EE8401 ELECTRICAL MACHINES – II

UNIT - 2 SYNCHRONOUS MOTOR

Starting Methods of Synchronous Motor

1. **Explain the various starting methods of a Synchronous Motor.**

Introduction

Synchronous motor is not self starting. So it is necessary to rotate the rotor at a speed very near to synchronous speed. The various method to start a synchronous motor are,

1. Using Pony motor
2. Using damper winding
3. As a slip ring induction motor
4. Using small d.c machine coupled to it.

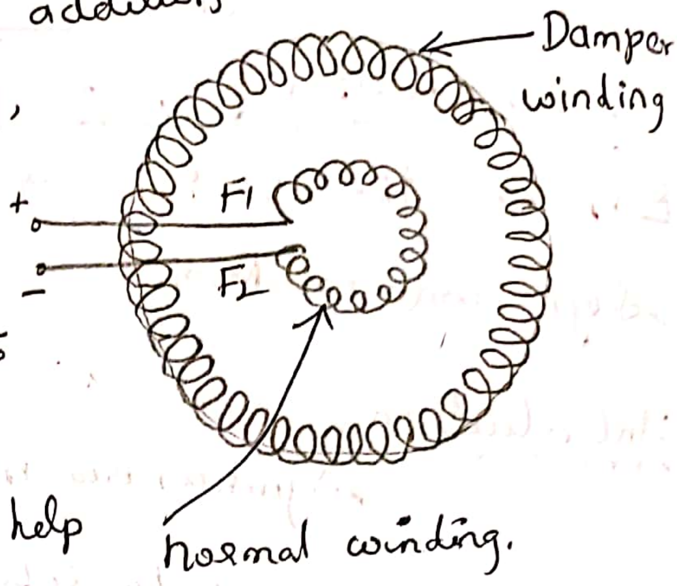
(i) **Using Pony Motor**

In this method the rotor brought to synchronous speed with the help of some external device like small induction motor. Such a external device is called 'pony motor'.

As the rotor attains the synchronous speed, the dc excitation to the rotor is switched on. Once synchronism is established pony motor is decoupled.

Using damper winding

In Synchronous motor, in addition to the normal field winding, the additional winding consisting of copper bars placed in the slots in the pole faces. The bars are short circuited with the help of end rings



Such an additional winding on the rotor is called damper winding. This winding acts as a squirrel cage rotor winding of an induction motor.

Once the stator is excited by a 3ϕ supply, the motor starts rotating as an induction motor. then dc supply is given to the field winding. At a particular instant motor gets pulled in to synchronism and starts rotating at a syn. speed.

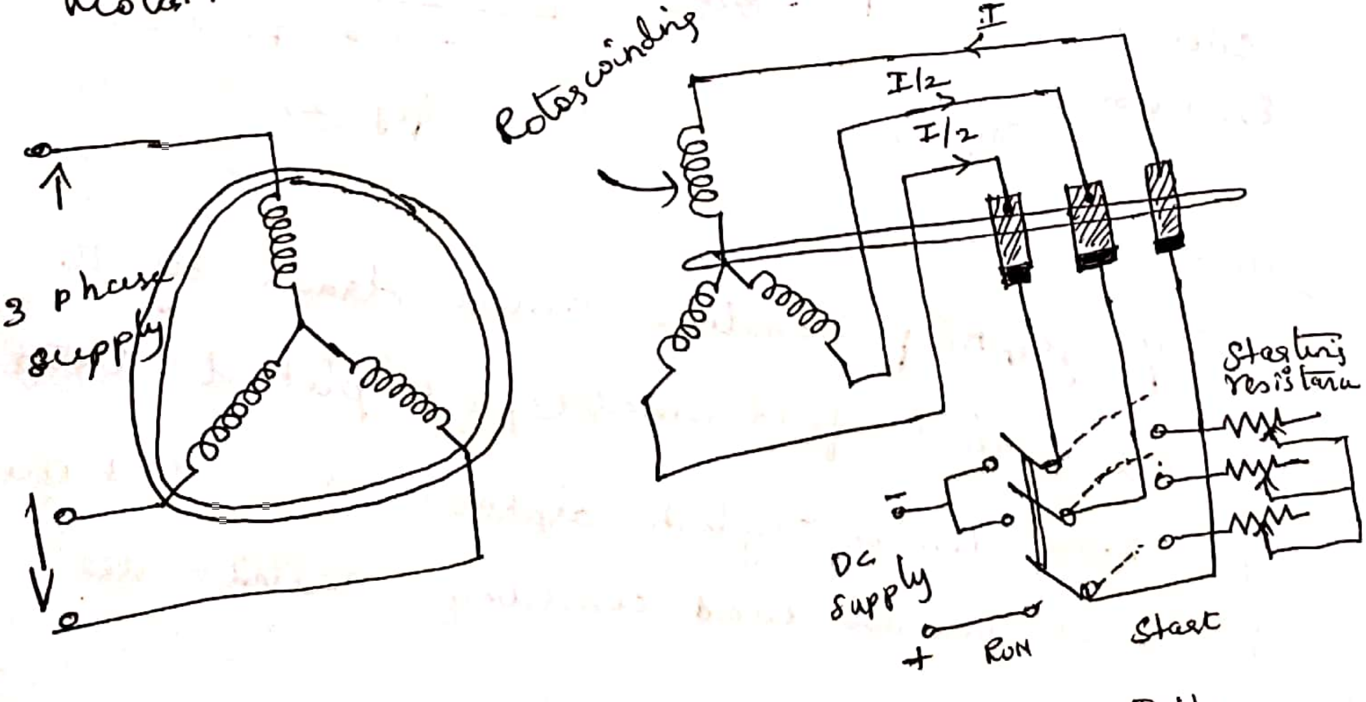
(iii) As a slip Ring Induction Motor:-

Starting a synchronous motor as a squirrel cage induction motor does not provide high starting torque. So to acheive this instead of

Shorting the damper winding, designed to form a 3Φ star or delta connected winding the ends are brought out through slip ring.

So when the stator is excited the motor starts as a slip ring induction motor and provides high starting torque. The resistance is then gradually cut-off as motor gathers speed.

When the motor gathers the speed near to synchronous speed dc excitation is provided to the rotor and the motor pull in to synchronism and starts rotating at synchronous speed. The synchronous motor started by this method is called a slip ring induction motor.



TP DT SWITCH.

2. V- Curves and Inverted V- Curves

* Draw the V and Inverted V curves and explain the effect of excitation on armature current and power factor of synchronous motor.

In Synchronous Motor if the excitation is varied from very to very high value, the armature current I_a decreases becomes minimum at unity pf and then again increases as shown in fig.(1)

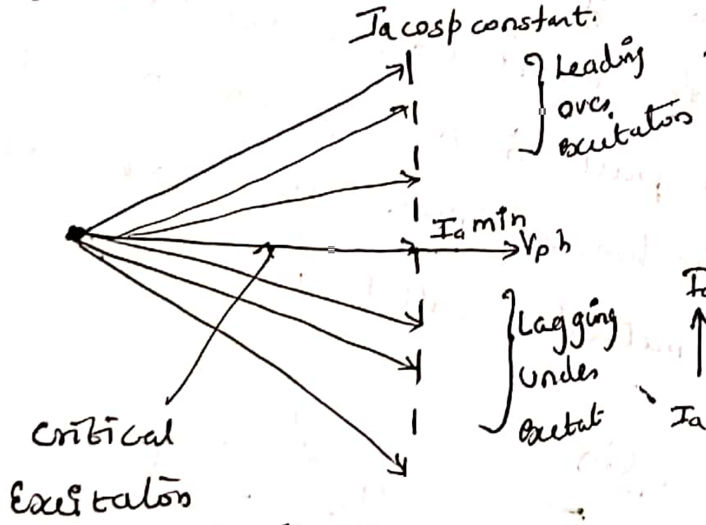


Fig (1)

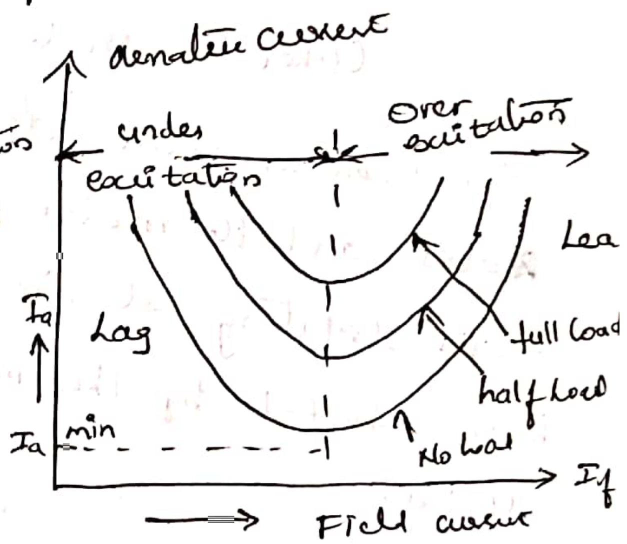


fig (2)

V curve

If graph of armature current drawn by the motor (I_a) against field current (I_f) is plotted, then its shape looks like an english alphabet 'V'. Such curve obtained at various load conditions, called the 'V curve shown in fig (2)

Inverted V curve

If the graph is plotted between power factor and field current (I_f) then the shape of the graph looks like an inverted 'V'. Such curve is called Inverted 'V' curve as shown in fig (3).

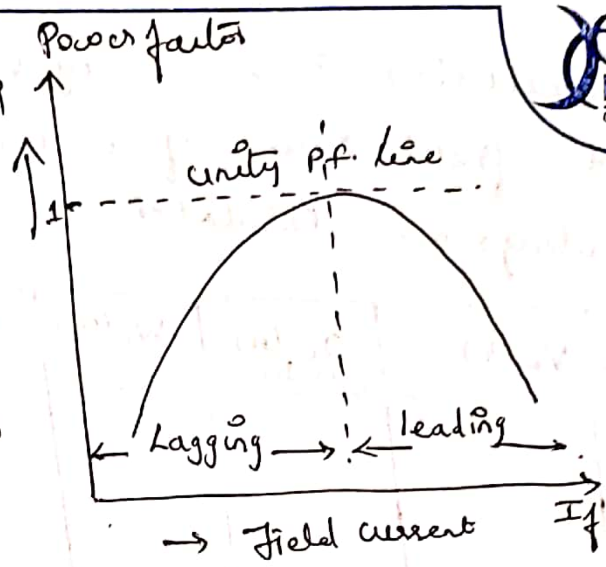
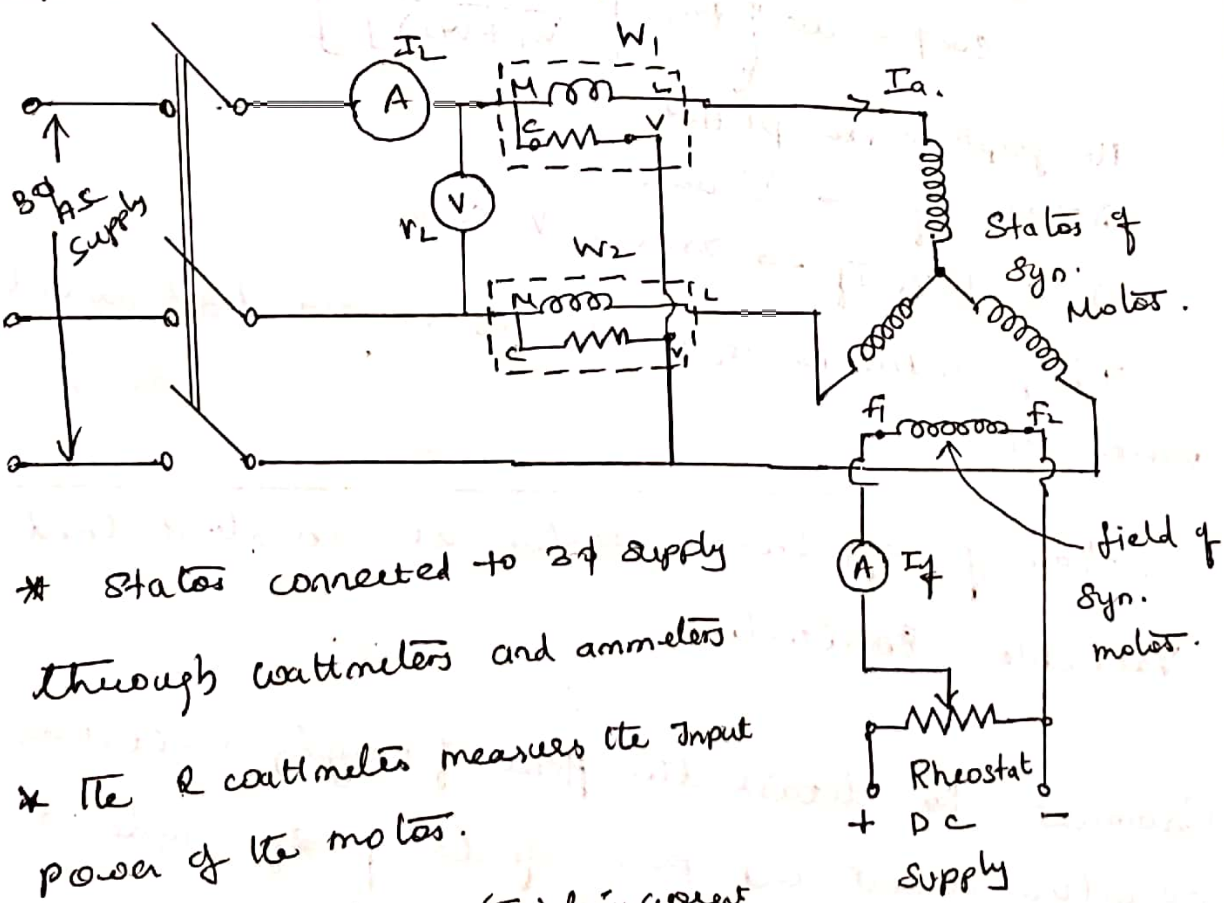


Fig (3)

Experimental set up to obtain V-curve



* Stator connected to 3ϕ supply through wattmeters and ammeters.
* The 2 wattmeters measures the input power of the motor.
* Ammeter reads the (I_L) line current same as the armature current (I_a)

* Excitation is varied by varying the rheostat and field current I_f is noted from Ammeter & readings are tabulated.

S.No.	V_L (V)	I_L (A) (or) I_a	W_1 (W)	W_2 (W)	I_f (A)	$\cos\phi$ (Pf)

$I_L = I_{aph}$ for Star connection

$\frac{I_L}{\sqrt{3}} = I_{aph}$ for Δ connection.

Power factor is calculated as

$$\cos\phi = \cos\left\{\tan^{-1}\left[\frac{\sqrt{3}(W_1 - W_2)}{(W_1 + W_2)}\right]\right\}$$

The graph can be plotted.

1) I_a Vs I_f → V curve.

2) $\cos\phi$ Vs I_f → Inverted V- curve.

The procedure is repeated for various load conditions various pf.

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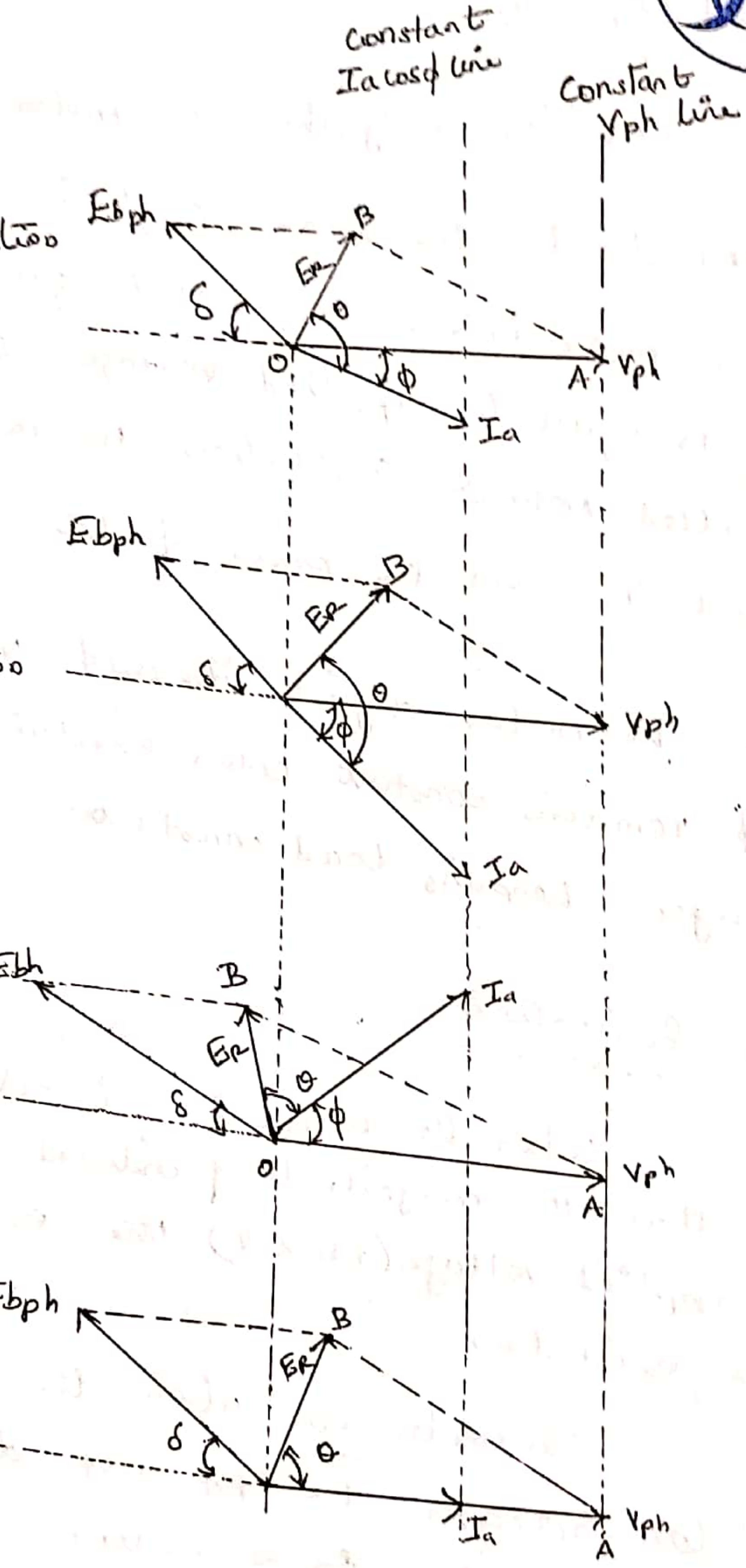
3. Operation of Synchronous Motor at constant load variable excitation.

Enumerate in detail the effect of varying excitation armature current and power factor of syn. motor.?



(a) Normal excitation

$E_{bph} = V_{ph}$

lagging pf

(b) Under excitation

$E_{bph} < V_{ph}$

more lagging pf

I_a increases

(c) Over excitation

$E_{bph} > V_{ph}$

leading pf.

(d) Critical excitation

$E_{bph} = V_{ph}$

unity pf

I_a is minimum

II

Normal Excitation

Consider a synchronous motor operating at a certain load. The load angle is δ. . At start when excitation is adjusted to get $E_b = V$ ie induced emf is equal to applied voltage such excitation is called normal Excitation. The motor draws a certain current I_a and the power factor is lagging in nature.

The motor adjust its $\cos\phi$ value so that $I_a \cos\phi$ remains constant. when excitation of the motor changes keeping load constant.

Under Excitation:-

When the excitation is adjusted in such a way that the magnitude of induced emf is less than the applied voltage ($E_b < V$) the excitation is called under excitation

In under excitation the current drawn by the motor increases. The p.f $\cos\phi$ decreases and become more and more lagging in nature.

E_R shift in such a way to keep $I_a \cos\phi$ constant.

Over Excitation:-

The excitation to the field winding for which the induced emf becomes greater than applied voltage ($E_b > V$) is called Over Excitation

Due to increased magnitude of E_b, E_R also increases in magnitude, E_R also change $E_R \wedge I_a = \theta$ is constant. Ia also changes its phase so ϕ changes. Ia increases to keep $I_a \cos\phi$ constant.

So power factor becomes leading in nature. Pf decreases as over excitation increases but it becomes more and more leading in nature.

Critical Excitation.

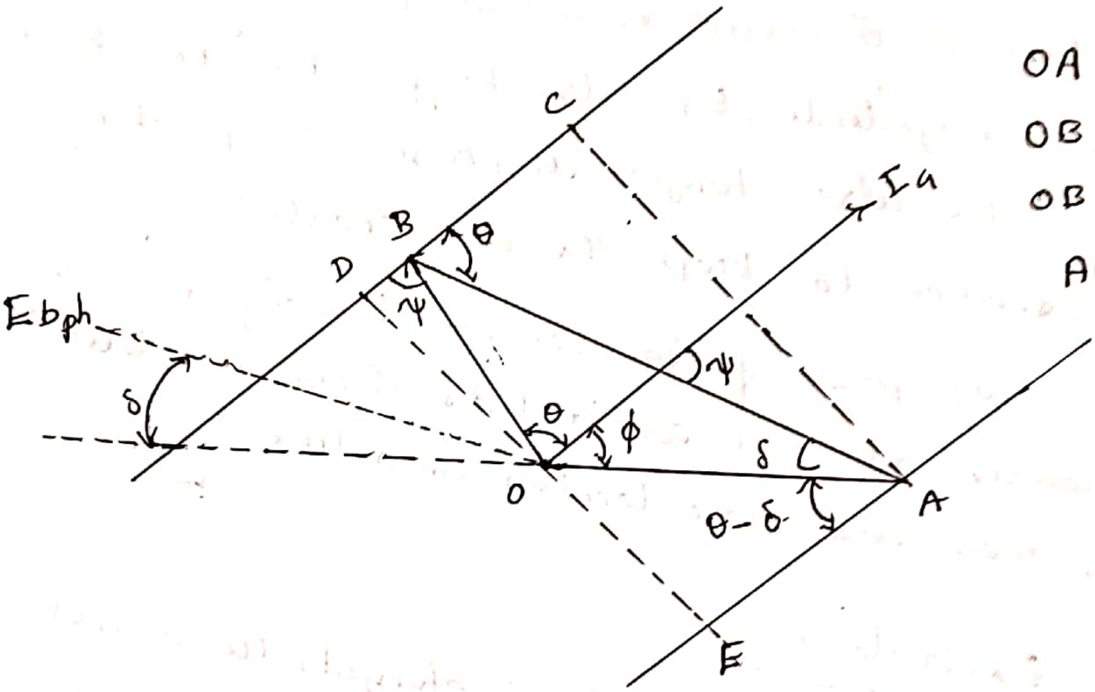
When the excitation is changed, the power factor changes. The excitation for which the power factor of the motor is unity ($\cos\phi = 1$) is called critical Excitation

Then Iaph is in phase with Vph., Now $I_a \cos\phi$ must be constant and $\cos\phi = 1$. so for critical Excitation current drawn by motor is minimum.

Under Excitation	Lagging Pf	$E_b < V$
Over Excitation	Leading Pf	$E_b > V$
Critical Excitation	unity Pf	$E_b \cong V$
Normal Excitation	Lagging Pf	$E_b = V$.

4. Alternative Expression for power developed, by a synchronous Motor.

Derive an expression for the power, maximum Torque developed per phase of a synchronous Motor.



$OA = V_{ph}$.
$OB = E_{Rph}$
$OB = I_a Z_s$
$AB = E_{bph}$.

Consider a phasor diagram of a Synchronous motor running on leading power factor $\cos\phi$.

The line CD is drawn at an angle θ to AB
The lines AC & DE are perpendicular to CD and AE

$OB = E_{Rph} = I_a Z_s$, $\angle OBD = \psi$

The Mechanical power developed per phase is given by $P_m = E_{bph} I_{aph} \cos [E_{bph} \hat{\ } I_{aph}]$ — (1)

$= E_{bph} I_{aph} \cos\phi$

In Δ^{le} OBD,

$BD = OB \cos\phi = I_a Z_s \cos\phi$

$OD = OB \sin\phi = I_a Z_s \sin\phi.$

$BD = CD - BC = AE - BC$

$AE = OA \cos(\theta-\delta) \Rightarrow V_{ph} \cos(\theta-\delta)$ — (2).

$BC = E_b \cos\theta.$ — (3)

$\therefore BD = I_a Z_s \cos\phi = V_{ph} \cos(\theta-\delta) - E_b \cos\theta.$

$$\therefore I_a \cos\phi = \frac{V_{ph}}{Z_s}\cos(\theta-\delta) - \frac{E_b}{Z_s}\cos\theta. \quad (4)$$

sub eq (4) in eq (1).

$$P_m = E_b\left[\frac{V_{ph}}{Z_s}\cos(\theta-\delta) - \frac{E_b}{Z_s}\cos\theta\right]$$

$$\boxed{P_m = \frac{E_b V_{ph}}{Z_s}\cos(\theta-\delta) - \frac{E_b^2}{Z_s}\cos\theta,}$$

Gross torque $T_g = \frac{P_m}{\omega} = \frac{P_m}{\left(\frac{2\pi N_s}{60}\right)}$

$$T_g = \frac{60 P_m}{2\pi N_s} \Rightarrow \frac{9.55 P_m}{N_s}$$

Condition for max. power developed:-

$$\frac{dP_m}{d\delta} = 0.$$

$$\frac{d}{d\delta}\left[\frac{E_b V_{ph}}{Z_s}\cos(\theta-\delta) - \frac{E_b^2}{Z_s}\cos\theta\right] = 0$$

$$\boxed{\theta = \delta}$$

$$\therefore \quad P_{m(max)} = \frac{E_b V_{ph}}{Z_s} - \frac{E_b^2}{Z_s}\cos\theta.$$

when.
$\theta = 90°$
$\cos\theta = 0$
when R_a is negligible.

Then, $$P_{m\,(max)} = \frac{E_b V_{ph}}{Z_s}.$$

$\cos\theta = R_a/Z_s.$

$$\boxed{T_{max} = \frac{\left(\frac{E_b V_{ph}}{Z_s} - \frac{E_b^2 R_a}{Z_s^2}\right)}{\left(\frac{2\pi N_s}{60}\right)}}$$

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5 A 1000 kVA, 11000 V, 3-phase star connected synchronous motor has an armature resistance and reactance per phase of 3.5 Ω and 40 Ω respectively. Determine the induced emf and angular retardation of the rotor when fully loaded at 0.8 pf lagging and 0.8 pf leading.

Solution:-

Given: kVA rating = 1000 kVA,
Line voltage V_L = 11000 V

Armature Resistance $R_a = 3.5\Omega$
per phase

Syn. reactance per phase $X_s = 40\Omega$.

To find

Induced emf and angle of retardation (δ) at

(i) 0.8 pf lagging
(ii) 0.8 pf leading.

$Z_s = R_a + jX_s$.

Ans:-

$$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{11000}{\sqrt{3}} = \underline{\underline{6350.853V}}$$

$$KVA \Rightarrow \sqrt{3} V_L I_L = 1000 \times 10^3$$

$$I_L = \frac{1000 \times 10^3}{\sqrt{3} \times 11000} \Rightarrow 52.486 A.$$

$I_L = I_a$. since star connected. so

$$\boxed{I_a = 52.486 A}$$

$$Z_s = 3.5 + j40\Omega \Rightarrow 40.152 \angle 85^\circ \Omega.$$

$\therefore \theta = 85^\circ$. (or)

$$\theta = \tan^{-1}\left(\frac{X_s}{R_a}\right) = 85^\circ.$$

$$E_{Rph} = I_a Z_s \Rightarrow 52.486 \times 40.152$$

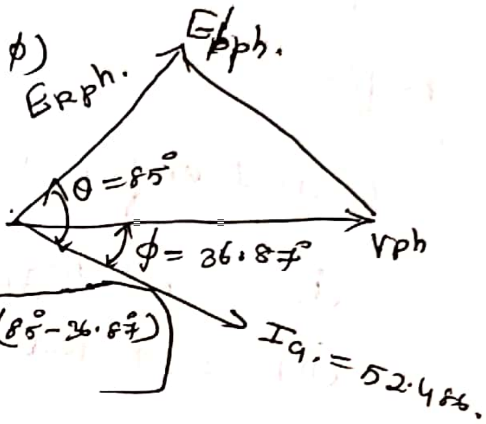
$$\boxed{E_{Rph} = 2107.47V}$$

$\cos\phi = 0.8$

$\phi = \cos^{-1} 0.8 \Rightarrow \phi = 36.87°$.

(i) For 0.8 pf lagging.

$E_{bph}^2 = V_{ph}^2 + E_{Rph}^2 - 2 V_{ph} E_{Rph} \cos(\theta - \phi)$



$$= \sqrt{(6350.853)^2 + (2107.47)^2 - 2 \times 6350.853 \times 2107.47 \times \cos(85° - 36.87°)}$$

$\boxed{E_{bph} = 5187.38\,V}$

$E_L = \sqrt{3} \times E_{bph} \Rightarrow \sqrt{3} \times 5187.38 \Rightarrow$

$\boxed{E_L = 8984.8\ V}$

$$\frac{E_{Rph}}{\sin\delta} = \frac{E_{bph}}{\sin(\theta - \phi)}$$

$$\sin\delta = \frac{2107.47 \times \sin(85° - 36.869°)}{5187.38}$$

$\boxed{\delta = 17.58°}$ retardation angle

(ii) 0.8 pf leading

$E_{bph}^2 = V_{ph}^2 + E_{Rph}^2 - 2 E_{bph} V_{ph} \cos(\theta + \phi)$

$E_{bph} = \sqrt{V_{ph}^2 + E_{Rph}^2 - 2 V_{ph} E_{Rph} \cos(\theta + \phi)}$

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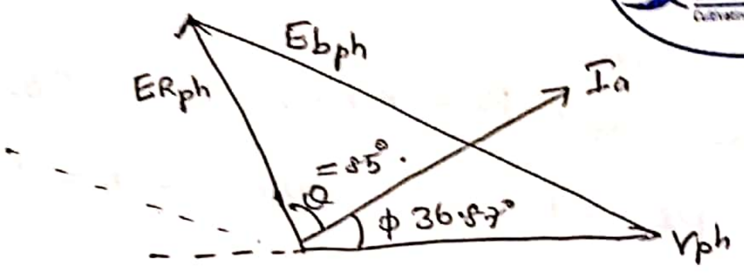


$$E_{bph} = \sqrt{(6350.853)^2 + (2107.47)^2 - 2\times 6350.853 \times 2107.47 \times \cos(85^\circ + 36.87^\circ)}$$

$$E_{ph} = 7675.17\ V$$

$$E_L = \sqrt{3}\, E_{ph} \Rightarrow 13293.79\ V$$

$$\frac{E_{Rph}}{\sin\delta} = \frac{E_{bph}}{\sin(\theta+\phi)}$$

$$\sin\delta = \frac{2107.47 \times \sin(85^\circ + 36.87^\circ)}{7675.17} = 0.233$$

$$\boxed{\delta = 13.474}$$

A 5 kW, three phase Y connected 50 Hz, 440 V, cylindrical rotor synchronous motor operates at rated condition with 0.8 pf leading. The motor efficiency excluding field and stator losses is 95% and $X_s = 2.5\ \Omega$ calculate.

(i) Mechanical power developed
(ii) Armature current
(iii) Back emf
(iv) Power angle
(v) maximum or pull out torque of the motor.

Solution:-

Given:

Power output $P_o = 5\,kw$, $f = 50\,Hz$, $V_L = 440V$

pf $\cos\phi = 0.8$ efficiency $\eta = 95\% = 0.95$

$X_s = 2.5\Omega$.

To find.

1) Max power $P_m = ?$.
2) Armature current $I_a = ?$
3) Back emf $E_{bph} = ?$
4) power angle $\delta = ?$.
5) Max (or) pull out torque $T_{max} = ?$

Solution

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500\,rpm.$$

$$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{440}{\sqrt{3}} = 254.034\,V$$

(i) Mechanical power developed

$$P_m = P_{in} = \frac{P_o}{\eta} = \frac{5 \times 10^3}{0.95} \Rightarrow 5263.158\,W$$

$$\boxed{P_{in} = 5.263\,KW}$$

(ii) Armature current I_a

$$I_a = \frac{P_m}{\sqrt{3}\,V_L \cos\phi}$$

$$= \frac{5.263 \times 10^3}{\sqrt{3} \times 440 \times 0.8}$$

$$\boxed{I_a = 8.63\ A}$$

$\cos\phi = 0.8$

$\phi = \cos^{-1} 0.8$

$\phi = 36.87^\circ$

(ii) Back emf.

$\because R_a = 0.$

$V_{ph} = E_{bph} + j I_a Z_s$

$V_{ph} = E_{bph} + j I_a X_s.$

$V_{ph} = \frac{440}{\sqrt{3}} = 254.034\,V$

$E_{bph} = V_{ph} - j I_a X_s.$

$= 254.034 - j\ 8.63 \angle 36.87^\circ \times 2.5 \angle 90^\circ \Rightarrow 266.979 - j17.26$

$E_b. = 267.536 \angle -3.7^\circ.$

(iv) power angle $\delta = \angle -3.7^\circ.$

(v) Max. Torque of the Motor

$$P_{max} = \frac{3 E_b V_{ph}}{X_s}$$

$$= \frac{3 \times 267.536 \times 254.034}{2.5}$$

$= 81555.858\,W$

$$\boxed{P_{max} = 81.55\ kW.}$$

$$T_m = \frac{9.55 \times P_m}{N_s.}$$

$$= 9.55 \times \frac{81.55 \times 10^3}{1500.}$$

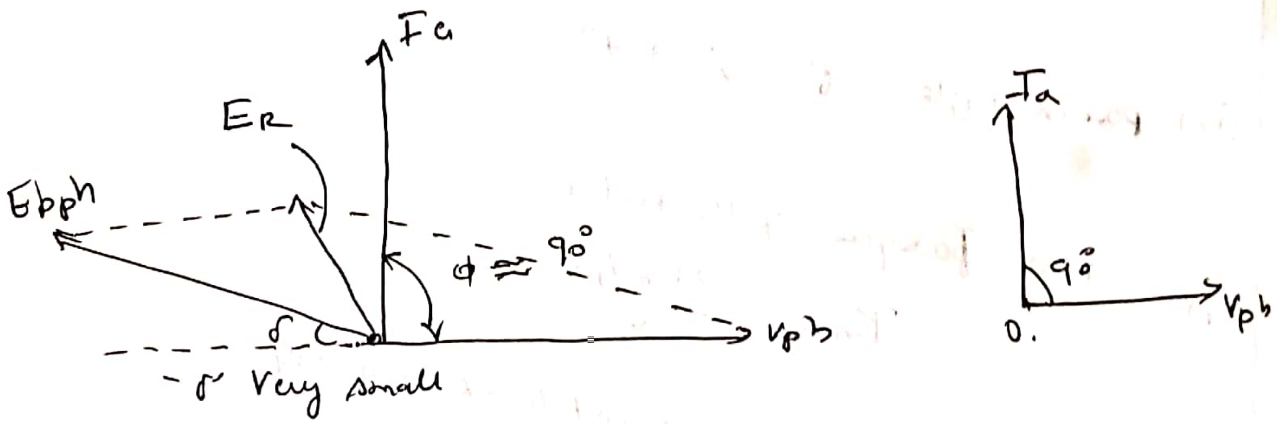
$$\boxed{T_m = 519.23\ Nm}$$

7. Synchronous Condenser.

write a short note on synchronous condenser for power factor improvement.

Synchronous Condenser or Syn. Capacitor

A synchronous motor under over excited conditions at no-loads acts as synchronous condenser and operates at leading powerfactor.

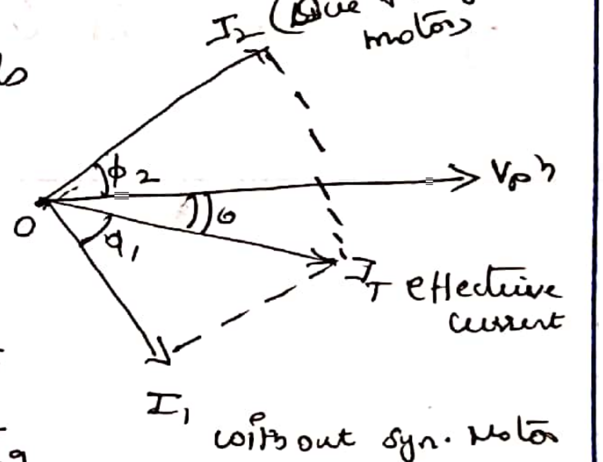


When synchronous Motor over excited it takes leading p.f current. If synchronous motor on no load where load angle 'δ' is very small and it is over excited ($E_b > V$) then power factor angle increases almost up to 90°. and motor runs with almost Zero leading power factor condition. the phasor diagram is shown.

This characteristic is similar to a normal capacitor which always takes leading power factor current. Hence overexcited synchronous motor operating on no load condition is called as synchronous

(ii) Use of Synchronous condenser in Power factor Improvement

Low power factor increases the cost of generation distribution and transmission of the electrical Energy.



Hence such low power factor needs to be corrected. Such power factor correction is possible by connecting synchronous motor across the supply and operating it on no load with over excitation.

Now let V_{ph} is the voltage applied and I_{1ph} is the current lagging V_{ph} by angle ϕ_1. This power factor is very low lagging.

The synchronous motor acting as a synchronous condenser is now connected across the same supply. This draws a leading current of I_{2ph}.

Total current drawn from the supply is now phasor of I_1 and I_2. This total current I_T now lags V_{ph} by smaller angle ϕ, due to which effective power factor gets improved

This is how the synchronous motor as a synchronous condenser is used to improve power factor of the combined load.