Final Approximate Model

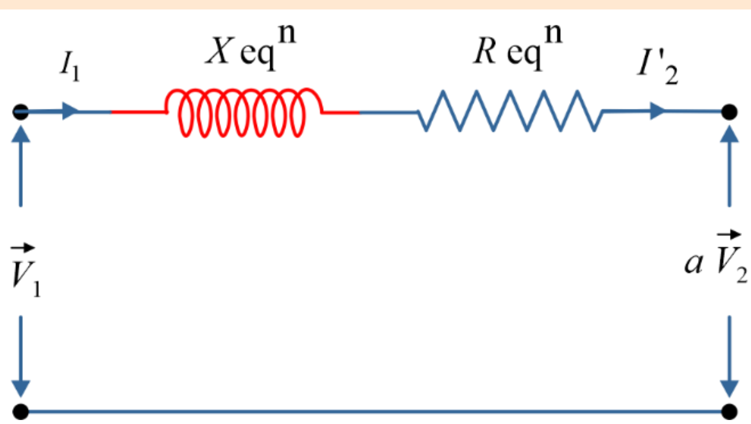


Fig. 1.6

1.1.6 Equivalent Circuit Referred to Primary

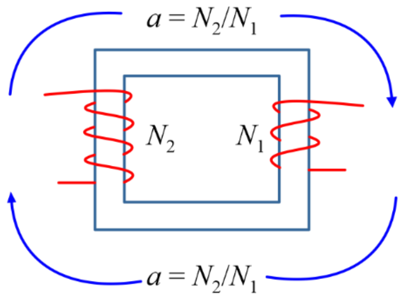
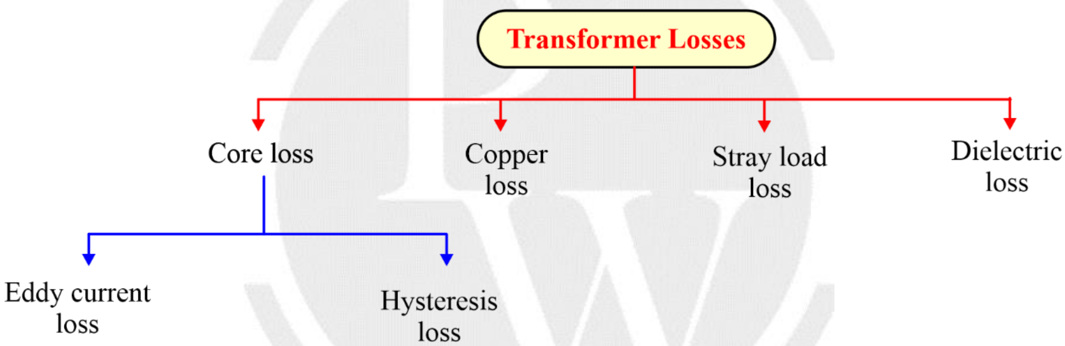


Fig. 1.7

- referred voltage = aV
- referred current = I/a
- referred resistance = a^2R
- referred reactance = a^2X
- referred impedance = a^2Z

Note : $B_m = \frac{\phi_m}{A}$ = maximum flux density

1.2. Transformer Losses



- Hysteresis loss $P_h = k_h f \cdot B_m^x$
- Eddy current loss $P_e = K_e \cdot f^2 \cdot B_m^2$

Total core loss = $P_e + P_h = k \cdot f^2 \cdot B_m^2 + k_h \cdot f \cdot B_m^x$

Note: $\frac{V}{f} \propto \phi_m \propto B_m \left\{V = \sqrt{2}\pi f \cdot \phi.N\right\}$

Case – 1. When V/f = constant ie B_m = constant

$$P_h \propto f \qquad P_e \propto f^2 \propto V^2$$

$$P_T = k_e f^2 \cdot B_m^2 + k_h \cdot f \cdot B_m^x \quad \begin{Bmatrix} A = k_e.B_m^2 \\ B = k_h.B_m^x \end{Bmatrix}$$

$$P_T = A \cdot f^2 + Bf$$

$$\frac{P_T}{f} = Af + B$$

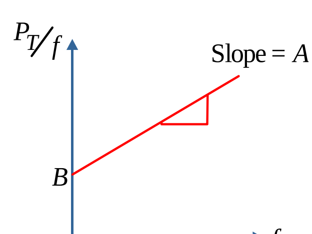


Fig. 1.8

Case-II. When $V/f \neq$ Constant *i.e* $B_m \neq$ constant.

$$P_h = k_h \cdot f \cdot B_m^x$$
$$P_h \propto f \cdot B_m^x$$
$$P_h \propto f \cdot P_h \propto f \cdot \left(\frac{V}{f}\right)^n$$
$$Ph \propto V^n f^{(1-x)}$$

$$P_e = k_e \cdot f^2 \cdot B_m^2$$
$$P_e \propto f^2 [V/f]^2$$
$$P_e \propto V^2$$

x = steinmetz constant value varies between (1.5 to 2.6) (typical 1.6)

- Eddy current and hysteresis loss can be reduced by proper choice of core material and thin Laminations.
- Cu – loss (ohmic loss) :-

$$P_{cu} = I^2 \text{Req}^n$$
$$P_{cu} \propto I^2$$
$$P_{cu} \propto S^2$$

where S = operating K.V.A

- Eddy current loss $\propto t^2, t \rightarrow$ thickness of lamination.

1.3. Open Circuit Test

- Conducted on L.V side, H.V side is open circuited.
- It gives core loss if test is conducted at rated voltage
- Low power factor wattmeter is used.

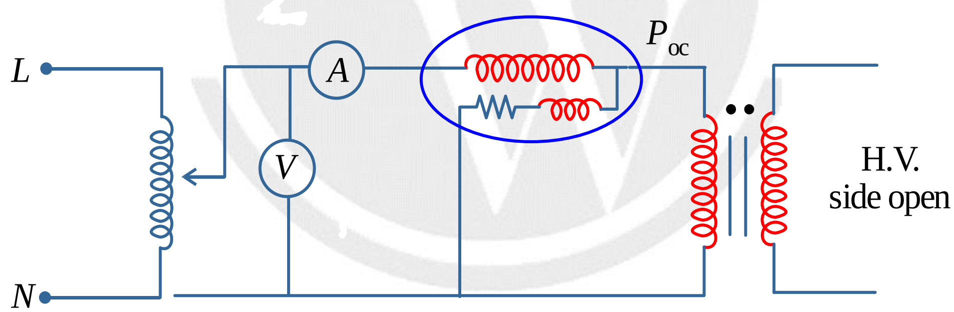


Fig. 1.9

$$R_c = \frac{(V_{oc})^2}{P_{oc}}$$
$$I_c = V_{oc} / R_c$$
$$P_{oc} = V_{oc} I_o \cos\phi_o$$

$$\text{I}_\text{m} = \sqrt{I_0^2 - I_c^2}$$
$$X_m = \frac{V_{oc}}{\text{I}_\text{m}}$$
$$\phi_o = \cos^{-1}\left[\frac{P_{oc}}{V_{oc} I_c}\right]$$

1.4. Short Circuit Test

- Test is conducted on H.V side and the L-V side is shorted by a thick wire.
- S.C test is carried out at rated current with the instruments placed on the H.V side.

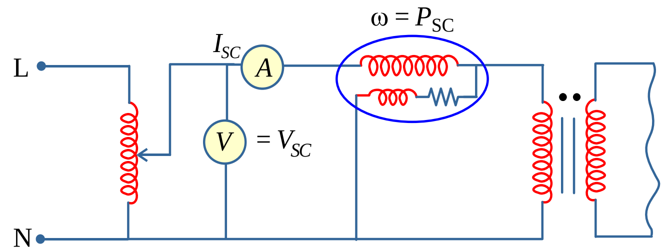


Fig. 1.10

- P_{SC} = full load Cu loss = $I_{Sc}^2 \text{Re}q^n$
- $\text{Re}q^n = \dfrac{P_{sc}}{(I_{sc})^2}$
- $Zeq^n = \dfrac{v_{sc}}{I_{sc}}$
- $Xeq^n = \sqrt{Zeq_n^2 - \text{Re}q_n^2}$

1.5. Polarity Test

The polarity test is essential if transformer are to be operated in parallel or are to be used in poly phase circuit.

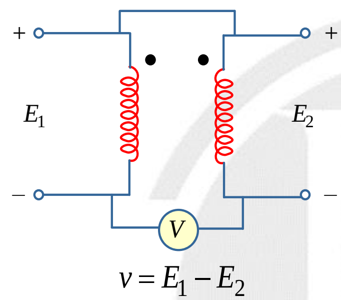


Fig. 1.11. Sub tractive polarity

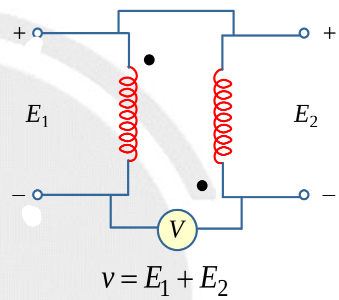


Fig. 1.12. Additive polarity.

1.6. Per Unit System

- Per unit value = $\dfrac{\text{Actual value}}{\text{Base value}}$
- $I_{\text{Base}} = \dfrac{V_{\text{Base}}}{I_{\text{Base}}}$
- $Z_{Base(H.V)} = a^2 Z_{Base(L.V)}$
- $Z_{\text{p.u(new)}} = Z_{\text{p.u(old)}} \times \left[\dfrac{M.V.A_b(\text{new})}{M.V.A_b(\text{old})}\right] \times \left[\dfrac{K \cdot V_b(\text{old})}{K \cdot V_b(\text{new})}\right]^2$ = p.u. voltage drop across resistance

$X_{\text{p.u}}$ = p.u. voltage drop across reactance = $\dfrac{X\,\text{eq}^n}{Z_{\text{Base}}}$

Note : During S.C Test

- $R_{p.u} = \dfrac{P_{cu(f \cdot l)}}{S_{\text{rated}}}$
- $Z_{p.u} = \dfrac{Zeq^n}{Z_{\text{Base}}} = \dfrac{V_{sc} / I_{sc}}{V_{\text{Base}} / I_{\text{Base}}}$
- When $I_{sc} = I_{rated} \Rightarrow Z_{p.u} = V_{\text{sc(p.u)}}$

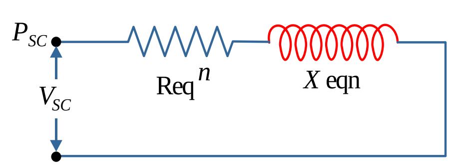


Fig. 1.13

- If $V_{sc} = V_{\text{rated}}$ then I_{sc} = short circuit current at rated voltage.
- $I_{sc} = \frac{I}{Z_{p.u}} \times I_{\text{Base}}$ and $MV.V_{sc} = \frac{I}{Z_{p.u}} \times MVA_{\text{rated}}$

1.7 Voltage Regulation

$$\%V \cdot R = \left[\frac{V_{nL} - V_{fL}}{V_{rated}}\right] \times 100$$

$$V.R = R_{P.u} \cos\phi_2 \pm X_{p.u} \sin\phi_2$$

+ → Lagging P.f load

– → Leading P.f load.

Condition for zero V.R	Condition for Maximum V.R.
$\text{Cos}\,\phi_2 = \left[\frac{Xp.u}{Zp.u}\right]_{\text{Leading}}$	$\text{Cos}\,\phi_2 = \left[\frac{Rp.u}{Zp.u}\right]_{\text{Lagging}}$

$$V \cdot R(\max) = Z_{p.u}$$

1.8. Transformer Efficiency

$$\eta = \left[\frac{x \times S \times \cos\phi_2}{x \times S \times \cos\phi_2 + Pi + x^2 P_{cu}(f.l)}\right]$$

x = Loading factor
S = rated K.V.A.

1.8.1. Condition for maximum efficiency

(1) $\cos\phi_2 = 1$

(2) $x^2 P_{cu(f \cdot L)} = P_i$

Current and K.V.A at which $\eta_{\max}$

- $I_{\eta_{\max}} = \sqrt{\frac{P_i}{R_{eq^n}}} = I_{\text{rated}} \sqrt{\frac{P_i}{P_{cu(f.l)}}}$
- $S_{\eta_{\max}} = S_{f \cdot l} \sqrt{\frac{P_i}{P_{cu(f \cdot l)}}}$

Loading at which $\eta_{\max}$ —

$$x = \frac{I\eta_{\max}}{I_{\text{rated}}} = \frac{S\eta_{\max}}{S_{\text{rated}}} = \sqrt{\frac{P_i}{P_{cu(f \cdot L)}}}$$

Maximum Efficiency

$$\eta_{\max} = \frac{S_{\eta_{\max}} \times \cos\phi_2}{S_{\eta_{\max}} \times \cos\phi_2 + 2P_i}$$

Note:-

- $P_i + x^2 P_{cu(f\cdot l)} = x \times S_{rated} \times \cos\phi_2 \times \left[\frac{1}{\eta} - 1\right]$
- $P_i = \frac{1}{2} \times S_{\eta_{max}} \times \cos\phi_2 \cdot \left[\frac{1}{\eta_{max}} - 1\right]$

All day Efficiency:

$$\eta_{All\,day} = \frac{\text{Energy o/p in kWh in 24 hrs}}{\text{Energy i/P in kWh in 24 hrs.}}$$

1.9. AUTO TRANSFORMER

1.9.1 Auto -Transformer

A transformer in which part of the winding is common to both primary and secondary circuit is called an auto transformer.

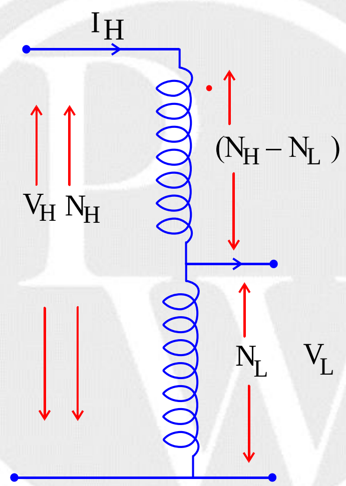


Fig. 1.14

- Since flux is common thus voltage per turn is same

$$\frac{V_H}{N_H} = \frac{V_L}{N_L}$$

$$\text{ie } \frac{V_H}{V_L} = \frac{N_H}{N_L} = a_{auto} = \frac{1}{K_{auto}}$$

- M.M.F Balance [on neglecting magnetizing current

$$(N_H - N_L) I_H = N_L (I_L - I_H)$$

$$N_H I_H = N_L \cdot I_L$$

$$\frac{N_H}{N_L} = \frac{I_L}{I_H}$$

$$\therefore \frac{V_H}{V_L} = \frac{N_H}{N_L} = \frac{I_L}{I_H} = a_{auto} \text{ and } S_{H.V} = S_{L.V}$$

- Saving of Cu material in auto transformer

$$\frac{(Cu\text{ weight})_{auto\,x-mer}}{(Cu\text{ weight})_{2\,winding}} = \left[\frac{a_{auto} - 1}{a_{auto}}\right]$$

Note: Both auto x-mer and 2-winding transformer have same ratings.

1.9.2 Inductive to Conductive Power Transfer

- Inductive power transfer = $\left[1-\frac{1}{a_{auto}}\right]\times S_{auto}$
- Conductive power transfer = $\left[\frac{1}{a_{auto}}\right]\times S_{auto}$.

Note: S_{auto} = K.V.A of auto transformer.

1.9.3 Two Winding Transformer Connected As Auto Transformer

$$S_{\text{auto}}=\left[\frac{a_{\text{auto}}}{a_{\text{auto}}-1}\right]S_{2-\text{winding}}$$

Note: above is useful only for series additive polarity.

- $\frac{\text{p.u. full load losses as auto} - x - \text{mer}}{\text{p.u. full load losses as 2} - \text{winding } x - \text{mer}}=\left[1-\frac{1}{a_{\text{auto}}}\right]$

  $\frac{\text{p.u impedance drop as an auto } x\text{-mer}}{\text{p.u impedence drop as a 2-winding } x\text{-mer}}=\left[1-\frac{1}{\text{a}_{\text{auto}}}\right]$

$$\frac{Z_{p.u(auto)}}{Z_{p.u(2-winding)}}=\frac{a_{auto}-1}{a_{auto}}$$

- $\frac{\text{Voltage regulation as an auto } x\text{-mer}}{\text{Voltage regulation as 2-winding } x\text{-mer}}=\left[\frac{a_{auto}-1}{a_{auto}}\right]$
- p.u short circuit current $I_{sc(p.u)}$

$$\frac{I_{sc(p.u)auto}}{I_{sc(p.u)(2-winding)}}=\left[\frac{a_{auto}}{a_{auto}-1}\right]$$

Note : $a_{auto}=\left[\frac{N_H}{H_L}\right]_{auto}=\left[\frac{V_H}{V_L}\right]_{auto}$.

- Auto transformer has higher efficiency and good voltage regulation.
- Due to decrease in % impedance fault level increases.

1.10. Multi-Winding Transformer

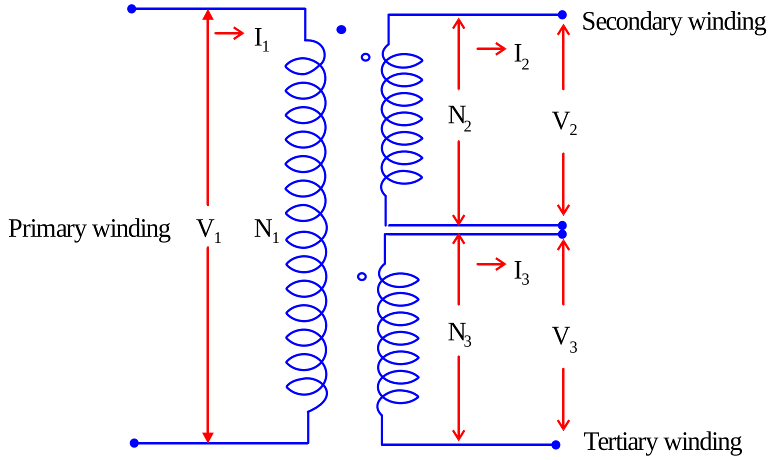


Fig. 1.15

- Voltage per turn is same for common flux so

$$\frac{V_1}{N_1}=\frac{V_2}{N_2}=\frac{V_3}{N_3}$$

- M.M.F. Balance

$$N_1\vec{I_1}=N_2\vec{I_2}+N_3\vec{I_3}$$

$$\vec{I_1}=\frac{N_2}{N_1}\vec{I_2}+\frac{N_3}{N_1}\vec{I_3}$$

- On considering magnitude only.

$$V_1\ I_1=V_2\ I_2+V_3\ I_3$$

$$S_1=S_2+S_3$$

1.11. Transformer as a Magnetically Coupled Circuit

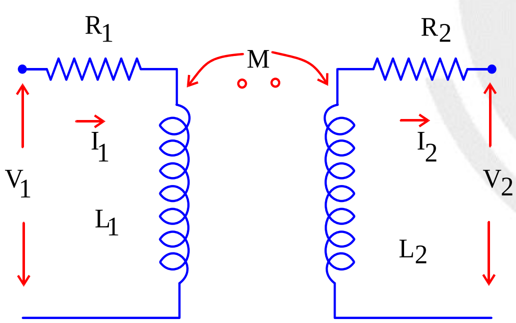
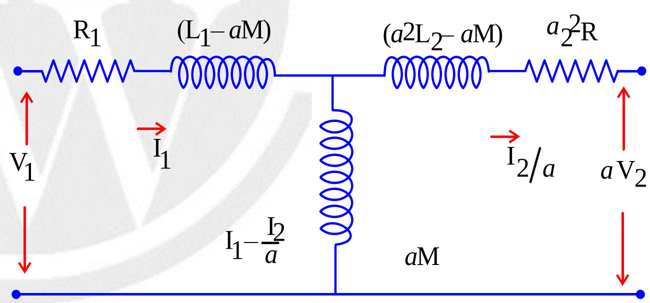


Fig. 1.16



(Conductively coupled circuit)

Fig. 1.17

L_1 = Self-inductance of primary winding

L_2 = Self-inductance of secondary winding

M = Mutual inductance of the primary winding

a = Turn ratio = $\frac{N_{H.V}}{N_{L.V}}=\frac{N_1}{N_2}$

1.11.1 Coefficient of coupling

- In coupled circuit the ratio of mutual flux to total flux produced by the same current acting alone is called coupling factor.
- For primary winding: $k_1=\frac{aM}{L_1}$

- For secondary winding: $k_2 = \dfrac{M}{aL_2}$

- Coefficient of coupling K is defined as the geometrical mean of the coupling factor K_1 & K_2.

$$K = \sqrt{K_1 K_2}$$

$$\boxed{K = \frac{M}{\sqrt{L_1 L_2}}}$$

Note: For zero leakage flux (tight coupling) $K = 1$

- k_1 ie $k_1 = \dfrac{aM}{L_1} = 1 \; ie \; \dfrac{N_1}{N_2} = \dfrac{L_1}{M}$
- $k_2 = 1 \; ie \; k_2 = \dfrac{M}{aL_2} = 1 \; ie \dfrac{N_1}{N_2} = \dfrac{M}{L_2}$
- $\therefore \dfrac{N_1}{N_2} \cong \sqrt{\dfrac{L_1}{L_2}}$

1.12. 3–ϕ Transformer

- In 3–ϕ transformer per phase induced e.m.f. are in same phase but line – line voltage are may or may not be in same phase depending upon the type of connection.
- Types of 3ϕ connection are based on electrical connection [Y or α] and line – line voltage angle difference.

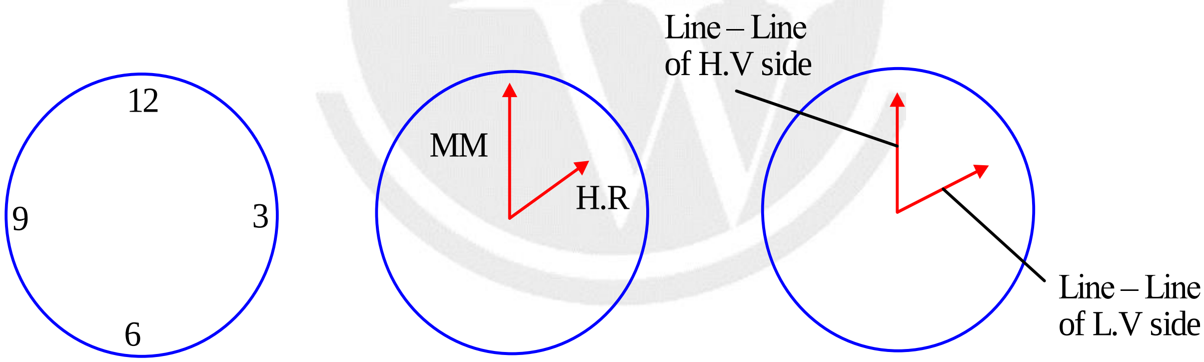


Fig. 1.18

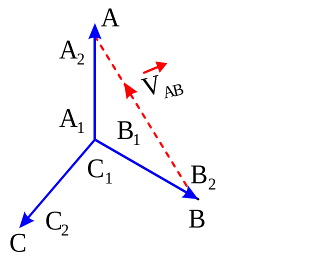
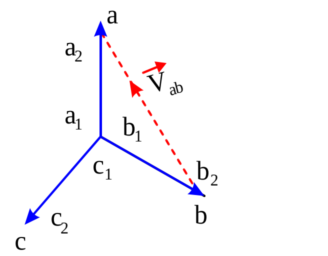
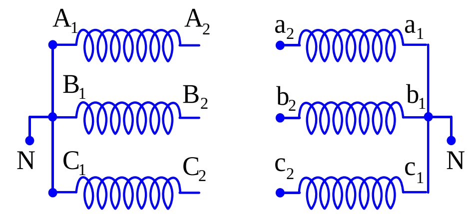
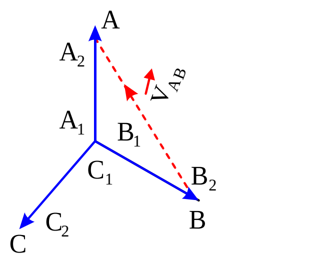
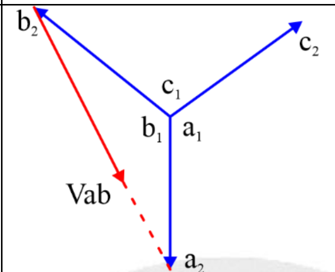
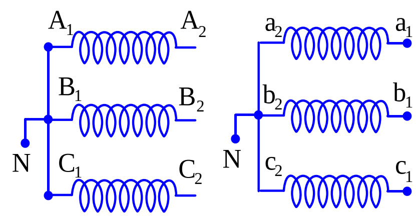
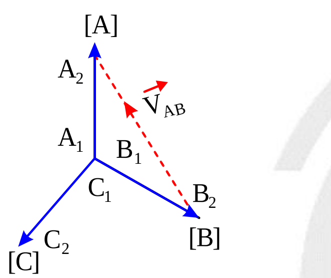
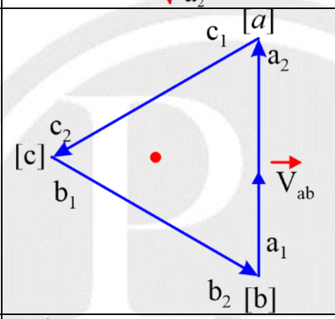
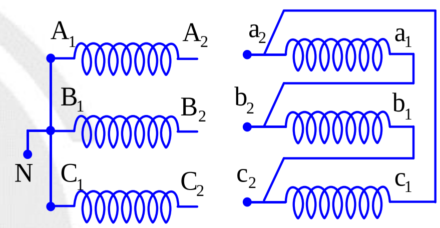
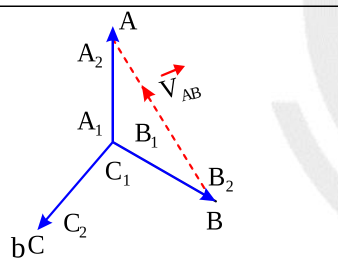
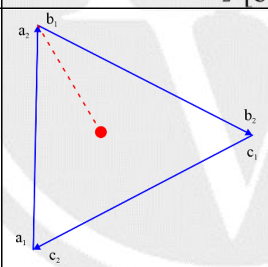
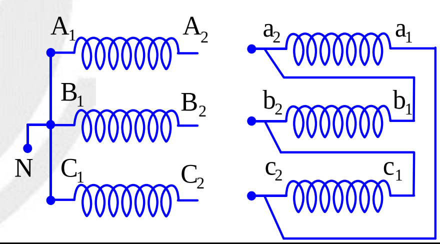
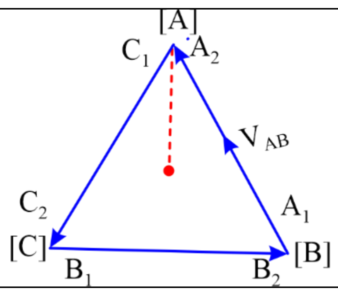
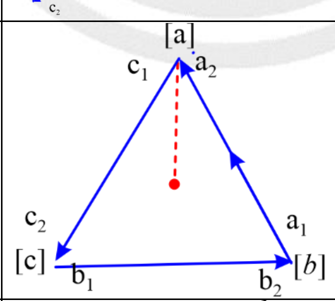
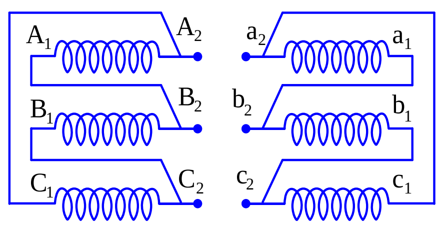
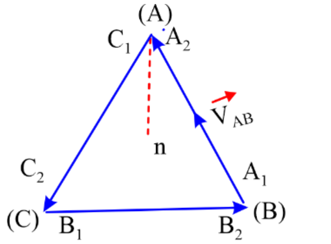
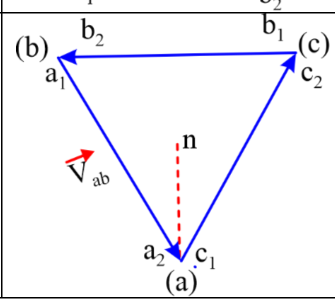
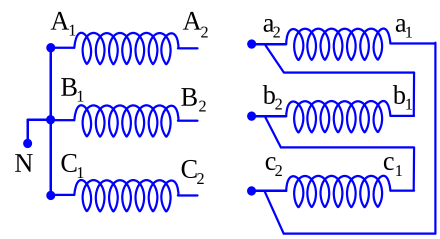
1.12.1 Types of 3-ϕ transformer connection

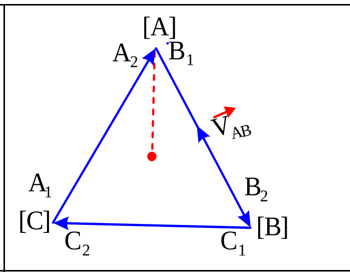
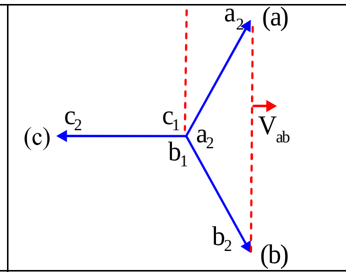
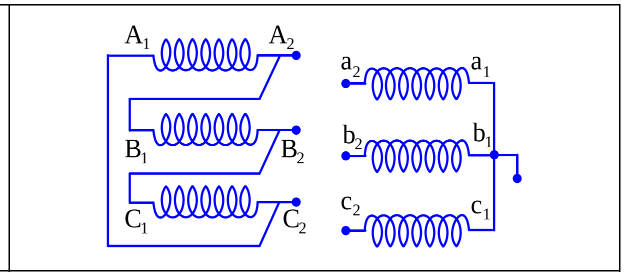
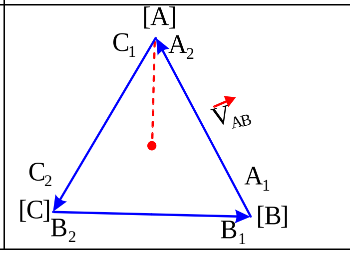
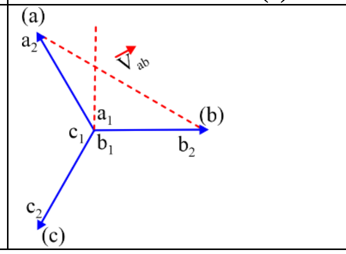
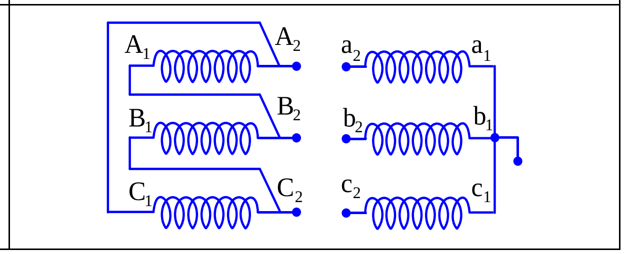
0° → Connection → Yy_0 ; Dd_0

180° → Connection → Yy_6 ; Dd_6

30° Lag connection → Yd_1; Dy_1

30° Lead connection → Yd_{11} ; Dy_{11}

Connection	Primary Side Time Phaser	Secondary Side Time Phaser	Electrical Connection both V_{AB} & V_{ab} are 0° displaced
Yy_0			
Yy_6			
Yd_1			
Yd_{11}			
Dd_0			
Dd_6			

Dy_1			
Dy_{11}			

Note: $a_t = \text{turn ratio} = \dfrac{N_{H.V}}{N_{L.V}} = \dfrac{V_{\text{phase}(H.V)}}{V_{\text{phase}(L.V)}}$

On neglecting magnetizing current, $a = \dfrac{I_{\text{phase}\,(L.V)}}{I_{\text{phase}(H.V)}}$

- For Yy_0 & Yy_6 Connection

  Phase voltage transformation ratio = $a_t:1$

  Line voltage transformation ratio = $a_t:1$

  Phase current transformation ratio = $1:a_t$

  Line current transformation ratio = $1:a_t$

- For Yd_1 & Yd_{11} connection

  Phase voltage transformation ratio = $a_t:1$

  Line voltage transformation ratio = $\dfrac{a_t}{\sqrt{3}}:1$

  Phase current transformation ratio = $1:a_t$

  Line current transformation ratio = $1:\dfrac{a_t}{\sqrt{3}}$

- For Dd_0 & Dd_6 connection

  Phase voltage transformation ratio = $a_t:1$

  Line voltage transformation ratio = $a_t:1$

  Phase current transformation ratio = $1:a_t$

  Line current transformation ratio = $1:a_t$

- Dy_1 & Dy_6 Connection

  Phase voltage transformation ratio = $a_t:1$

  Line voltage transformation ratio = $\dfrac{a_t}{\sqrt{3}}:1$

  Phase current transformation ratio = $1:a_t$

  Line current transformation ratio = $1:\dfrac{a_t}{\sqrt{3}}$

Note: **For Star connection,** $V_{ph} = \dfrac{V_L}{V_3}$ & $I_{Ph} = I_{Line}$ **For delta connection,** $V_{ph} = V_{Line}$ & $I_{phase} = \dfrac{I_{Line}}{V_3}$

- Star is preferred on H.V side & delta is preferred on L.V side except distribution due to mixed loading.

1.13 CORE

- There are two non-linearities in transformer :
  Core: (i) Saturation, (ii) Hysteresis

- The main objective in the transformer is to generate a pure sinusoidal waveform of e.m.f for that flux must be sinusoidal.
- Flux is sinusoidal when magnetizing current is peaky in nature (containing 3^{rd} harmonic current).
- 3^{rd} harmonic current in the transmission line produces communication interference.
- Sinusoidal magnetizing current produces flat topped flux which in turn produces peaky induced e.m.f.
- Peaky induced e.m.f causes oscillating neutral with twice of supply frequency.
- If 3^{rd} harmonic current has path to flow in 3–ϕ transformer connection, then flux & e.m.f are sinusoidal.
- In delta connection system path for 3^{rd} harmonic current is always available but in star connection path for 3^{rd} harmonic is available only when neutral has link through ground or load neutral.
- In Star-Star Connection, tertiary delta winding is used to provide path to harmonic and zero sequence current, thus called **neutral stabilizing winding**.
- The harmonic current increases Cu loss and causes electro-magnetic interference with Communication lines.
- Harmonic voltages increase dielectric loss and cause electro-static interference with Communication lines.

Note: 3^{rd} harmonic voltage exists only in phase voltage, it does not come in line voltage.

$$v_{ab} = \vec{v}_a - \vec{v}_b$$
$$\vec{v}_a = \vec{v}_a - \vec{v}_3$$
$$\vec{v}_b = \vec{v}_b - \vec{v}_3$$
$$\vec{V}_{ab} = \vec{V}_a - \vec{V}_b \left\{\text{as } 3^{rd} \text{ hormanic voltages are in phase}\right.$$

1.14 Open Delta connection or V - V connection

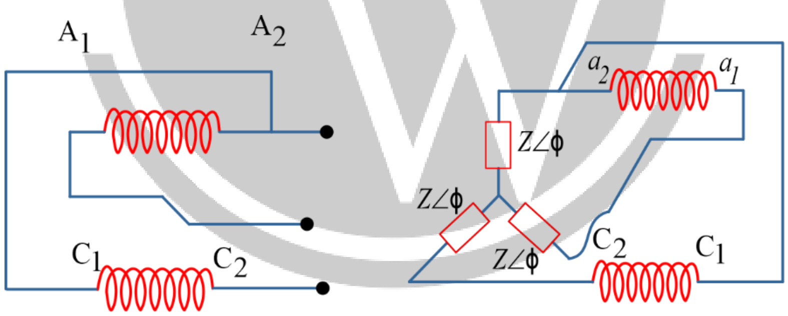


Fig. 1.19

- $\dfrac{S_{\text{open delta}}}{S_{\text{closed delta}}} = \dfrac{1}{\sqrt{3}}$
- Complex K.V.A shared by each x-mer

$$\vec{S}_A = \frac{|S_L|}{\sqrt{3}} \angle(\phi - 30°)$$

$$\vec{S}_C = \frac{|S_L|}{\sqrt{3}} \angle(\phi + 30°)$$

where, ϕ = Load of angle
S_L = Load K.V.A.

Note: If running Dd0 connection is converted into open delta connection by removing one transformer without reducing full Load, then each transformer gets overloaded by 73.2%.

1.15 Scott Connection (3–ϕ to 2–ϕ)

- Transformers are connected electrically

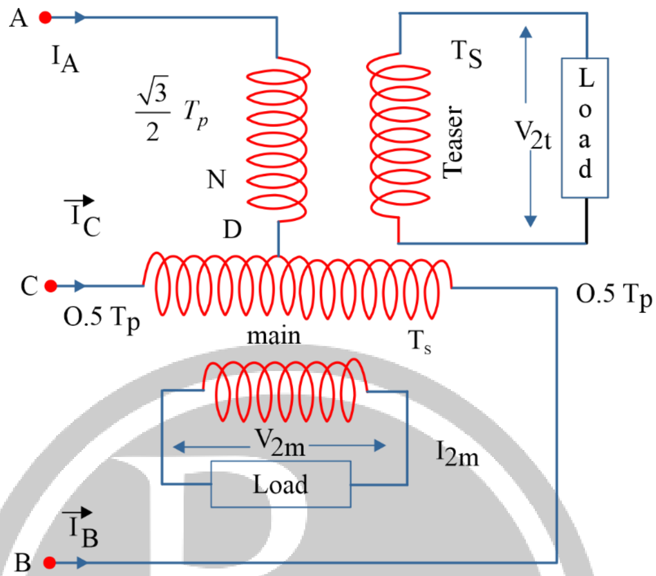


Fig. 1.20

- One transformer is called teaser transformer, the other transformer is called main transformer.
- a_t = turn ratio of teaser x-mer $= \frac{\sqrt{3}}{2}\frac{T_p}{T_s}$
- a_m = turn ratio of main x-mer $= \frac{T_p}{T_s}$
- $\vec{I}_A = \frac{\vec{I}_{2t}}{a_T}$
- $\vec{I}_B = \vec{I}_{BC} - \vec{I}_{A/2}\left\{\vec{I}_{BC} = \frac{\vec{I}_{2m}}{a_m}\right\}$
- $\vec{I}_C = -(\vec{I}_{BC} + \vec{I}_{A/2})$

Note: - Neutral point divides the primary of teaser in the ratio of AN : ND = 2 : 1

1.16 Parallel Operation of Transformer

Necessary Conditions

1. Correct polarity i.e, transformers should have the same polarity.
2. Same voltage ratio and voltage rating (slight difference may be tolerated).
3. Same phase sequence of both transformers.
4. Zero phase displacement i.e, transformers belonging to the same phasor group can only be paralleled.

Desirable Conditions

1. Same X/R ratio for same power factor of operation.
2. Same p.u impedance on their own base for proportional load sharing.

1.16.1 Parallel Operation of Transformers Having Equal Voltage Ratio

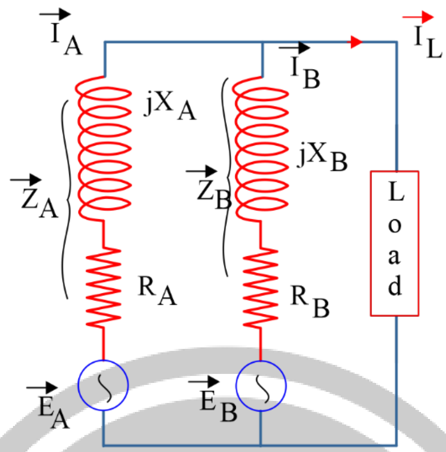


Fig. 1.21

- Current shared by each x-mer

$$\vec{I}_A = \vec{I}_L \times \left[\frac{\vec{Z}_B}{\vec{Z}_A + \vec{Z}_B}\right]$$

$$\vec{I}_B = \vec{I}_L \times \left[\frac{\vec{Z}_A}{\vec{Z}_A + \vec{Z}_B}\right]$$

- K.V.A shared by each x-mer

$$\vec{S}_A^* = \left[\frac{\vec{Z}_B}{\vec{Z}_A + \vec{Z}_B}\right] \times \vec{S}_L^*$$

$$\vec{S}_B^* = \left[\frac{\vec{Z}_A}{\vec{Z}_A + \vec{Z}_B}\right] \times \vec{S}_L^*$$

Where Z_A and Z_B are either in actual ohms or in p.u on common base.

Note: (i) Maximum Load K.V.A supplied by parallel operation

$$|S_{L(max)}| = S_A + S_B \cdot \left[\frac{Z_A}{Z_B}\right] + S_C \left[\frac{Z_A}{Z_C}\right]$$

When $Z_A < Z_B < Z_C$ and $Z_A, Z_B \& Z_C$ are in p.u on their own base values.

1.17. Magnetizing Inrush Current

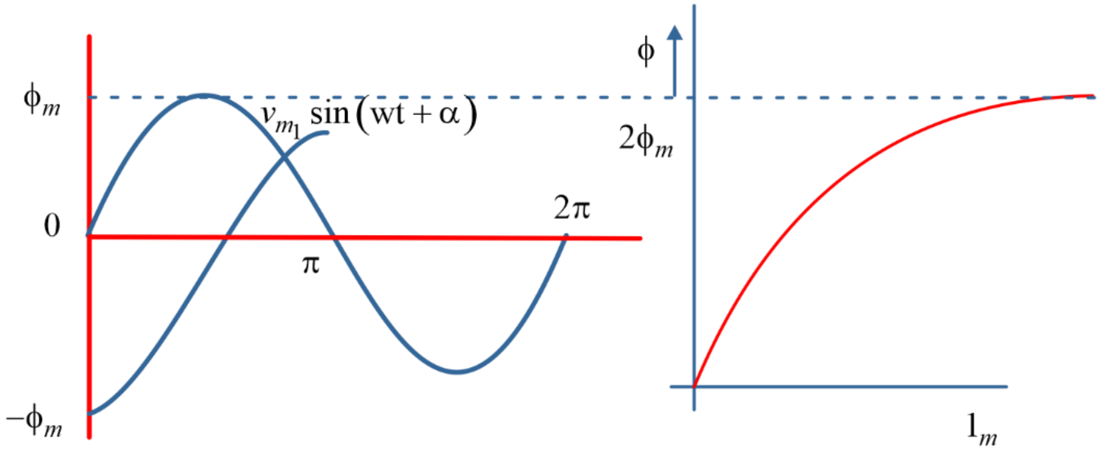


Fig. 1.21

- α = instant at which the transformer is switched onto the supply.
- $\Delta_\phi = (-\phi_m \; to + \phi_m)$in half cycle i.e, $2\phi_m \; in \; \frac{1}{2}$ cycle. In order to produces $2\phi_m$ flux in half Cycle, Transformer draws large lagging current in small span of time called **inrush current**.
- Inrush current is minimum for $\alpha = \pi/2$ i.e, near positive or negative maximum voltage.

Note: Stacking factor; $S_k = \dfrac{\text{Gross Cross} - \text{Sectional area}}{\text{Net Cross} - \text{Sectional area}}$

$$E = \sqrt{2}\pi f \cdot \phi_m \cdot N = \sqrt{2}\pi f \cdot \phi_m \cdot (S_k A) \cdot N$$

- Core – stepping not only gives a high space factor but also results in reduced length of the mean turn and consequently I^2R loss.
- Yoke cross – section is 20% higher than the core cross-section in order to reduce leakage flux.
- Magnetostriction $\rightarrow$ contraction and elongation of the stampings due to rapid reversal of flux.
- Cross over coils are used for H.V windings of small transformers when current is less than 20A.
- Disc – coil have efficient cooling due to oil contact at every turn.
- Spiral coils are used for low voltage and high current.
- Conservator is placed above the main tank and inclined at 3 to 5°. It takes expansion and contraction of oil due to load changes.

❒❒❒

2 INDUCTION MACHINE

2.1. 3-ϕ Induction Machine

- When a 3-ϕ stator winding displaced in space by 120° is supplied from a balance 3-ϕ current displaced in time by 120° then a rotating magnetic field is produced which rotates in space at synchronous speed
- The direction of rotation of magnetic field depends upon the phase sequence of supply and magnitude of the field is constant $\frac{3}{2}\phi_m$.

ϕ_m = Minimum flux produced per phase

Speed of magnetic field, $N_s = \frac{120f}{P}$

Note :

- Number of stator poles = Number of rotor poles
- Frequency of induced e.m.f = $\frac{P.\Delta N}{120}$
- ΔN = relative speed between field and winding
- $s = \frac{N_s - N_r}{N_s}$
- N_r = speed of rotor in the direction of field.

Types of Induction Motor

S.C.I.M

- Supply can be possible only on stator
- Self Induced pole
- External resistance can't be connected.

Wound Rotor I.M

- Supply may given to stator, rotor or Both
- Wound per same number of pole as stator
- External resistance can be connected.

2.2. Stator to rotor magnetic field

Case – I : When supply is given to stator,

Speed of stator magnetic field w.r.t to stator $N_S = \frac{120f_1}{P}$

f_1 = supply frequency

The rotor rotates in same direction as the stator magnetic field with a speed N_r

$$\text{Slip } s = \left(\frac{N_s - N_r}{N_s}\right)$$

Relative speed of	With Respect to			
	Stator	**Rotor**	**Stator field**	**Rotor field**
(i) Stator	0	$-N_s(1-s)$	$-N_s$	$-N_s$
(ii) Stator field	N_s	sN_s	0	0
(iii) Rotor	$N_r = (N_s(1-s))]$	0	$-sN_s$	$-sN_s$
(iv) Rotor filed	N_s	sN_s	0	0

Note : Frequency of induced e.m.f $= \left(\frac{P.\Delta N}{120}\right)$

$f_2 = sf_1$

Case – II : When supply is given to rotor, speed of rotor magnetic field w.r.t rotor winding (body) is

$$N_S = \frac{120 f_1}{P}$$

f_1 = supply frequency

Rotor rotates in opposite direction to rotor magnetic field with speed "N_r"

Relative speed of	With Respect to			
	Rotor	**Rotor field**	**Stator**	**Stator field**
(i) Rotor Field	N_s	0	sN_s	0
(ii) Rotor	0	$-N_s$	N_r	$-N_s$
(iii) Stator	$-N_r$	$-sN_s$	0	$-sN_s$
(iv) Stator field	N_s	0	sN_s	0

Frequency of induced e.m.f $= \frac{P.\Delta N}{120}$

$f_2 = sf_1$

Case – III: When supply is given to both stator & rotor of W.R.I.M at different frequency.

$$\text{Rotor speed } N_r = \frac{120}{P}[f_1 \pm f_2]$$

f_1 = supply frequency to stator

f_2 = supply frequency to rotor

(+) = When both stator & rotor filed are in opposite direction

(–) = When both stator & rotor field are in same direction

2.3. Per–Phase Equivalent circuit

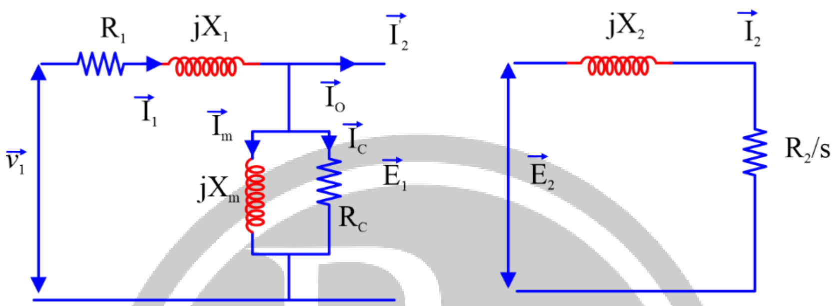


Fig. 2.1.

$$E_1 = \sqrt{2}\pi f_1 \phi N_1 kw_1$$

$$E_2 = \sqrt{2}\pi f_2 \phi N_2 kw_2$$

$f_2 = sf_1$ [s = 1 at stand still]

E_2 = stand still rotor induced e.m.f

$$= \sqrt{2}\pi f_1 \phi N_2 k\omega_2$$

$$\frac{E_1}{E_2} = \frac{N_1 kw_1}{N_2 kw_2} = \frac{N_{e_1}}{N_{e_2}} = \frac{\text{effective stator turns}}{\text{effective rotor turns}}$$

$$\frac{E_1}{E_2} = \frac{Ne_1}{Ne_2} = a \text{ = reduction factor}$$

From m.mf balance, $\vec{I}_1 = \frac{\vec{I}_2}{a} + \vec{I}_a$

2.3.1. Per Phase Electric Model

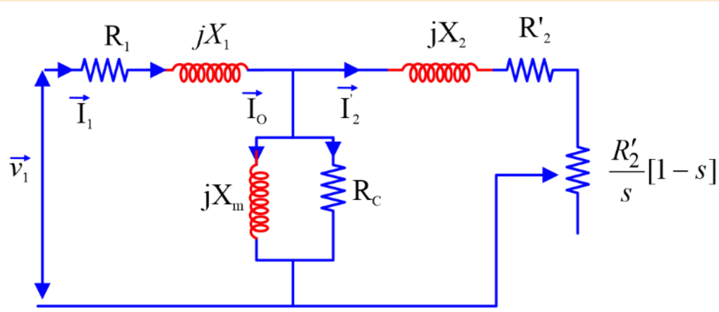


Fig. 2.2

$$R_2' = a^2 R_2 \;\; \& \;\; X_2' = a^2 X_2$$

2.4. Power flow in Induction Motor

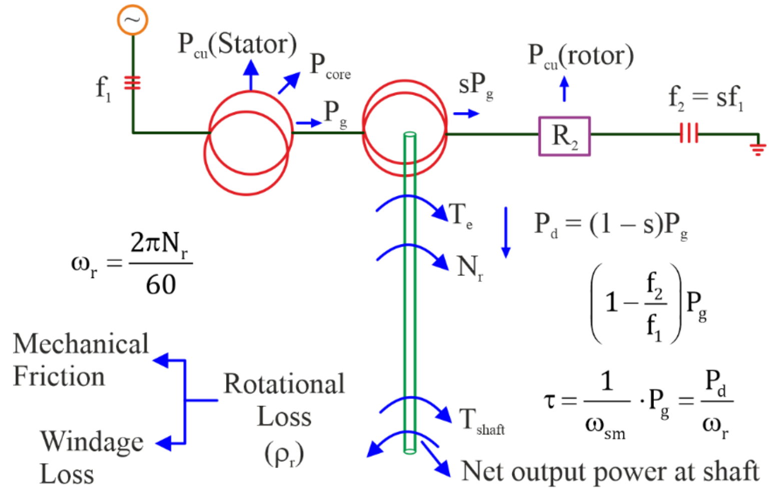


Fig. 2.3

$$T_{Shaft} = \frac{P_d - P_r}{\omega_r} = \frac{P_d}{\omega_r} - \frac{P_r}{\omega_r} = \tau_e - \tau_{loss}$$

Note : $P_g : P_{cu(rotor)} : P_d = 1 : s : (1 - s)$

2.5. Torque slip curve of 3-ϕ Induction Motor

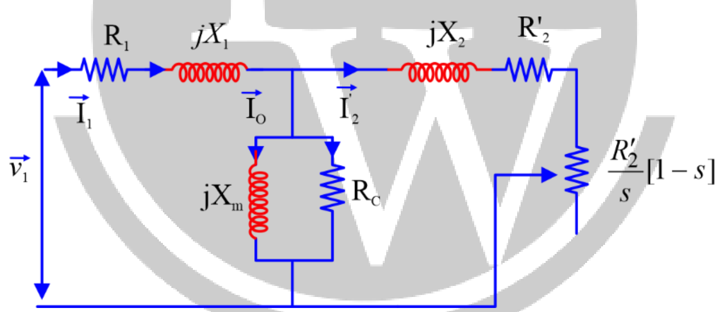


Fig. 2.4

On neglecting ($R_1 + jX_1$) i.e stator impedance
Then

$$|I_2'| = \frac{v_1}{\sqrt{\left(\frac{R'_2}{s}\right)^2 + (x'_2)^2}}$$

$$P = |I'_2|^2 . \frac{R'_2}{s}$$

$$\boxed{\tau = \frac{3}{\omega_{sm}} . \left[\frac{v_1^2}{(R'_2/s)^2 + (x'_2)^2}\right] . \frac{R'_2}{s}}$$

Low Slip Zone	High Slip Zone
$\tau = \frac{3}{\omega_{sm}} \cdot \left[\frac{v_1^2}{(R_2')}\right] \times s$ $\tau \propto s$	$\tau = \frac{3}{\omega_{sm}} \times \left[\frac{V_1^2}{(X_2')^2}\right] \times \frac{R_2'}{s}$ $\tau \propto \frac{1}{s}$

2.5.1. Condition for Maximum Torque

$$s_{T(max)} = \frac{R_2'}{X_2'} = \frac{R_2}{X_2}$$

$$s_{T(max)} \propto R_2$$

2.5.2. Maximum Torque

$$T_{(max)} = \frac{3}{2\omega_{sm}} \cdot \left[\frac{v_1^2}{(x_2')}\right]$$

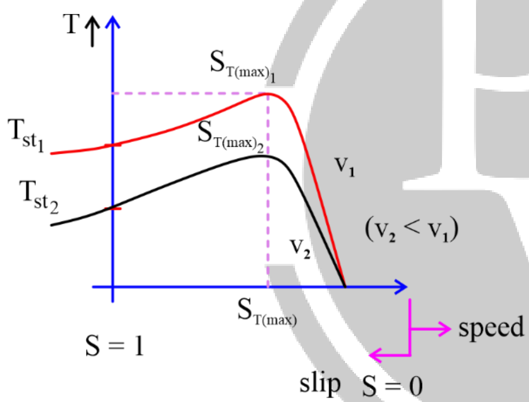


Fig. 2.5

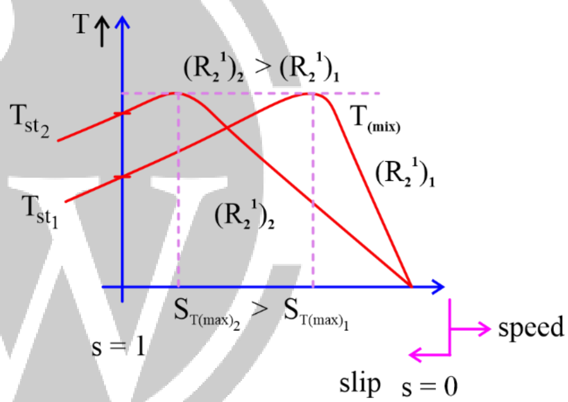


Fig. 2.6

Note : $\frac{T_{st}}{T_{(max)}} = \frac{2}{(R_2'/x_2') + \left(\frac{x_2'}{R_2'}\right)} = \frac{2}{\frac{s_{T(max)}}{1} + \frac{1}{s_{T(max)}}}$

2.6. No Load and Blocked Rotor Test

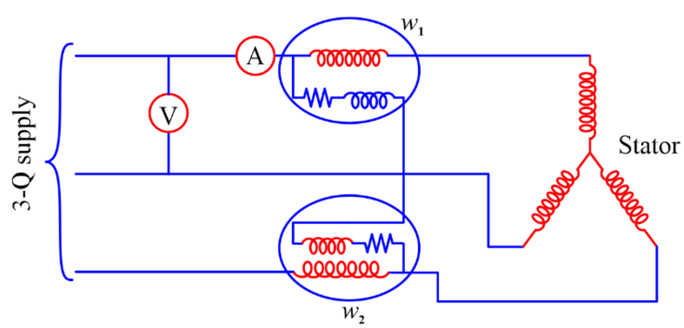
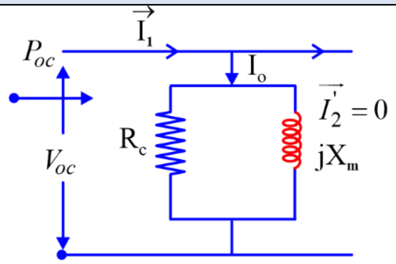
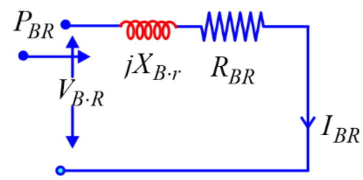


Fig. 2.7

Total input power is measured through wattmercs & under no-load or blocked rotor condition

No Load Test	Blocked Rotor Test
 $P_{OC} = \frac{V_{OC}^2}{R_c}$ $R_c = \frac{V_{OC}^2}{P_{OC}}$ $I_C = \frac{V_{OC}}{R_C}$ $I_m = \sqrt{I_0^2 - I_c^2}$ $X_m = \frac{V_{OC}}{I_c}$ V_{OC} = Per phase voltage I_0 = no – load per phase current P_{oc} = per phase no – load loss	 $R_{B.R} \cong R_1 + R_2' = \frac{P_{B.R}}{(I_{B.R})^2}$ $Z_{B.R} = V_{B.R} / I_{B.R}$ $X_{B.R} = \sqrt{Z_{B.R}^2 - R_{BR}^2}$ $X_{B.R} \cong (X_1 + X_2')$ $V_{B.R}$ = per phase voltage (reduced voltage) $I_{B.R}$ = current under B.R condition $P_{B.R}$ = per phase I/P power under B.R condition (Cu loss)

2.6.1. Graph between No- load Loss & Voltage

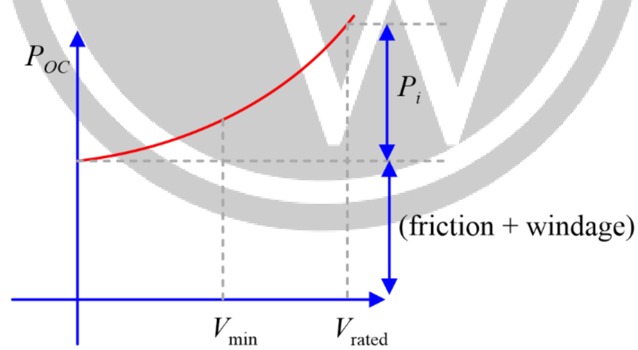


Fig. 2.8

Electric model from O.C – SC test (Approx model)

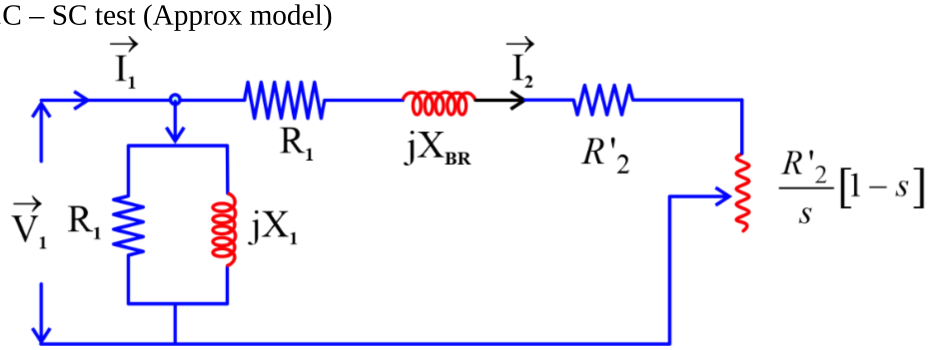


Fig. 2.9

Torque Equation

$$T=\frac{3}{\omega_{sm}}\times\left[\frac{v_1^2}{\left(R_1+R'_2/s\right)^2+\left(x_1+x'_2\right)^2}\right]\times\frac{R'_2}{s}$$

2.7. Staring of Induction Motor

Starter is needed to reduce the starting current (short circuit) taken by motor from supply

2.7.1. Direction on line starting

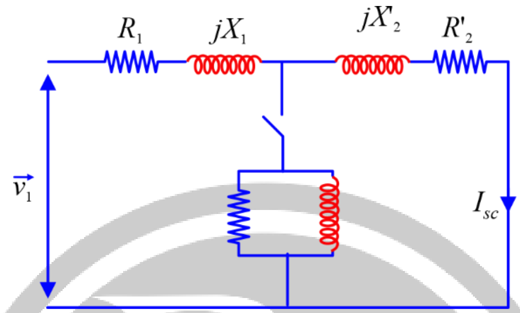


Fig. 2.10.

$$I_{SC} = I_{st}$$

$$\frac{T_{st}}{T_{fL}}=\left[\left(\frac{I_{SC}}{I_{fL}}\right)^2 s_{fL}\right]$$

2.7.2. Impedance Starting

$$I_{SC}=\frac{xv_1}{Z_{sc}}=xI_{sc}$$

$$\frac{T_{st}}{T_{fL}}=x^2\left(\frac{I_{SC}}{I_{fL}}\right)^2\times s_{fL}$$

Lowest starting torque among all starting method.

2.7.3. Auto Transfer Starting Method

$$I_{st(motor)} = x.I_{sc}$$

$$I_{st(supply)} = x^2 I_{sc}$$

$$\frac{I_{st}}{I_{fL}} = x^2.\left(\frac{I_{sc}}{I_{fL}}\right)^2.s_{fL}$$

2.7.4. Star–Delta Starting

- Used for delta designed motors
- At start stator is star connected while at rated speed stator is delta connected

$$\frac{I_{st(line)}(Y)}{I_{st(Line)}(\Delta)} = \frac{1}{3};\ \frac{T_{st}(Y)}{T_{st}(\Delta)} = \frac{1}{3}$$

$$\frac{T_{st(y)}}{T_{fl(\Delta)}} = \left(\frac{1}{\sqrt{3}}\right)^2 \times \left[\frac{I_{sc(\Delta)}}{I_{fL(\Delta)}}\right] \times s_{fL}$$

2.7.5. Rotor Resistance Starting

Only for S.R.I.M, $$I_{sc} = \frac{V_1}{\sqrt{\left(R_1 + R_2' \uparrow\right)^2 + \left(x_1 + x_2'\right)^2}}$$

2.8. Speed control of 3 ϕ Induction Motor

$$N_r = N_s [1 - s]$$

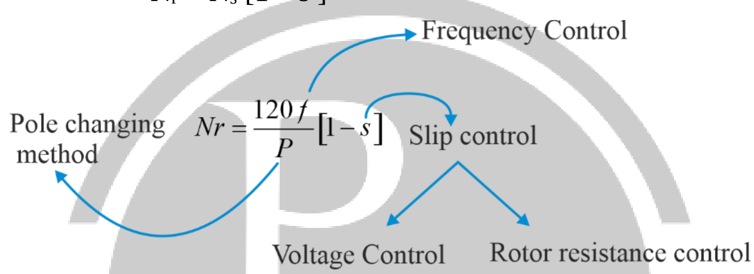


Fig. 2.11.

2.8.1. Voltage Control

$$\tau = \frac{3}{\omega_{sm}} \times \left[\frac{V^2}{(R'_2/s)^2 \times (x'_2)^2}\right] \times \frac{R'_2}{s}$$

In low slip zone, $$\tau = \frac{3}{\omega_{sm}} \times \frac{V^2}{(R'_2)} \times s \qquad \text{i.e} \quad \tau \propto sV^2$$

For constant torque load $\rightarrow$ $s \propto \frac{1}{V^2}$

Rotor resistance control, $$\tau \propto \left(\frac{s}{R_2'}\right)$$

For constant torque load, $$s \propto R_2'$$

2.8.2. Frequency Control Method

$$\tau \propto \frac{v^2}{f \times \left(R_2'\right)} s$$

We keep v/f = constant i.e ϕ = constant be avoid magnetic saturation is stator and rotor core.

$$\tau \propto \frac{f^2 s}{f} \text{ i.e. } \boxed{\tau \propto sf}$$

$\boxed{\text{For constant load} \rightarrow sf = \text{constant}}$

Note :

Above base speed, v/f ≠ constant so maximum torque changes with change in frequency

$$T_{(max)} \propto \left[\frac{1}{f^2}\right] \text{ when v/f} \neq \text{constant}$$

$T_{(max)}$ = constant when v/f = constant

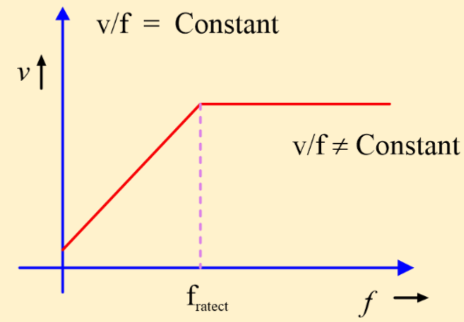


Fig. 2.13.

2.9. Double cage rotor (Two Cages Outer & Inner)

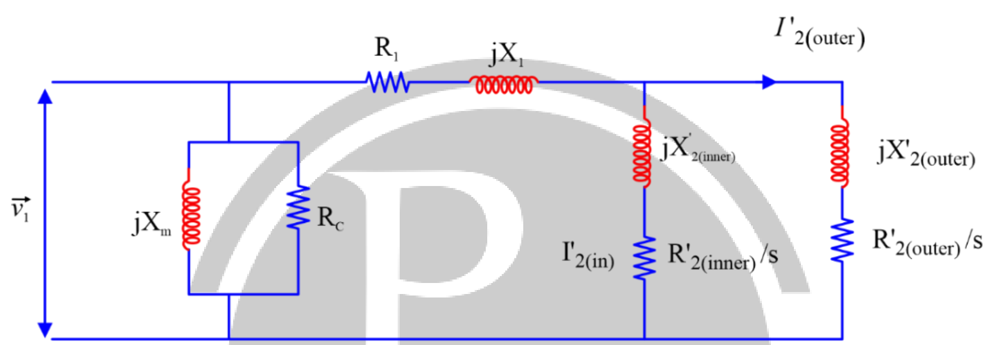


Fig. 2.14.

$$\frac{I'_{2(outer)}}{I'_{2(inner)}} = \frac{\sqrt{(R'_{2(inner)/s}) + (X'_{2(inner)})^2}}{\sqrt{(R'_{2(outer)/s}) + (X'_{2(outer)})^2}}$$

$$\frac{T_{outer}}{T_{inner}} = \left[\frac{I'_{2(outer)}}{I'_{2(inner)}}\right]^2 \times \frac{R'_{2(outer)}}{R'_{2(inner)}}$$

2.10. Induction Motor stability

Stable operation of the system consisting of motor and load is possible, if the motor speed increases with decrease in load torque or vice – versa

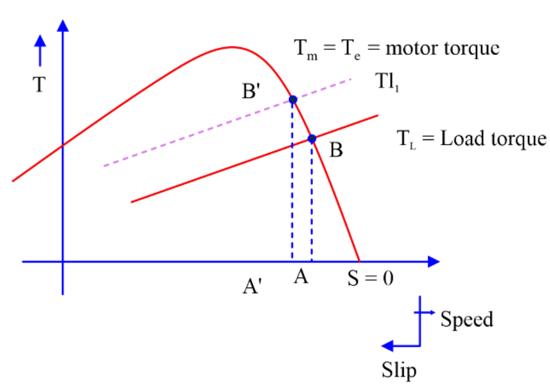


Fig. 2.15.

B is stable point.

2.11. Concept of time and Space Harmonics

Time harmonics are present in supply current. Speed of rotating field due to fundamental component = $\frac{120f}{P} = N_s$

Speed of $(6m \pm 1)^{th}$ time harmonic = $(6m \pm 1)\, N_s$

(+) = rotate in the direction of fundamental

(–) = rotate opposite to the direction of fundamental

Space harmonics are Present due to

(i) Winding arrangement

(ii) Slotting

(iii) Saturation

(iv) Gap length irregularity

Speed of $(6m \pm 1)^{th}$ space harmonics $= \left(\frac{Ns}{6m \pm 1}\right)$

(+) = rotate in the direction of fundamental

(–) = rotate in the direction of fundamental

Cogging

The motor fails to start if number of stator slots and rotor slots are equal or integral multipole due to alignment (reluctance) torque

Crawling

Cage motor runs stably at low speed due to space harmonics

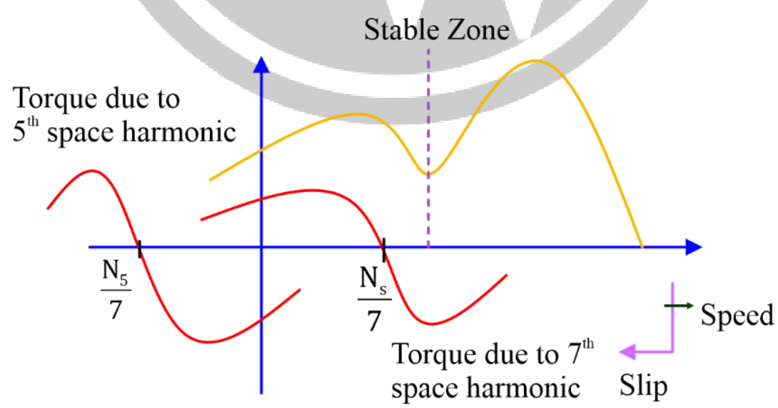


Fig. 2.16.

2.12. Single Phase Induction Motor

- It is not self starting.
- It has stator and rotor.
- It rotates at a speed lesser than synchronous speed.

2.12.1. Construction

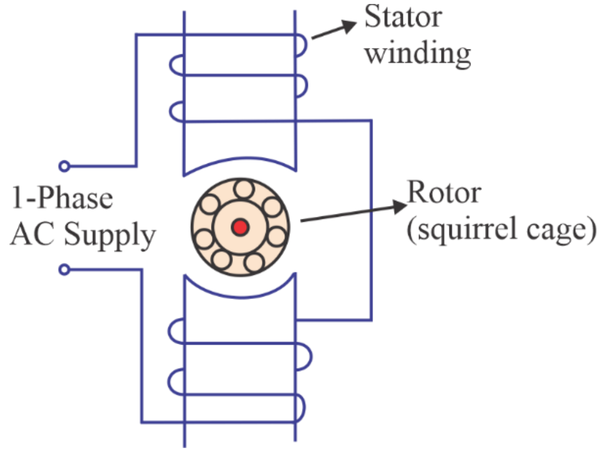


Fig. 2.17.

2.12.2. Double Revolving Field Theory

- Pulsating AC field is resolved into two components which rotate in opposite direction to each other. Their magnitudes are half as that of maximum magnitude.
- $\phi_f \rightarrow$ Forward component
- $\phi_b \rightarrow$ Backward component
- Resultant of these two gives instantaneous flux.

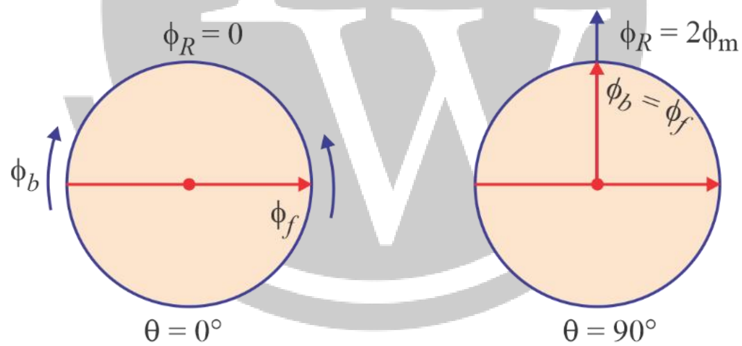


Fig. 2.18.

For $\theta = 0°$ to $\theta = 360°$, the net stator flux varies as stator flux.

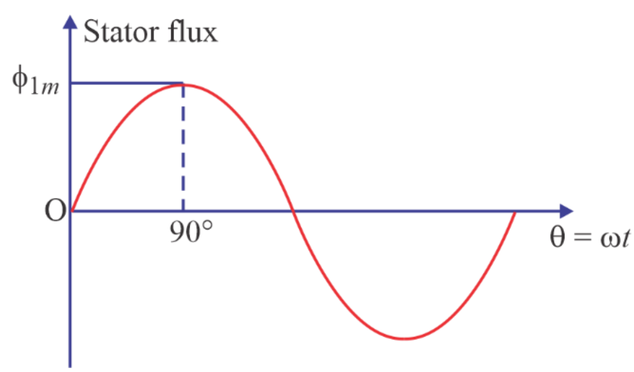


Fig. 2.19.

Hence, resultant torque is zero at starting.

Torque – speed characteristics of 1-ϕ induction motor:

$$T = T_f + T_b$$

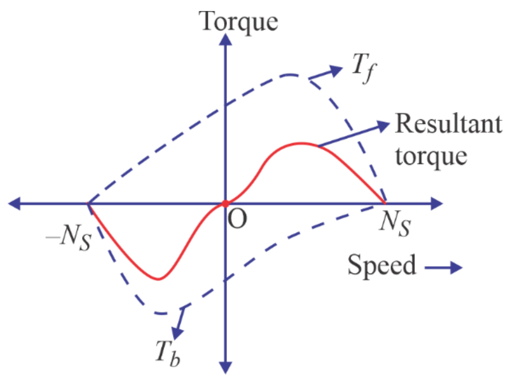


Fig. 2.20.

If initial torque is provided, then it can rotate.

2.12.3. Cross Field Theory

- If two fluxes are at some angle, then rotating magnetic field is produced.
- According to this theory; stator flux is resolved into two mutually perpendicular components.

2.12.4. Types of Single Phase Induction Motor

1. Split phase induction motor.
2. Capacitor start induction motor.
3. Capacitor start capacitor run induction motor.
4. Permanent capacitor induction motor.
5. Shaded pole induction motor.

2.12.4.1. Split phase induction motor:

- Stator has main as well as auxiliary windings.
- Auxiliary winding has a series resistance but main winding is inductive.
- Because of inductive nature, the current in main winding lags behind the supply voltage by more angle as compared to auxiliary winding.
- Hence, it causes phase difference between fluxes of both windings.
- Hence, rotating field is produced.
- It has low starting current and medium starting torque.
- Phase shift between both winding currents lies between 30° to 45°.

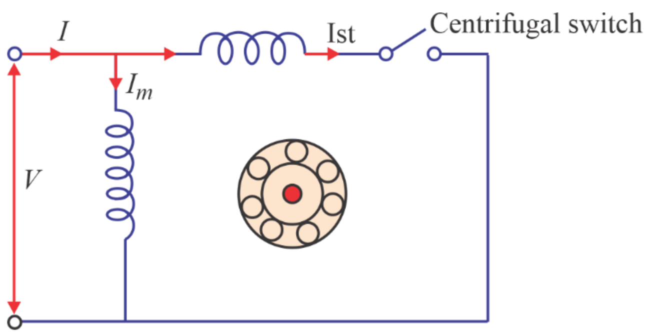


Fig. 2.21.

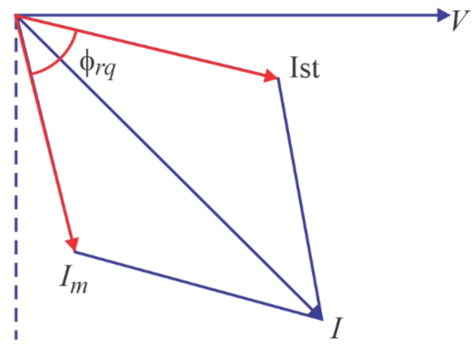


Fig. 2.22.

2.12.4.2. Capacitor Start Induction Motors

- Capacitor is connected in auxiliary winding with an auxiliary switch.

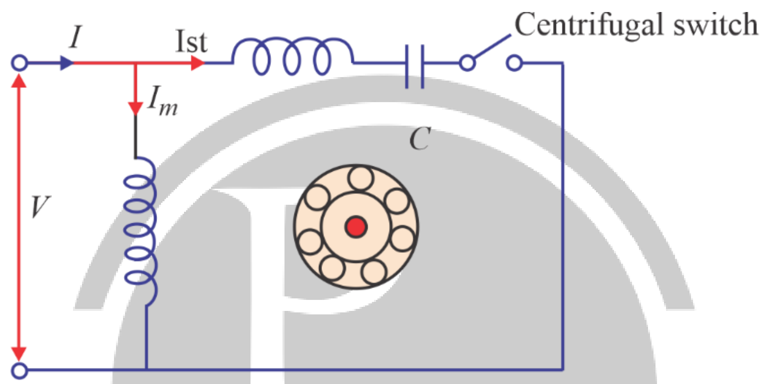


Fig. 2.23.

- When the motor reaches the speed of 70 to 80% of N_S, centrifucal switch operates and auxiliary winding gets disconnected.
- It produces very high starting torque.
- Condition at which the phase difference between main winding and auxiliary winding current is 90°

$$\theta_A + \theta_m = 90°$$

$$\boxed{\tan^{-1}\left[\frac{X_c - X_A}{R_A}\right] + \tan^{-1}\left[\frac{X_m}{R_m}\right] = 90°}$$

- Condition for maximum torque :-

$$\theta_A = \frac{90° - \theta_m}{2}$$

$\Rightarrow$

$$\boxed{\tan^{-1}\left[\frac{X_c - X_A}{R_A}\right] = \frac{90° - \tan^{-1}\left(\frac{X_m}{R_m}\right)}{2}}$$

2.12.4.3. Capacitor start capacitor run induction motors:

- Two parallel capacitors are connected in series with auxiliary winding.

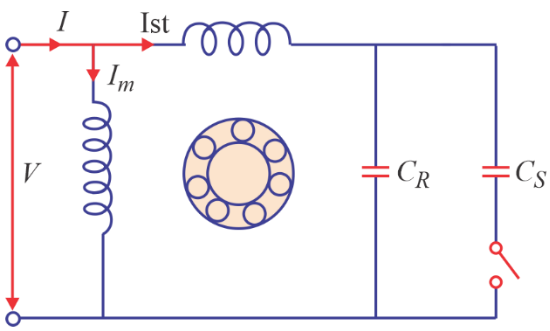


Fig. 2.24.

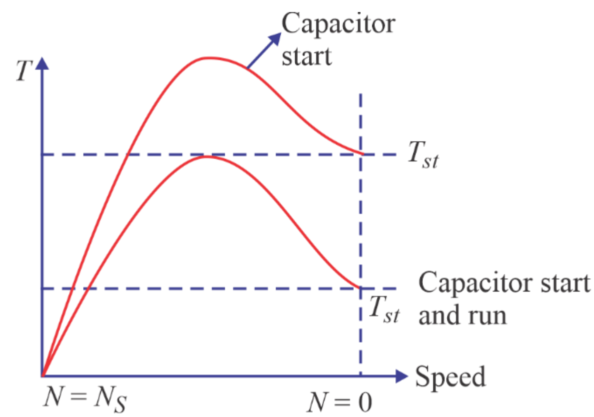


Fig. 2.25.

- C_S is short time rated capacitor and is removed when motor attains some speed.

2.12.4.4. Permanent Capacitor Induction Motor

- There is a capacitor connected in series with auxiliary winding without any switch.

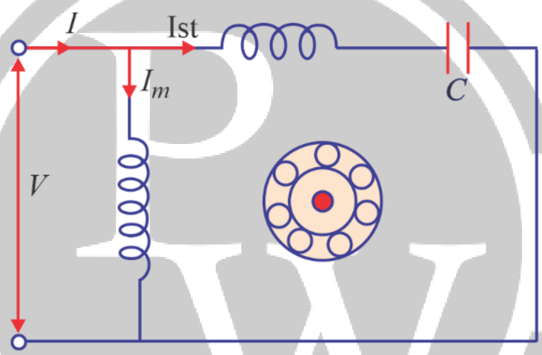


Fig. 2.26.

2.12.4.5. Shaded Pole Induction Motors:

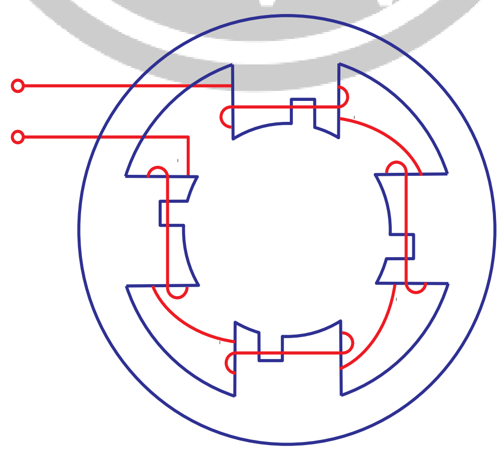
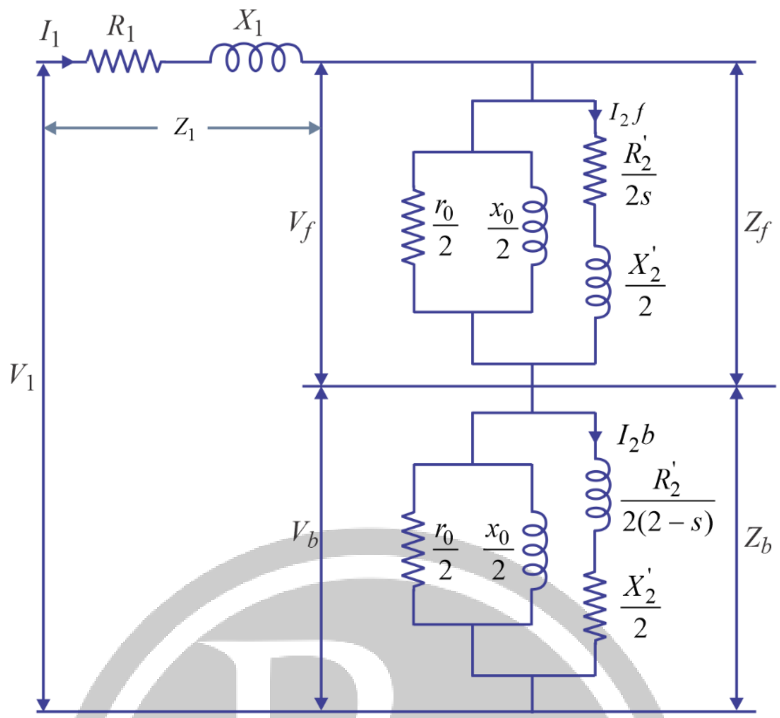


Fig. 2.27.

- Rotor is squirrel case and stator is salient pole type.
- The direction of rotating magnetic field is from non shaded pole to shaded part of the pole.
- It's starting torque as well as power factor is low.

2.12.5. Equivalent circuit of 1-phase induction Motor Referred to Stator



$$\vec{I_1} = \frac{\vec{V_1}}{\vec{Z_1} + \vec{Z_f} + \vec{Z_b}}$$

Fig. 2.28.

❒❒❒

3 SYNCHRONOUS MACHINE

3.1. Why field winding on rotor?

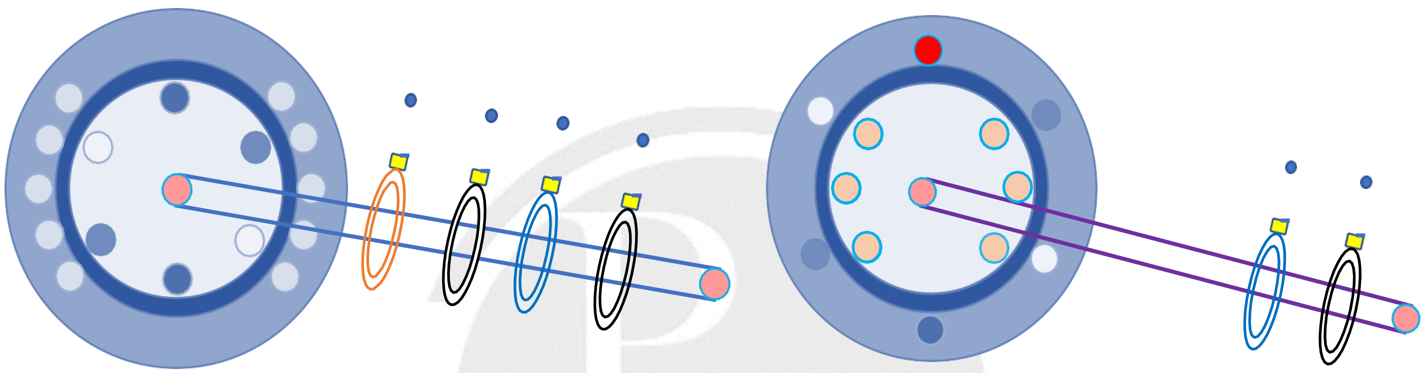


Fig. 3.1.

- Only 2 – slip rings and brushes are required
- Insulation corresponding to low voltage is required.
- Current carrying capacity is low, so rotor winding weight is less and Low centrifugal force.

3.1.1. Working Principle

Faraday's Law

Whenever magnetic flux linking the coil changes with time an EMF is induced across the coil and magnitude of EMF is

$$E = \pm N \frac{d\phi}{dt}$$

Lenz's Law

The polarity of induced EMF is such that if it allows to cause a current then current so produced oppose the cause.

3.1.2. Frequency of induced EMF

Let P = Number of poles in machine

N = Speed in RPM

$$\text{Number of cycles in one revolution} = \frac{P}{2}$$

$$\text{Number of rotation per second} = \frac{N}{60}$$

$$\text{Number of cycles per second} = \frac{P \times N}{2 \times 60} = \frac{P \times N}{120} H_Z$$

$$f = \frac{P \times N}{120} Hz$$

3.1.3. Voltage Generated in 3 – ϕ Synchronous Machine

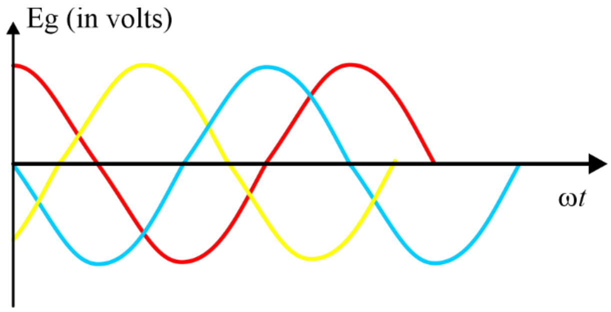


Fig. 3.2.

Note: Phase sequence of induced emf depends upon direction of rotation.

3.2. Production of Rotating Magnetic Field

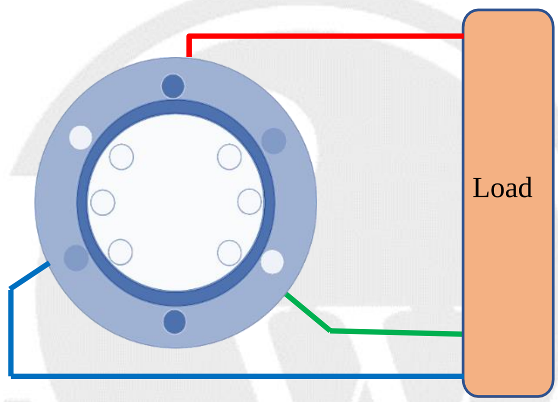


Fig. 3.3.

- When 3-ϕ stator displaced in space by 120° is supplied by 3 − ϕ current displaced in time by 120°,then a rotating magnetic field is produced. which rotates in space at synchronous speed and direction of rotation is same as phase sequence of supply.
- Both stator and rotor fields are stationary with respect to each other (this is the necessary condition for production of torque in motor and power transfer in generator).
- Frequency of induced emf depends upon speed, which depends on the type of prime mover chosen.

3.2.1. Construction of Synchronous Machine

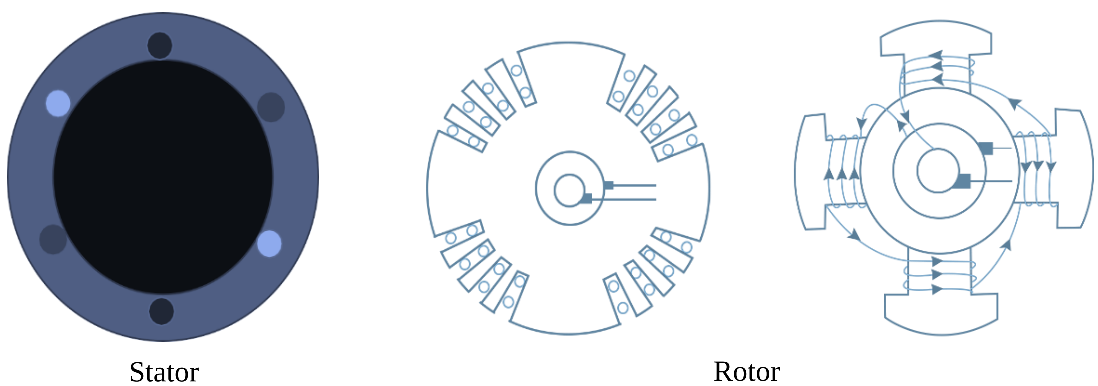
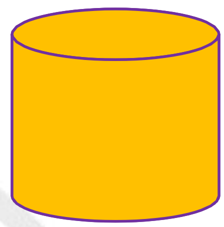


Fig. 3.4.

Non-Salient poles Synchronous Machine	Salient Synchronous Machine
• Preferred for turbo alternator (Low centrifugal force). • Less number of poles. • Called high speed alternator. • More iron loss. • Damper bars are not required. • Flux is uniformly distributed. • Diameter is smaller, and length is larger. 	• Preferred for hydro generator (High centrifugal force). • More number of poles. • Called low speed alternator. • Less iron loss. • Damper bars are required. • Flux is non uniform. • Diameter is large, and length is smaller. 

3.2.2. Induced EMF in AC Rotating Machine

P = number of poles

ϕ = flux per pole

N = speed in RPM

f = frequency = $\frac{PN}{120} H_Z$

T_{ph} = number of turns per phase

$$E_{rms} = \sqrt{2}\pi f \phi T_{ph} \rightarrow \text{ Valid only for concentrated and full pitched windings}$$

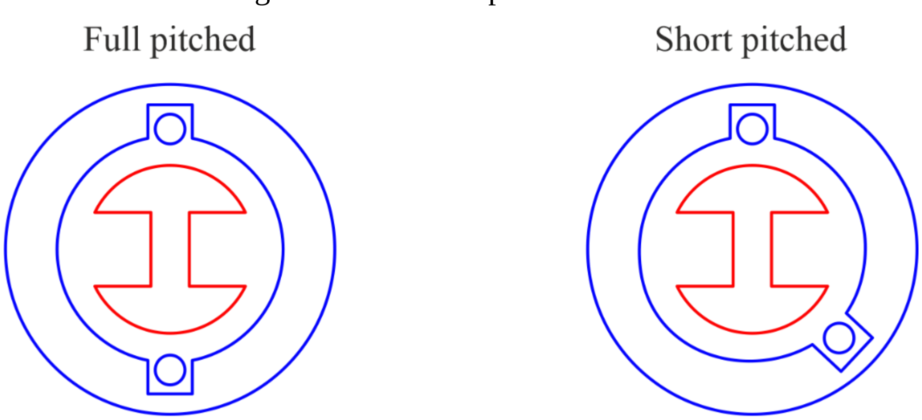
$$E_{rms} = \sqrt{2}\pi f \phi T_{ph} K_p K_d \rightarrow \text{Distribution factor}$$

(K_p ↓ short pitch factor)

3.2.2.1. Coil Span Factor or Pitch Factor (Kc)

The distance between the two coil – sides of a coil is called coil-span or coil-pitch.

$$K_C = \frac{\text{Voltage Generated in short pitched coil}}{\text{Voltatge Generated in full pitched coil}}$$



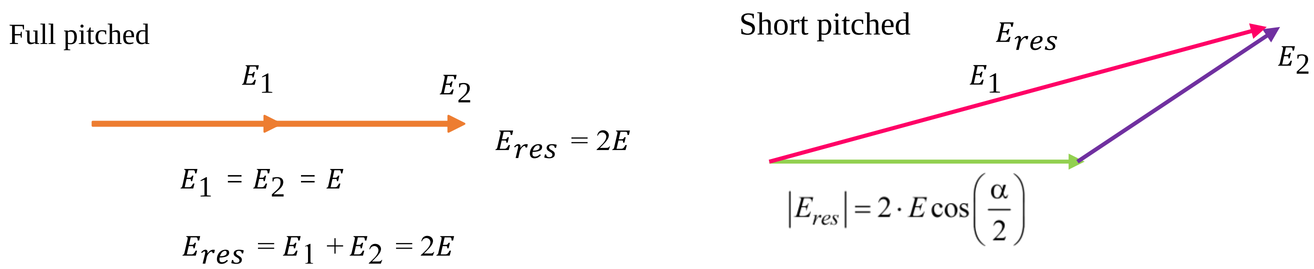


Fig. 3.5.

$$\therefore \quad K_c = \frac{2E_c \cos\alpha/2}{2E_c} = \cos\left(\frac{\alpha}{2}\right)$$

$$K_c = \cos\left(\frac{\alpha}{2}\right) \longrightarrow \text{For fundamental.}$$

$$K_{cn} = \cos\left(\frac{n\alpha}{2}\right) \longrightarrow \text{For } n^{th} \text{ harmonic.}$$

3.2.2.2. Distribution Factor or Belt Factor (K_d)

$$K_d = \frac{\text{Phasor sum of coil voltages induced}}{\text{Arithemetic sum of coil voltages}}$$

$$K_d = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}}, \text{ For fundamental component}$$

$$K_{dn} = \frac{\sin\frac{mn\beta}{2}}{m\sin\frac{n\beta}{2}}, \text{ For } n^{th} \text{ harmonic}$$

$$m = \frac{\text{slot}}{\text{pole x phase}} \qquad \beta = \frac{180°}{\text{slot/pole}}$$

3.3. Armature Reaction in Synchronous Generator

For generator, $\vec{F_f}$ always leads $\vec{F_{ar}}$ in the direction of rotation

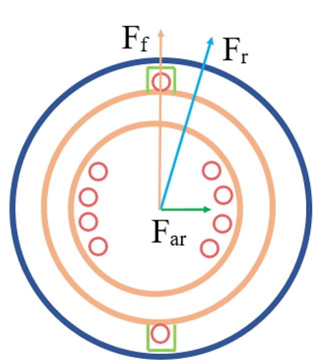
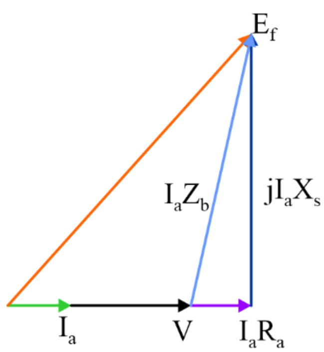
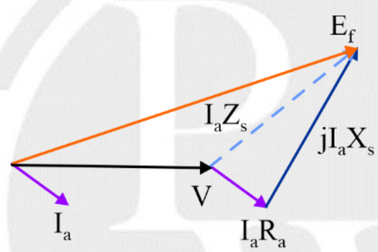
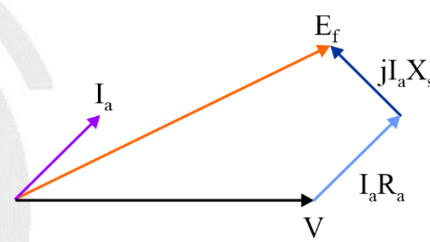


Fig. 3.6.

Condition	Armature reaction effect
• At UPF	• Cross magnetising effect, Normally excited.
• At Zero PF lagging	• Directly demagnetising effect, Over excited.
• At zero PF leading	• Directly magnetising effect, Under excited.
• At 0.8 PF lagging	• Both demagnetising and cross magnetising effects, Over excited.
• At 0.8 PF leading	• Both cross magnetising and magnetising effects, Under excited.

3.4. Phasor diagram – Cylindrical Rotor Synchronous Generator

At UPF	At 0.8 PF lagging	At 0.8 PE leading
		
$\psi = \delta = \tan^{-1}\left(\frac{I_aX_s}{V+I_aR_a}\right)$ $\lvert E_f \rvert = \sqrt{(V+I_aR_a)^2+(I_aX_s)^2}$	$\psi = \tan^{-1}\left(\frac{V\sin\phi+I_aX_s}{V\cos\phi+I_aR_a}\right)$ $\delta = \psi - \phi$ $\lvert E_f \rvert = \sqrt{(V\cos\phi+I_aR_a)^2+(V\sin\phi+I_aX_s)^2}$	$\psi = \tan^{-1}\left(\frac{V\sin\phi-I_aX_s}{V\cos\phi+I_aR_a}\right)$ $\delta = \lvert\phi\rvert - \lvert\psi\rvert$ $\lvert E_f \rvert = \sqrt{(V\cos\phi+I_aR_a)^2+(V\sin\phi-I_aX_s)^2}$

3.5. Open Circuit Test and Short Circuit Test

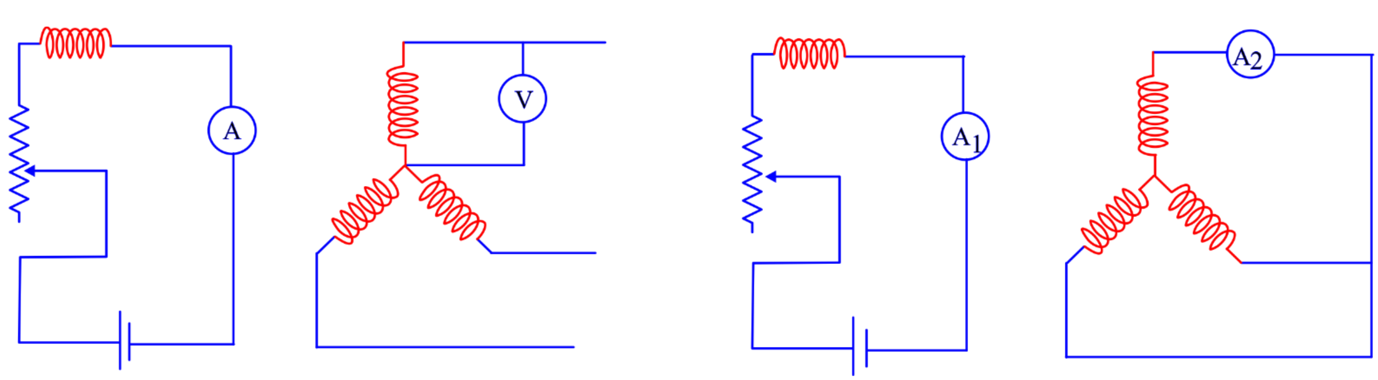


Fig. 3.7.

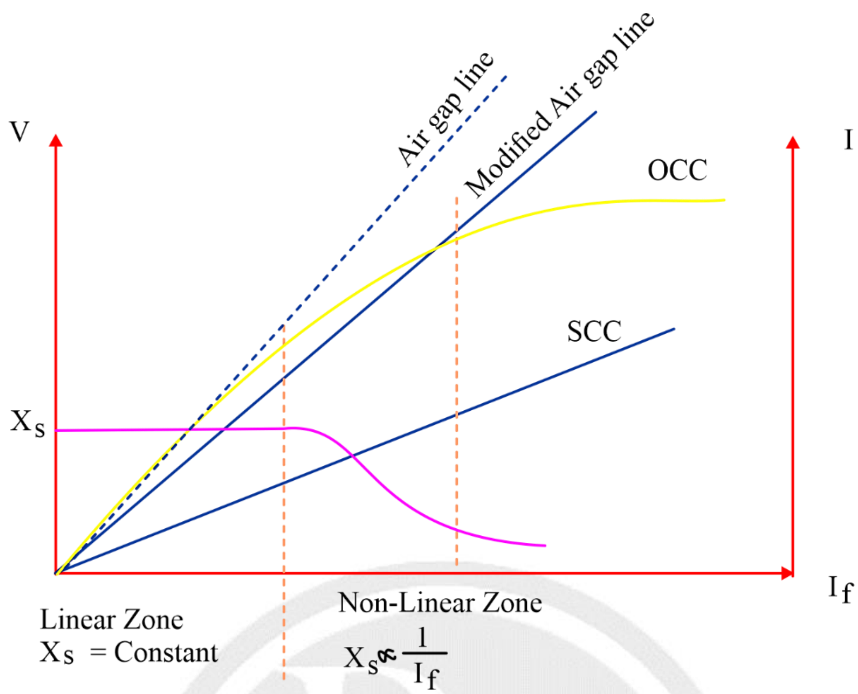


Fig. 3.8.

3.6. Power Angle Equation of Round Rotor Synchronous Generator

Complex power developed = $\vec{S}_{dev} = \vec{E}_f \, \vec{I}_a^{\,*} = P_{dev} + jQ_{dev}$

$$P_{dev} = \frac{E_f^2}{Z_s}\cos\theta_s - \frac{E_f V}{Z_s}\cos(\theta_s + \delta)$$

$$Q_{dev} = \frac{E_f^2}{Z_s}\sin\theta_s - \frac{E_f V}{Z_s}\sin(\theta_s + \delta)$$

Output complex power = $\vec{S}_{out} = \vec{V}\vec{I}_a^{\,*} = P_{out} + jQ_{out}$

$$P_{out} = \frac{VE_f}{Z_s}\cos(\theta_s - \delta) - \frac{V^2}{Z_s}\cos\theta_s$$

$P_{out(max)}$ occurs at $\delta = \theta_s$

$$Q_{out} = \frac{VE_f}{Z_s}\sin(\theta_s - \delta) - \frac{V^2}{Z_s}\sin\theta_s .$$

On neglecting R_a:

$Z_s = X_s ; \theta_s = 90^\circ .$

$$\boxed{P_{out} = \frac{VE_f}{X_s}\sin\delta}$$

$$\boxed{Q_{out} = \frac{V}{X_s}\left(E_f \cos\delta - V\right)}$$

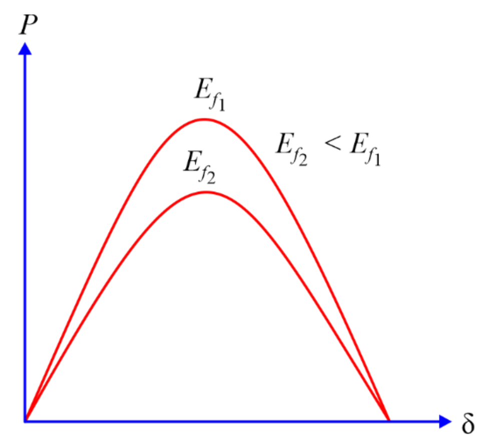


Fig. 3.9

3.7. Armature Reaction in Synchronous Motor

Condition	Armature reaction effect
• At UPF	• Cross magnetising effect, Normally excited.
• At Zero PF lagging	• Directly magnetising effect, Under excited.
• At zero PF leading	• Directly demagnetising effect, Over excited.
• At 0.8 PF lagging	• Both demagnetising and cross magnetising effects, Under excited.
• At 0.8 PF leading	• Both cross magnetising and magnetising effects, Over excited.

3.7.1. Power Angle Equation of Round Rotor Synchronous Motor

Complex power developed = $\vec{S}_{dev} = \vec{E}_f \, \vec{I}_a^{\,*} = P_{dev} + jQ_{dev}$

$$P_{dev} = \frac{E_f V}{Z_s}\cos(\theta_s - \delta) - \frac{E_f^2}{Z_s}\cos\theta_s$$

$$Q_{dev} = \frac{E_f V}{Z_s}\sin(\theta_s - \delta) - \frac{E_f^2}{Z_s}\sin\theta_s$$

Input Complex power $= \overrightarrow{S_{input}} = \vec{V}\vec{I}_a^{\,*} = P_{input} + jQ_{input}$

$$P_{in} = \frac{V^2}{Z_s}\cos\theta_s - \frac{VE_f}{Z_s}\cos(\theta_s + \delta)$$

$P_{in(max)}$ *occurs at* $\delta = 180 - \theta_s$

$$Q_{in} = \frac{V^2}{z_s}\sin\theta_s - \frac{VE_f}{Z_s}\sin(\theta_s + \delta)$$

On neglecting R_a:

$$Z_s = X_s; \theta_s = 90^\circ$$

$$P_{in} = \frac{VE_f}{X_s}\sin\delta$$

$$Q_{in} = \frac{V}{X_s}(V - E_f\cos\delta)$$

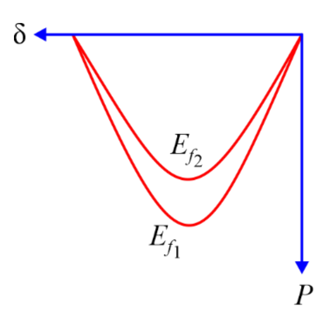
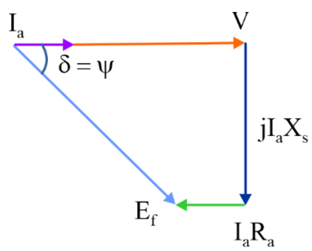
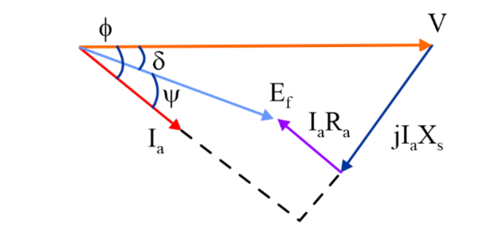
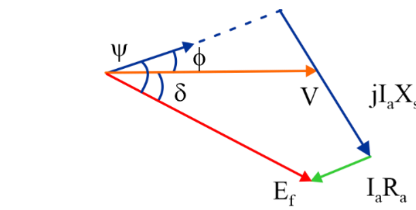


Fig. 3.10.

3.8. Phasor Diagram – Cylindrical Rotor Synchronous Motor

At UPF	At 0.8 PF lagging	At 0.8 PF leading
 $\psi = \delta = \tan^{-1}\left(\frac{I_a X_s}{V - I_a R_a}\right)$ $\lvert E_f \rvert = \sqrt{(V - I_a R_a)^2 + (I_a X_s)^2}$	 $\psi = \tan^{-1}\left(\frac{V\sin\phi - I_a X_s}{V\cos\phi - I_a R_a}\right)$ $\delta = \phi - \psi$ $\lvert E_f \rvert = \sqrt{(V\cos\phi - I_a R_a)^2 + (V\sin\phi - I_a X_s)^2}$	 $\delta = -\lvert\psi\rvert - \lvert\phi\rvert$ $\psi = \tan^{-1}\left(\frac{V\sin\phi + I_a X_s}{V\cos\phi - I_a R_a}\right)$ $\lvert E_f \rvert = \sqrt{(V\cos\phi - I_a R_a)^2 + (V\sin\phi + I_a X_s)^2}$

3.9. V – Curve

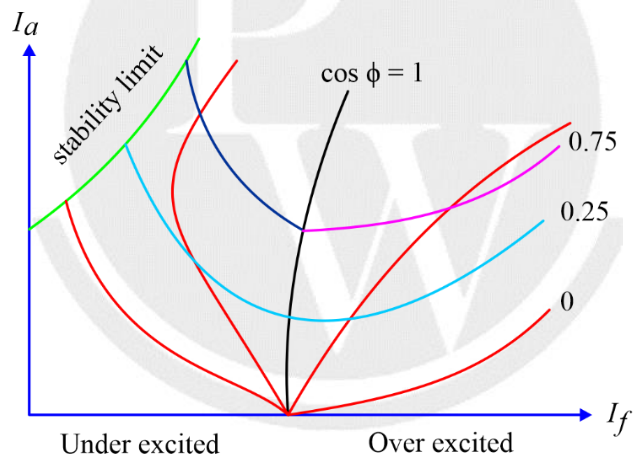


Fig. 3.11.

3.10. Inverse V – Curve

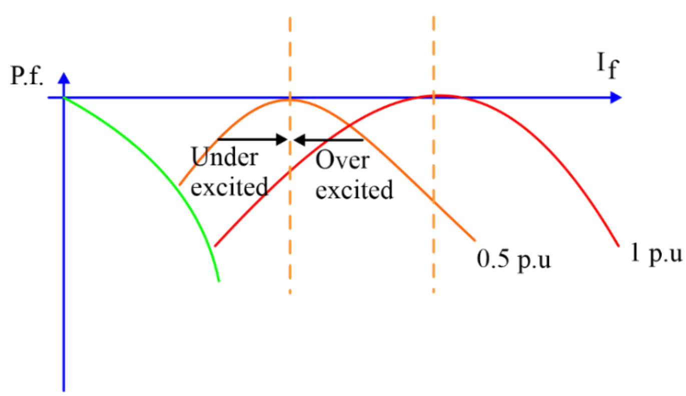


Fig. 3.12.

3.11. Methods to start Synchronous Motor

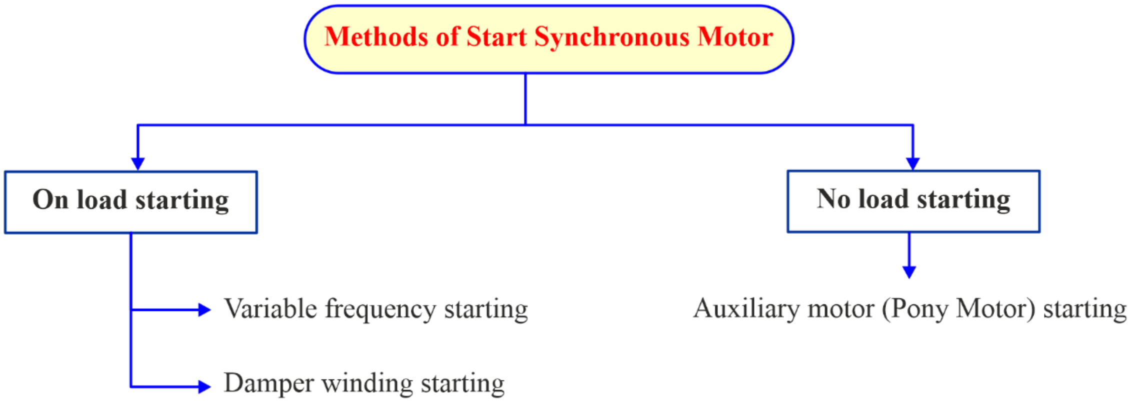


Fig. 3.13.

Voltage Regulation in Descending Order

Round rotor

Uniform air gap ($X_s = X_{ar} + X_1$)

Salient pole

Non uniform air gap ($X_d = X_{dr} + X_{ld}$ $X_q = X_{qr} + X_{lq}$)

Fig. 3.14.

3.12. Slip Test

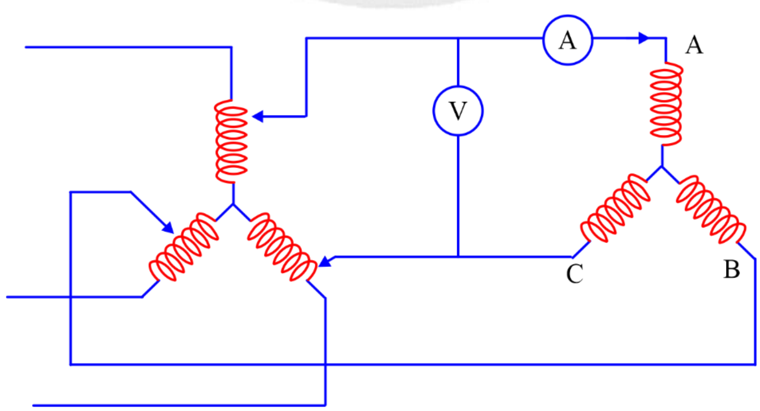
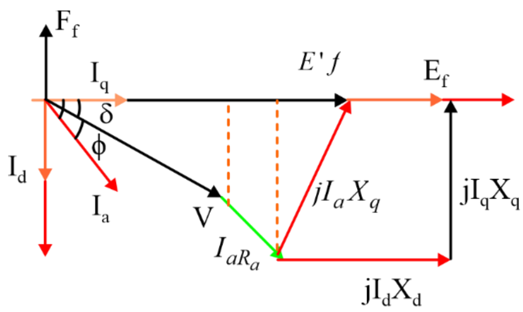
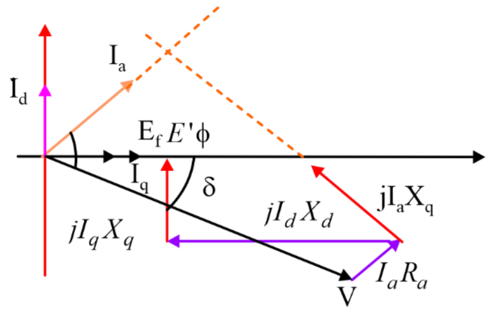


Fig. 3.15.

$$X_d = \frac{V_{max}}{I_{min}} \qquad X_q = \frac{V_{min}}{I_{max}}$$

Where V max and V min are phase voltages. I max and I min are phase currents.

3.13. Salient pole Synchronous Generator

Over-excited	Under-excited
 $\delta = \psi - \phi$	 $\delta = \phi - \psi$

$$E'_f = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi \pm I_aX_q)^2}$$

$$\psi = \tan^{-1}\left(\frac{V\sin\phi \pm I_aX_a}{V\cos\phi + I_aR_a}\right)$$

'+' sign is for Overexcited

'–' sign is for Under-excided

$$P_{out} = \frac{VE_f}{X_d}\sin\delta + \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

Per phase output power — Excitation power — Reluctance power

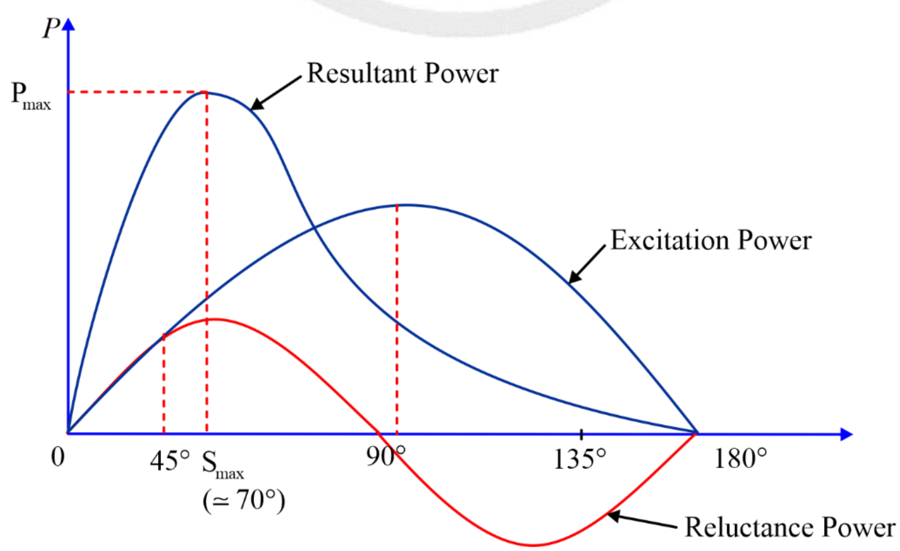
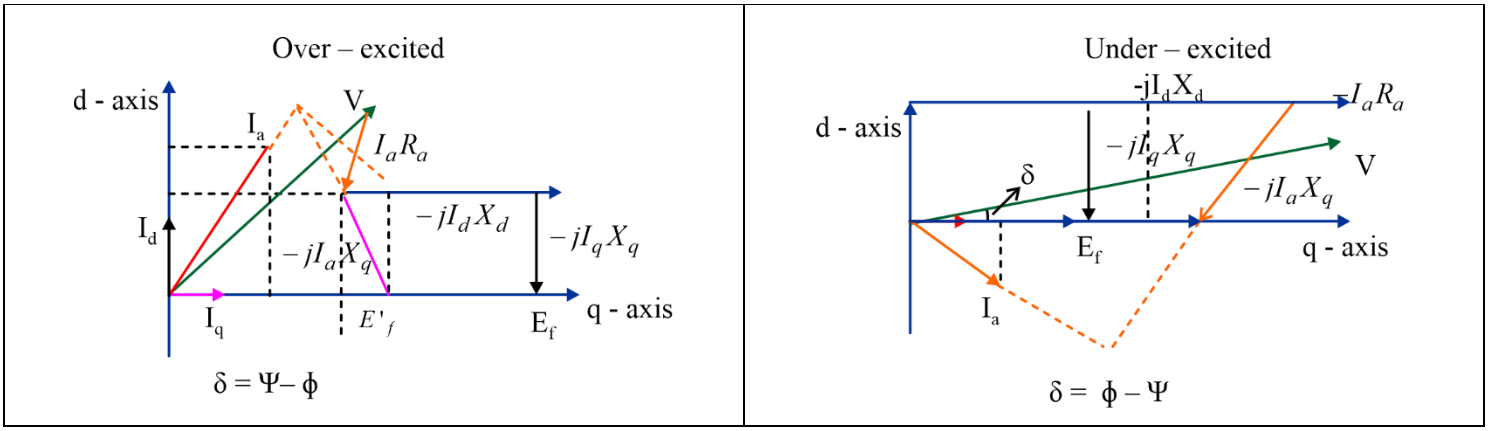


Fig. 3.16.

3.14. Salient pole Synchronous Motor



$$E'_f = \sqrt{(V\cos\Phi - I_aR_a)^2 + (V\sin\Phi \pm I_aX_q)^2}$$

$$\Psi = \tan^{-1}\left(\frac{V\sin\Phi \pm I_aX_q}{V\cos\Phi - I_aR_a}\right)$$

\+ For Overexcited generator

– For Under-excided generator

3.15. Methods for Synchronization

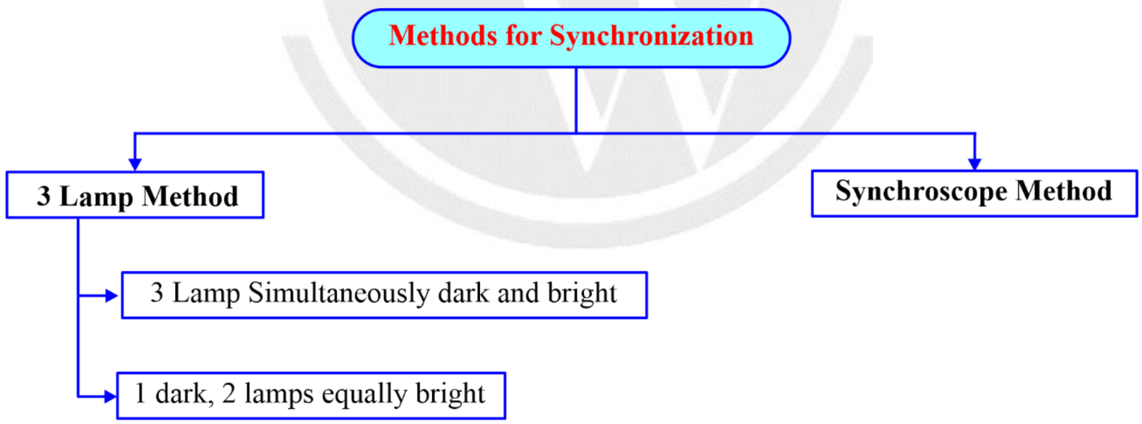


Fig. 3.17.

3.15.1. Synchronizing Power (P_{sy}) and Synchronizing Torque (τ_{sy})

For m – phase

$$P_{sy} = m \cdot \left[\frac{VE_f}{X_s}\cos\delta\right]\Delta\delta_{elect} \quad \text{(radian)}$$

$$P_{sy} = m \cdot \left[\frac{VE_f}{X_s}\cos\delta\right]\Delta\delta_{mech} \times \frac{P}{2} \times \frac{\pi}{180}$$

$$\tau_{sy} = \left[\frac{P_{sy}}{\omega_{sm}}\right]$$

3.15.2. Synchronizing Power Coefficient / Stability Factor / Rigidity/Stiffness of Coupling

Synchronizing power coefficient is the rate at which synchronous power varies with respect to load angle.

$$S_p = \frac{\partial P}{\partial \delta}$$

For round rotor machine

$$S_p = \frac{\partial}{\partial \delta}\left[\frac{VE_f}{X_s}\text{Sin}\delta\right] = \frac{VE_f}{X_s}\text{Cos}\delta$$

- If $\frac{\partial P}{\partial \delta} = +$ ve Machine is said to be stable.
- If $\frac{\partial P}{\partial \delta} = -$ ve Machine is said to be unstable.

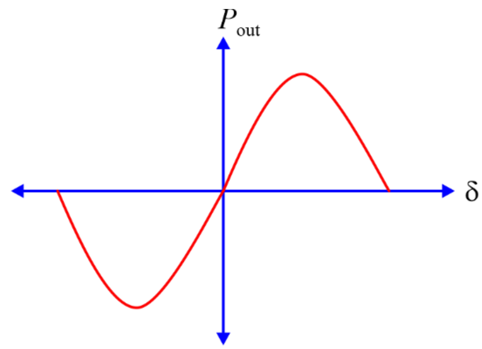


Fig. 3.18.

For salient pole machine

$$S_p = \frac{\partial P}{\partial \delta} = \frac{\partial}{\partial \delta}\left[\frac{VE_f}{X_s}\text{Sin}\delta + \frac{V^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\text{Sin}2\delta\right]$$

$$\boxed{S_p = \frac{VE_f}{X_s}\text{Cos}\delta + V^2\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\text{Cos}2\delta}$$

$$P_{sy} = S_p \cdot \Delta\delta$$

$$\boxed{\tau_{sy} = \left[\frac{P_{sy}}{\omega_{sm}}\right]}$$

3.16. Voltage Regulation

$$\text{Regulation} = \frac{E - V}{V} \times 100$$

Condition for zero voltage Regulation

Zero voltage regulation is possible only in leading power factors

$$\boxed{\text{Cos}(\theta + \phi) = -\frac{I_a Z_s}{2\text{ V}}}$$

Condition for Maximum voltage Regulation

Maximum voltage regulation is possible only at lagging power factors

$$\theta = \phi$$

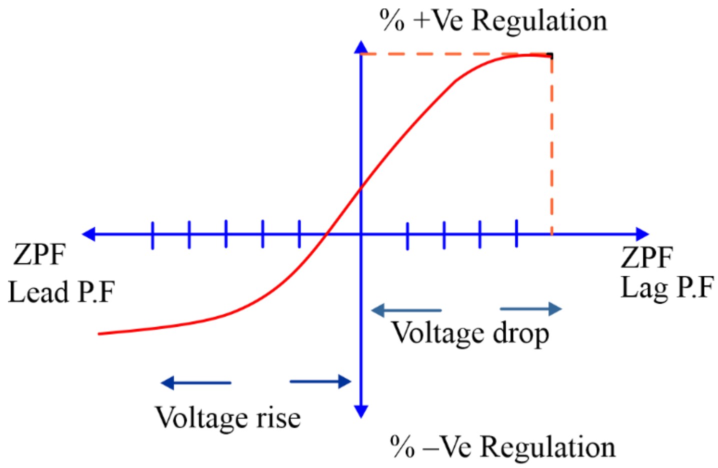


Fig. 3.19.

- The voltage regulation is always positive for unity and lagging power factor.
- The voltage regulation may be positive, zero or negative for leading power factor.

3.17. Voltage Regulation Methods

- EMF method/Synchronous impedance method
- MMF method/Rothert's Ampere Turns method
- Zero Power Factor(ZPF) method/Potier method
- American Standard Association method

Voltage Regulation in Descending Order

EMF method > Saturated synchronous method > ASA > ZPF > MMF

3.17.1. Short Circuit Ratio

$$\text{SCR} = \frac{\text{The main field current required to generate rated voltage under O.C condition}}{\text{The main field current required to generate reate armature current under S.C condition}}$$

$$\text{SCR} = \frac{I_{fm}}{I_{fa}} = \frac{1}{Z_S(\text{ Adjusted or saturated})\text{P.U}}$$

$$\text{SCR} = \frac{I_{fm}}{I_{fa}} = \frac{1}{X_S\ (\text{Adjusted or saturated})\text{P.U}}$$

$$\text{SCR} \propto \frac{1}{X_a} \propto \frac{1}{\text{Armature Reaction}}$$

$$X_a \propto \text{Armature Reaction}$$

$$\text{SCR} \propto \frac{1}{X_a} \propto \frac{1}{\text{Armature Reaction}} \propto \frac{1}{\text{Voltage Regulation}} \propto \frac{\text{air gap}}{\text{No.of turns per phase}}$$

❑❑❑

4 D.C. MACHINE

4.1. D.C. Machine

4.1.1. As a Generator

- When a conductor moves in a magnetic field, voltage is induced in the conductor.
- Fleming's right-hand rule is used to determine direction of induced e.m.f. for generating action.

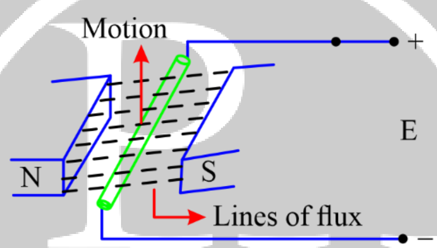


Fig. 4.1.

- The magnitude of induced e.m.f. is given by $E = Blv$.
- B = flux density
- l = active length of conductor
- v = relative velocity component of conductor in m/s in the direction perpendicular to direction of flux.

4.1.2. As a Motor

- When current carrying conductor is placed in a magnetic field, the conductor experiences a force.
- Fleming's left-hand rule is used to determine direction of force.

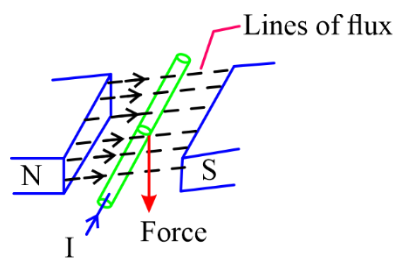


Fig. 4.2.

- The magnitude of force experienced by the conductor in a motor is given by F = B.I.L.
- B = flux density
- I = current through the conductor
- L = Active length of the conductor.

Note: -Polarity of induced e.m.f. depends upon the direction of motion in both Generator and Motor Action.

- For generator, the induced e.m.f. and current in a conductor are in the same direction.
- For motor the induced e.m.f. and current are in opposite to the flow of conductor current.

4.1.3. Commutator

It is made from a number of v-shaped hard drawn copper bar segments insulated from each other and from the shaft.

- Commutator is used to
  (i) Convert AC to D.C. or vice versa
  (ii) Keep the rotor or armature m.m.f. stationary in space.
- Voltage generated in armature coil of D.C. machine is of A.C. in nature. It becomes D.C. after being rectified by the commutator.
- Frequency of included e.m.f. in armature coil = $\frac{PN}{120}$

  Where N = speed of rotor and P = no. of poles.

4.2. Classification of DC Machines

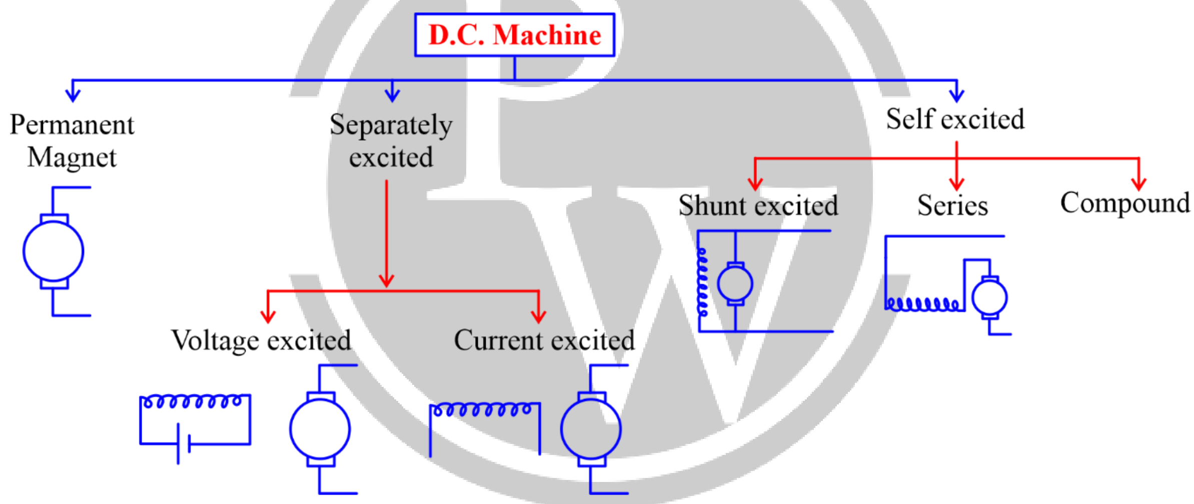


Fig. 4.3.

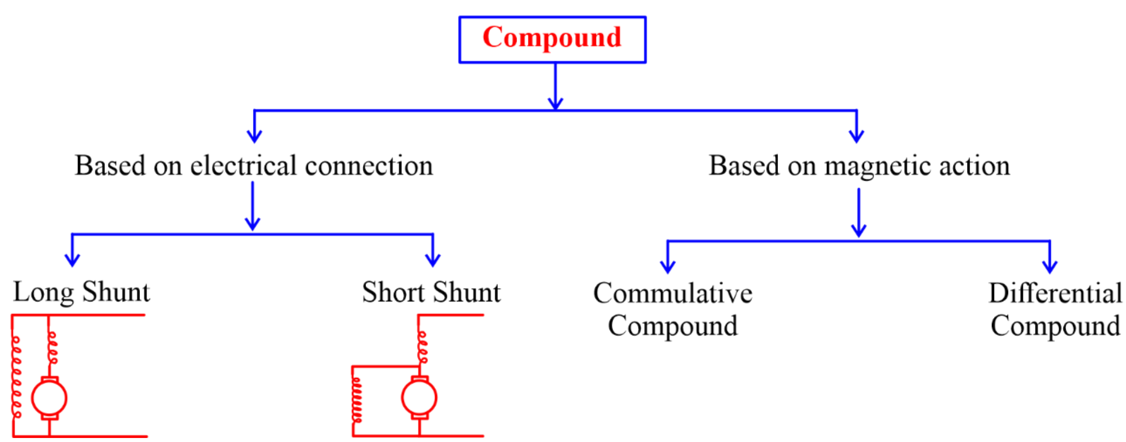


Fig. 4.4.

4.3. Induced e.m.f.

P = Number of poles
ϕ = Flux per pole
Z = Total number of conductors
N = Speed in r.p.m.
A = no. of parallel paths = 2 for wave
= P for Lap

- Flux cut by one conductor in one rotation = P ϕ
- Number of revolutions per second = $\frac{N}{60}$
- Flux cut by one conductor in one sec = $\frac{P\phi N}{60}$
- No. of conductor in sense per parallel path = $\frac{Z}{A}$
- EM.F. induced in armature = $\frac{P\phi Z.N}{60A}$

Note: $Ea = \frac{P.\phi Z.N}{60A} = \frac{P.Z\ \phi.N}{60A} = K\phi N$

$\because \quad w_m = \frac{2\pi N}{60} \qquad i.e., \quad N = 60\frac{w_m}{2\pi}$

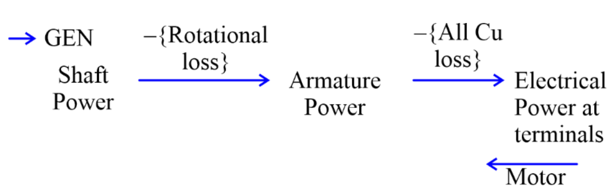
$\therefore \quad E_a = \frac{P.Z.\phi.w_m}{2\pi A} = K'\phi.w_m$

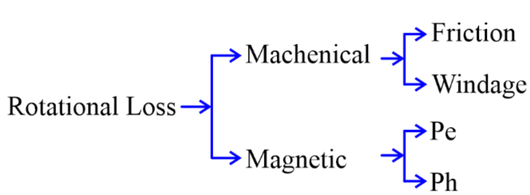
4.4. Torque Equation

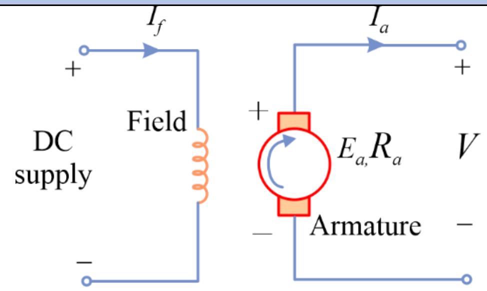
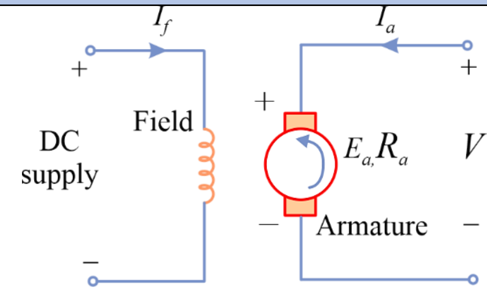
Let Armature current = I_a
Armature power developed "Pa" = E_a Ia = $\tau \times w_m$

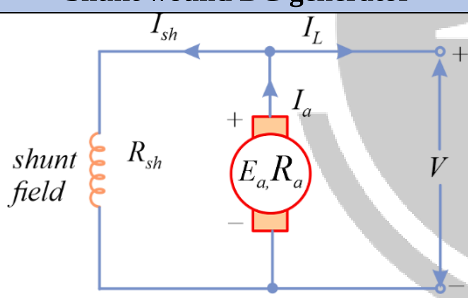
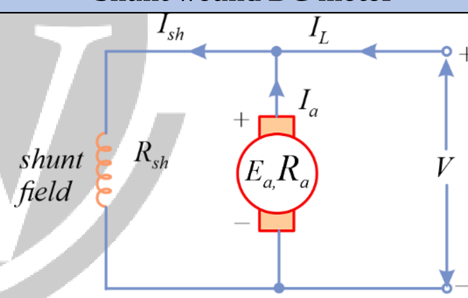
$$\tau = \frac{Ea.Ia}{w_m} = k'\phi I_a$$

4.5. Power balance in D.C. Machine

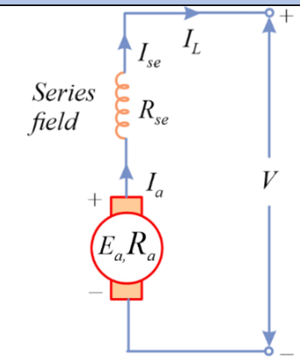


- 

Separately excited DC generator	Separately excited DC motor
	
$I_a = I_L$ $\quad E_a = V + I_a R_a$	$I_a = I_L$ $\quad E_a = V - I_a R_a$
$E_a I_a = VI_a + I_a^2 R_a = VI_L + I_a^2 R_a$ Armature power = Output power + Armature copper loss	$E_a I_a = VI_a - I_a^2 R_a = VI_L - I_a^2 R_a$ Armature power = Input power – Armature copper loss
Counter torque $\tau = \frac{E_a I_a}{w_m}$ $\tau = k'\phi I_a$	Motor Electromagnetic torque $\tau = \frac{E_a I_a}{w_m} = k'\phi I_a$ $N = \frac{V - I_a R_a}{k\phi}$ $T_{shaft} = \left[\frac{P_a - P_R}{w_m}\right]$

Shunt wound DC generator	Shunt wound DC motor
	
$I_a = I_L + I_{sh}$ $\quad I_{sh} = \frac{V}{R_{sh}}$ $\quad E_a = V + I_a R_a$	$I_a = I_L - I_{sh}$ $\quad I_{sh} = \frac{V}{R_{sh}}$ $\quad E_a = V - I_a R_a$
$E_a I_a = VI_a + I_a^2 R_a = V(I_L + I_{sh}) + I_a^2 R_a = VI_L + VI_{sh} + I_a^2 R_a$ $E_a I_a = VI_L + I_{sh}^2 R_{sh} + I_a^2 R_a$ Armature power = Output power + Shunt field copper loss + Armature copper loss	$E_a I_a = VI_a + I_a^2 R_a = V(I_L - I_{sh}) - I_a^2 R_a = VI_L - VI_{sh} - I_a^2 R_a$ $E_a I_a = VI_L - I_{sh}^2 R_{sh} - I_a^2 R_a$ Armature power = Input power – Shunt field copper loss – Armature copper loss
Counter torque $\tau = \frac{E_a I_a}{w_m} = k'\phi I_a$ $\tau = k'\phi I_a$	Motor Electromagnetic torque $\tau = \frac{E_a I_a}{w_m} = k\phi I_a$ $N = \frac{V - I_a R_a}{k\phi}$ $T_{shaft} = \frac{P_a - P_R}{w_m}$

<table>
<tr><th>DC series generator</th><th>DC series motor</th></tr>
<tr><td>



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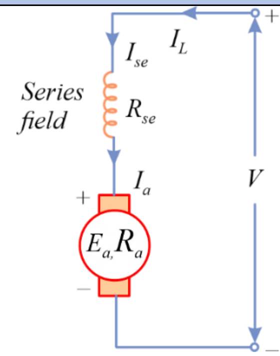

</td></tr>
<tr><td>$I_a = I_{se} = I_L \qquad E_a = V + I_a(R_a + R_{se})$</td><td>$I_a = I_{se} = I_L \qquad E_a = V - I_a(R_a + R_{se})$</td></tr>
<tr><td>

$$E_a I_a = VI_a + I_a^2(R_a + R_{se}) = VI_L + I_{se}^2 R_{se} + I_a^2 R_a$$

Armature power = Output power + Series field copper loss + Armature copper loss

</td><td>

$$E_a I_a = VI_a - I_a^2 R_a - I_a^2 R_{se} = VI_L + I_{se}^2 R_{se} - I_a^2 R_a$$

Armature power = Input power – Series field copper loss – Armature copper loss

</td></tr>
<tr><td>

Counter torque

$$\tau = k'\phi I_a$$

</td><td>

Motor Electromagnetic torque

$\tau = k'\phi I_a$

$$N = \frac{V - I_a(R_a + R_{se})}{k\phi}$$

(unsaturated) or linear magnetizationon neglecting losses

$$N \propto \left(\frac{V}{I_a}\right)$$

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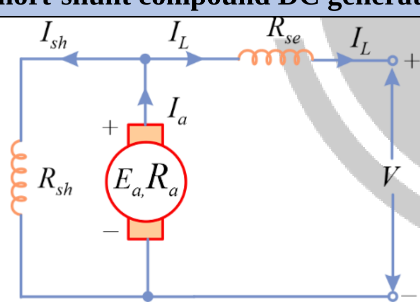
</table>

<table>
<tr><th>Short-shunt compound DC generator</th><th>Short-shunt compound DC motor</th></tr>
<tr><td>



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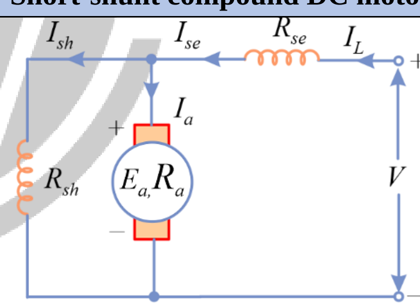

</td></tr>
<tr><td>$I_a = I_{sh} + I_{se} = I_{sh} + I_L \qquad E_a = V + I_{se}R_{se} + I_a R_a$</td><td>$I_a = I_{se} - I_{sh} = I_L - I_{sh} \qquad E_a = V - I_{se}R_{se} - I_a R_a$</td></tr>
</table>

<table>
<tr><th>Long-shunt compound DC generator</th><th>Long – shunt compound DC motor</th></tr>
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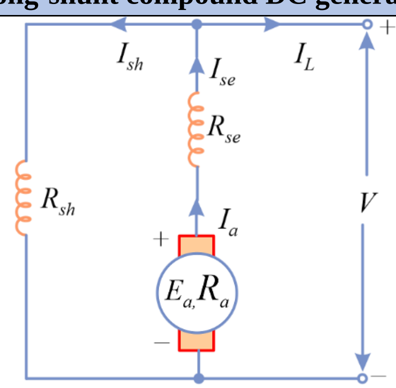

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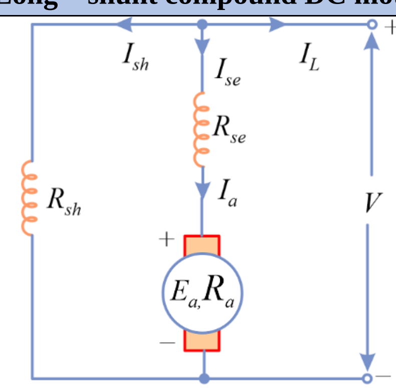

</td></tr>
</table>

$I_a = I_{se} = I_L + I_{sh}$	$I_a = I_{se} = I_L + I_{sh}$
$E_a = V + I_{se}R_{se} + I_aR_a = V + I_a\left(R_a + R_{se}\right)$	$E_a = V - I_{se}R_{se} - I_aR_a = V - I_a\left(R_a + R_{se}\right)$
$E_aI_a = VI_a + I_a^2R_a + I_a^2R_{se}$ $= V\left(I_L + I_{sh}\right) + I_a^2R_a + I_{se}^2R_{se}$ $= VI_L + VI_{sh} + I_{se}^2R_{se} + I_a^2R_a$ $E_aI_a = VI_L + I_{sh}^2R_{sh} + I_{se}^2R_{se} + I_a^2R_a$ Armature power = Output power + Shunt field copper loss + series field copper loss + Armature copper loss	$E_aI_a = VI_a - I_a^2R_a - I_a^2R_{se}$ $= V\left(I_L - I_{sh}\right) - I_a^2R_a - I_{se}^2R_{se}$ $= VI_L - VI_{sh} - I_{se}^2R_{se} - I_a^2R_a$ $E_aI_a = VI_L - I_{sh}^2R_{sh} - I_{se}^2R_{se} - I_a^2R_a$ Armature power = Input power – Shunt field copper loss – series field copper loss – Armature copper loss

4.6. D.C. Generator and Motor Characteristics

The main characteristics of a DC generator are:

1. **Magnetization characteristics or no load characteristics** gives the variation of generated voltage or no load voltage with field current at a constant speed.
2. **Internal characteristics** is the plot between the generated voltage and load current.
3. **External characteristics** is the plot between the terminal voltage and load current.

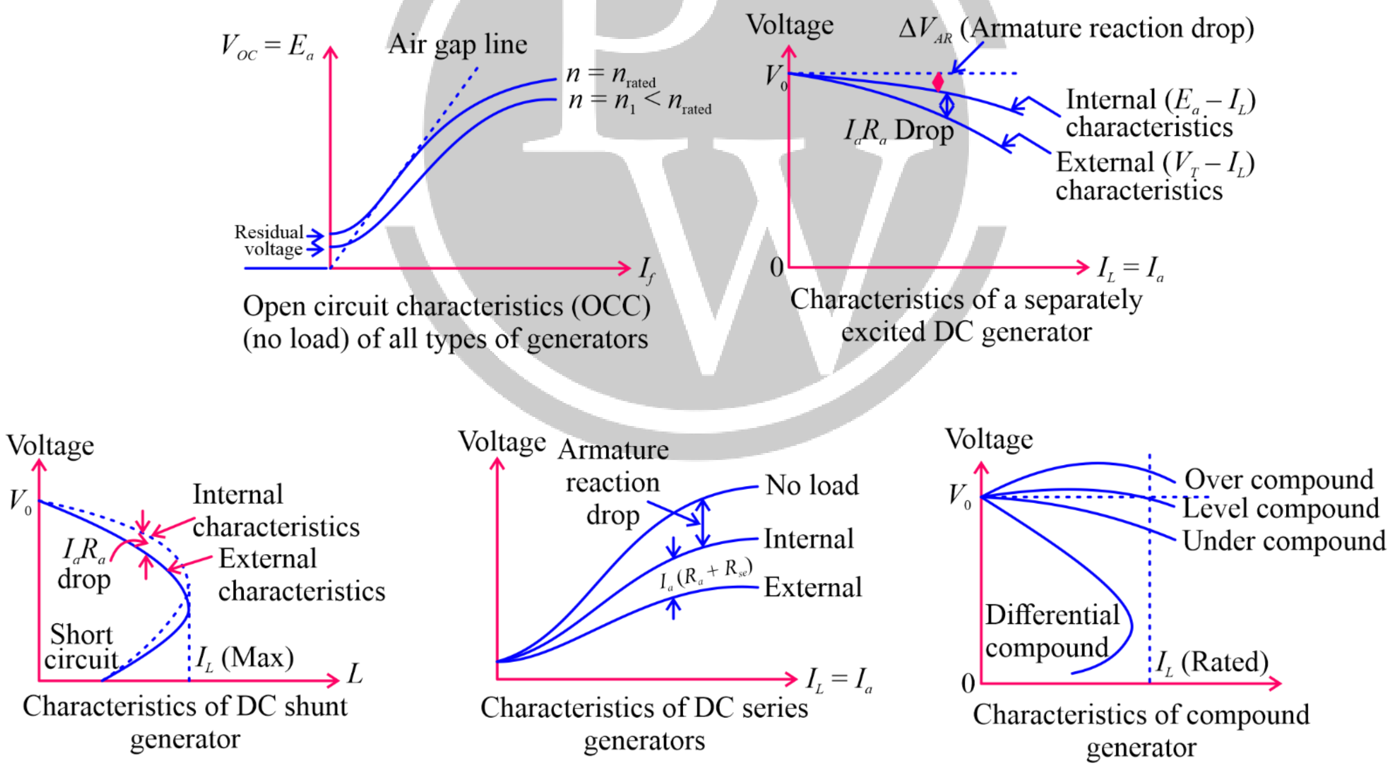

Fig. 4.5.

4.6.1. Shunt Motor Characteristics

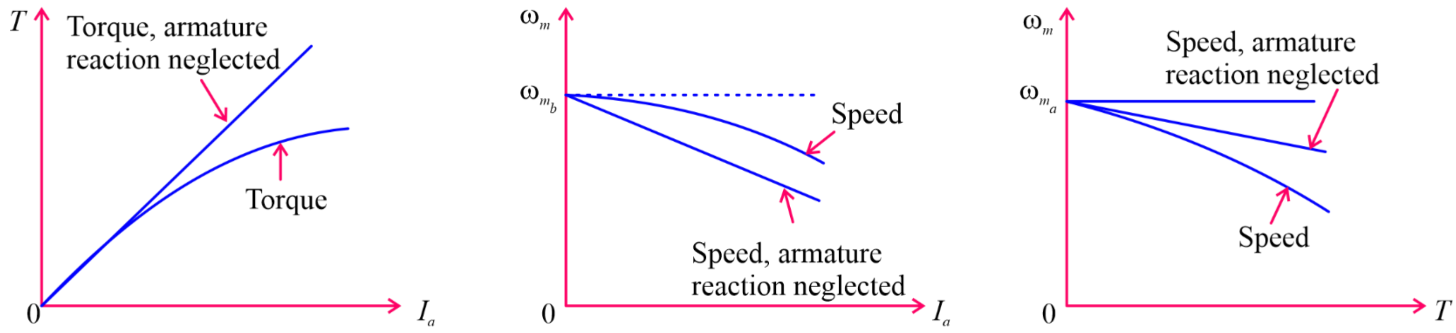

Fig. 4.6.

4.6.2. Series Motor Characteristics

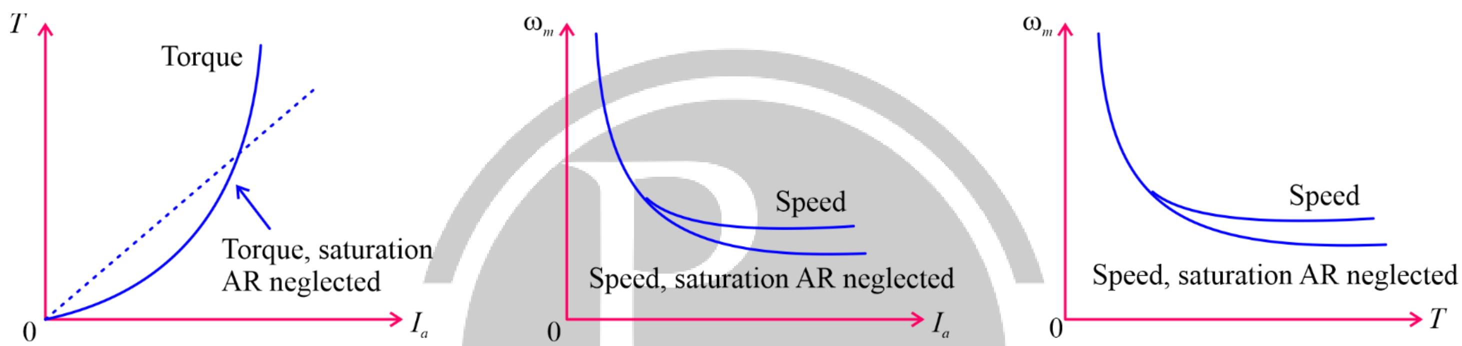

Fig. 4.7.

4.6.3. Compound Motor Characteristics

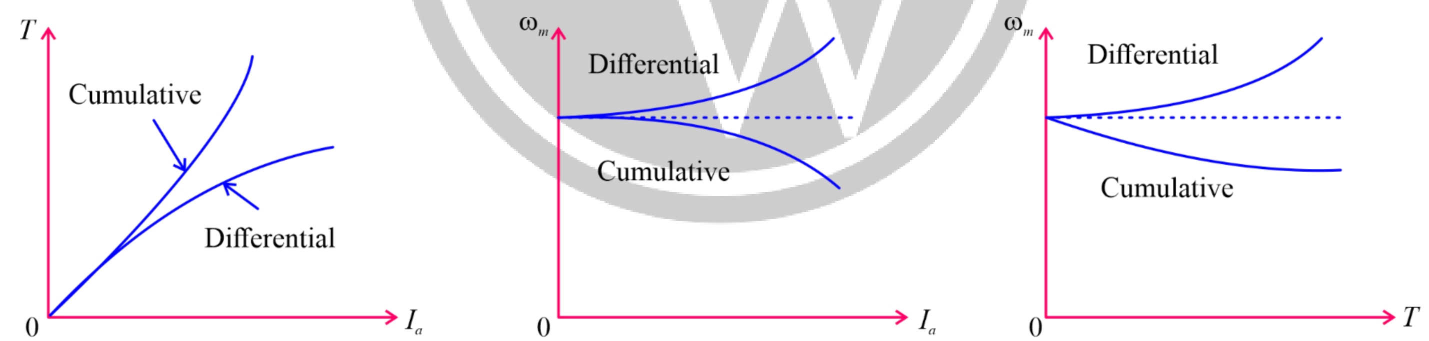

Fig. 4.7.

4.7. Voltage build up in DC generators

A DC shunt generator is developing rated voltage at some speed.

1. Direction of rotation is reversed.

$$+E_a \longrightarrow -E_a \qquad -E_a \longrightarrow +E_a$$

2. Field connections are reversed.

$$+I_F \longrightarrow -I_F \qquad -I_F \longrightarrow +I_F$$

3. Residual magnetism is reversed.

$$+E_a \longrightarrow -E_a \qquad -E_a \longrightarrow +E_a$$

$$+I_F \longrightarrow -I_F \qquad -I_F \longrightarrow +I_F$$

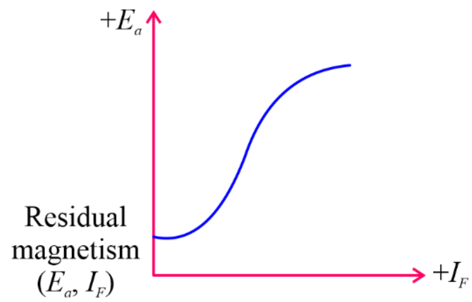

Fig. 4.8.

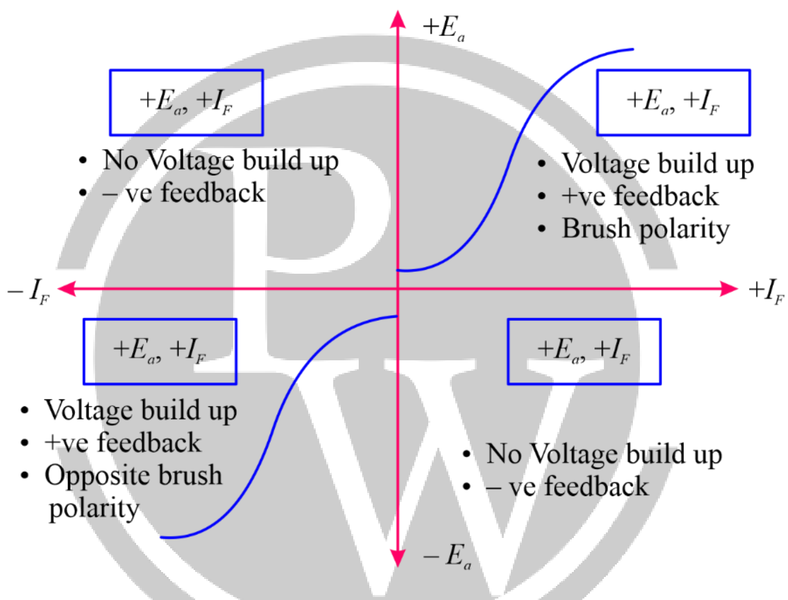

Fig. 4.9.

$+E_a, +I_F$

1. If only the direction of rotation is reversed then voltage will not build up [$-E_a$, $+I_F$]
2. If only the field terminals are reversed then voltage will not build up [$+E_a$, $-I_F$]
3. If both the direction of rotation and field terminals are reversed then voltage will build up but with opposite brush polarity [$-E_a$, $-I_F$].
4. If only residual magnetism is reversed then voltage will build up with opposite brush polarity [$-E_a$, $-I_F$].
5. If direction of rotation and residual magnetism are reversed, then voltage will not build up [$+E_a$, $-I_F$].
6. If field terminal and residual magnetism and reversed, then voltage will not build up [$-E_a$, $+I_F$].
7. If direction of rotation, field connection and residual magnetism are reversed then voltage will build up with same brush polarity [$+E_a$, $+I_F$].

When field connections are reversed w.r.t. armature circuit or vice versa then voltage does not build up due to negative feedback.

Remedies:

1. Reverse only field connection, or
2. Reverse only direction or rotation.

4.8. Efficiency of D.C. Machine

$$\eta = \frac{\text{output}}{\text{output + Losses}}$$

No-load rotational loss, $P_{R(NL)} = E_{a(NL)} \bullet I_{a(NL)}$

$$\text{If } E_{a(nL)} = V_T - I_{a(NL)} R_a \text{ then}$$

$$P_{R(NL)} = [V_T - I_{a(nL)} \bullet R_a] I_{a(nL)}$$

4.8.1. Condition for Maximum Efficiency

$$\text{Variable loss} = \text{Constant loss}$$

$$P_v = I_a^2 (R_a + R_{se}) = I_a^2 R'$$

$$P_k = P_i + P_{wf} + P_{sh}$$

$$= P_R + I_f^2 R_f$$

$$\boxed{I_a = \sqrt{\frac{P_k}{R'}}}$$ Current at maximum efficiency

Note: Name plate power rating for both generator and motor is output power.

4.9. Armature Reaction in D.C. Machine

The effect of armature flux (rotor flux) on main field flux (stator flux) is called armature reaction.

Undesirable effects

(i) Net reduction in the main field flux per pole

(ii) Distortion of the main field flux wave along the airgap periphery.

(iii) Armature reaction establishes a flux in the neutral zone. This will induce a voltage in a coil undergoing commutation.

(iv) The flux wave is distorted and there is shift in the position of the magnetic neutral axis (M.N.A.) in the direction of rotation for generator and against the direction of rotation for motor action.

Note: -M.NA is always perpendicular to the axis of resultant field axis.

- Brushes are always placed along M.N.A.
- MNA at no-load coincides with G.N.A.

4.9.1. Flux distribution and flux density wave form

(i) Air gap flux density wave at no-load is FLAT TOPPED (due to main field only)

(ii) Air gap flux density wave due to armature current is triangular in shape.

(iii) The resultant flux density wave depends upon saturation and it is trapezoidal in shape.

(iv) If brushes are shifted to appropriate angle, then the resultant flux density is flat topped wave.

4.9.2. Demagnetising and Cross Magneting Ampere Turns

- F_{ar} (demagnetising) = $\left[\frac{Z/2}{P} \times \frac{2\beta_{electrical}}{180} \times \frac{I_a}{A}\right]$
- F_{ar} (Cross-magnetising) = $\frac{Z/2}{P} \cdot \left[1 - \frac{2\beta_{electrical}}{180}\right] \times \frac{I_a}{A}$

Note: $\theta_{electrical} = \frac{P}{2}\theta_{mechanical}$

4.9.3. Commutation

- Reversal of current in armature coil along brush axis during the time of short circuit by the brush.

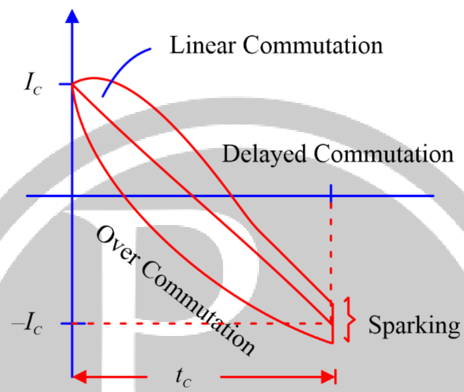

Fig. 4.10.

t_c = time period of commutation

$$= \frac{\text{Brush width}(w_d)}{\text{Commutation peripheral speed}}$$

$$= \left[\frac{w_d}{\pi DN/60}\right] \quad \begin{Bmatrix} \text{D = Commutator dia} \\ \text{N = Speed in r.p.m.} \end{Bmatrix}$$

4.9.4. Remedies For Armature Reaction

(1) Cross magnetising effect can be reduced by using high reluctance pole tips.

(2) Cross magnetising effect can be compensated by compensating winding Compensating windings are placed in axial slot of pole face and carries armature current in the direction opposite to that of armature conductors under pole arm.

- $F_{c.w.} = \left[\frac{Z/2}{P} \times \left(\frac{\text{Pole arc}}{\text{Pole pitch}}\right) \times \frac{I_a}{A}\right]\left(\frac{\text{AT}}{\text{Pole}}\right)$ = Number of turns of compensating winding per pole × I_a

(3) The cross-magnetising effect under the interpolar region can be neutralized by using the interpoles.

- Interpole is use to eliminate the effect of reactance voltage by generating the equal and opposite rotational voltage in a coil undergoing commutation.
- Commutation provided by interpole is called voltage commutation.
- The polarities of interpole are the same as the succeeding main pole in generator action and preceding main pole in motor action.
- Interpole carries armature current and are placed in interpolar region.

$$F_{ar\,(inter\,pole)}\text{ per pole} = \frac{Z/2}{P}\times\left[1-\frac{\text{Pole arc}}{\text{Pole pitch}}\right]\times\frac{I_a}{A}\times\frac{B_i}{\mu_0}\times l_{(gap)}$$

Where B_i = flux density in interpolar region

$$\mu_0 = 4\pi\times10^{-7}\text{ H/m}$$

l_{gap} = gap between interpole and armature conductor in interpolar region.

4.10. Speed Control of D.C. Motor

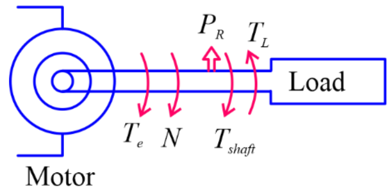

Fig. 4.11.

Note: If rotational loss ($P_R = 0$) neglected, then $T_e = T_L$ under steady state condition.

$$E_a = k'\phi\, w_m = V - I_a R_a$$

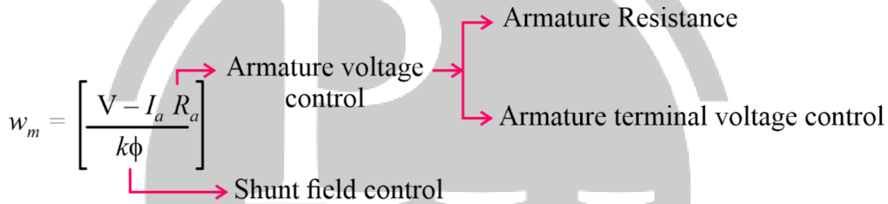

Fig. 4.12.

$$\frac{N_2}{N_1} = \left(\frac{V_2 - I_{a_2}R_{a_2}}{V_1 - I_{a_1}R_{a_1}}\right)\times\left[\frac{\phi_1}{\phi_2}\right]$$

Note: First find current from torque expression then substitute in speed expression to solve speed control questions.

4.11. Torque and Power Limits

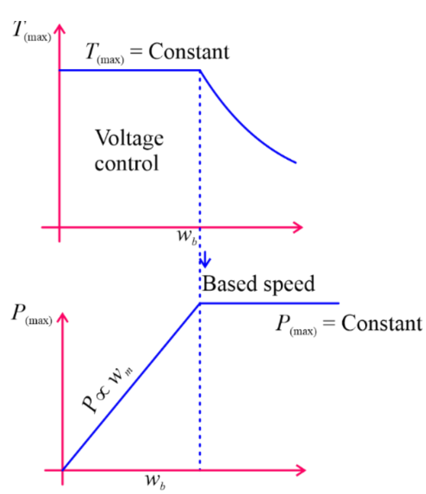

Fig. 4.13.

4.12. Testing of DC Machines

Testing of DC Machines

- Direct or Block Rotor
- Indirect Swinburn's Method
- Regenerative or Hopkinson's Method

4.13. Braking in DC Machines

Braking

- Regenerative
  - $\uparrow E_a \propto \phi \uparrow$
  - $E_a > v_T$
- Plugging
  - Armature terminals are reversed
  - Plugging voltage $= V + E_a$
  - $V + E_a = I_a (R_a + \text{Rext})$
  - Rext = current limiting resistor
- Dynamic
  - Supply is switched off and load is connected at output terminals

For more questions, kindly visit the library section: Link for web: https://smart.link/sdfez8ejd80if

PW Mobile APP: https://smart.link/7wwosivoicgd4