III. Synchronous Motors

Synchronous Motors are three-phase AC motors which run at synchronous speed,

Synchronous motors have the following characteristics:

- A three-phase stator similar to that of an induction motor. Medium voltage stators are often used.
- A wound rotor (rotating field) which has the same number of poles as the stator, and is supplied by an external source of direct current (DC). Both brush-type and brushless exciters are used to supply the DC field current to the rotor. The rotor current establishes a north/south magnetic pole relationship in the rotor poles enabling the rotor to "lock-in-step" with the rotating stator flux.
- Starts as an induction motor. The synchronous motor rotor also has a squirrel-cage winding, known as an Amortisseur winding, which produces torque for motor starting.
- Synchronous motors will run at synchronous speed in accordance with the formula:

$$\text{Synchronous RPM} = \frac{120 \times \text{Frequency}}{\text{Number of Poles}}$$

Example: the speed of a 24 -Pole Synchronous Motor operating at 60 Hz would be: 120 x 60 / 24 = 7200 / 24 = 300 RPM

Synchronous Motor Operation

- The squirrel-cage Amortisseur winding in the rotor produces *Starting Torque* and *Accelerating Torque* to bring the synchronous motor up to speed.

- When the motor speed reaches approximately 97% of nameplate RPM, the DC field current is applied to the rotor producing *Pull-in Torque* and the rotor will pull-in -step and "synchronize" with the rotating flux field in the stator. The motor will run at synchronous speed and produce *Synchronous Torque*.

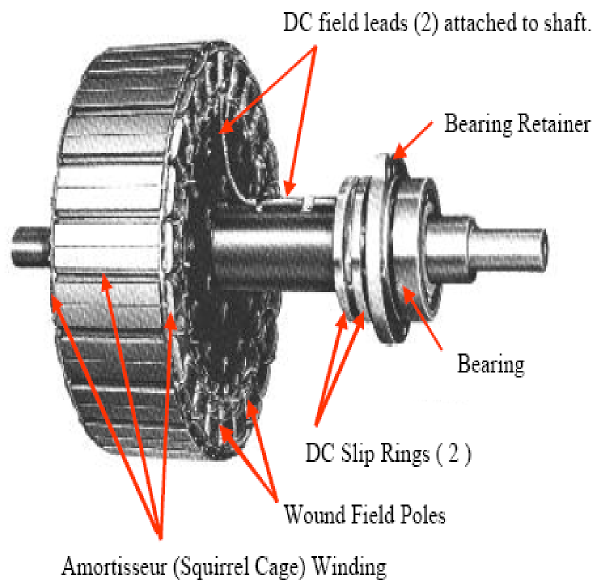
- ❖ After synchronization, the *Pull-out Torque* cannot be exceeded or the motor will pull out-of-step. Occasionally, if the overload is momentary, the motor will “slip-a-pole” and resynchronize. Pull-out protection must be provided otherwise the motor will run as an induction motor drawing high current with the possibility of severe motor damage.

Characteristics and Features

- ➢ The rotation of a synchronous motor is established by the phase sequence of the three-phase AC applied to the motor stator. As with a three-phase induction motor, synchronous motor rotation is changed by reversing any two stator leads. Rotor polarity has no effect on rotation.
- ➢ Synchronous motors are often direct-coupled to the load and may share a common shaft and bearings with the load.
- ➢ Large synchronous motors are usually started acrossthe- line. Occasionally, reduced voltage starting methods, such as autotransformer or part-winding starting, may be employed.

Synchronous Motor Rotors

- The Salient-Pole unit shown at the right is a brush-type rotor that uses slip rings for application of the DC field current.
- Low voltage DC is used for the rotating field. 120 VDC and 250 VDC are typical.
- Slip ring polarity is not critical and should be periodically reversed to equalize the wear on the slip rings. The negative polarity ring will sustain more wear than the positive ring due to electrolysis.
- Slip rings are usually made of steel for extended life.



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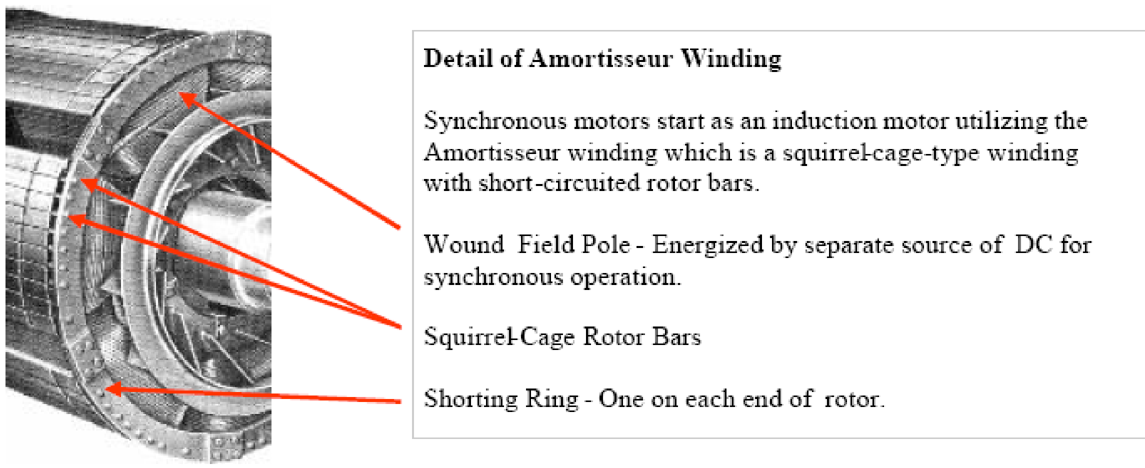

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Equivalent Circuit and Phasor Diagram of a Synchronous Motor

The steady-state performance characteristics of the synchronous motor may be studied using the equivalent circuit shown in Fig. 2. Comparing this with Fig. 1, it should be noted that the direction of ***armature current*** $\boldsymbol{I_a}$ has been reversed.

<u>Equivalent circuit and phasor diagram of a synchronous generator per phase</u>

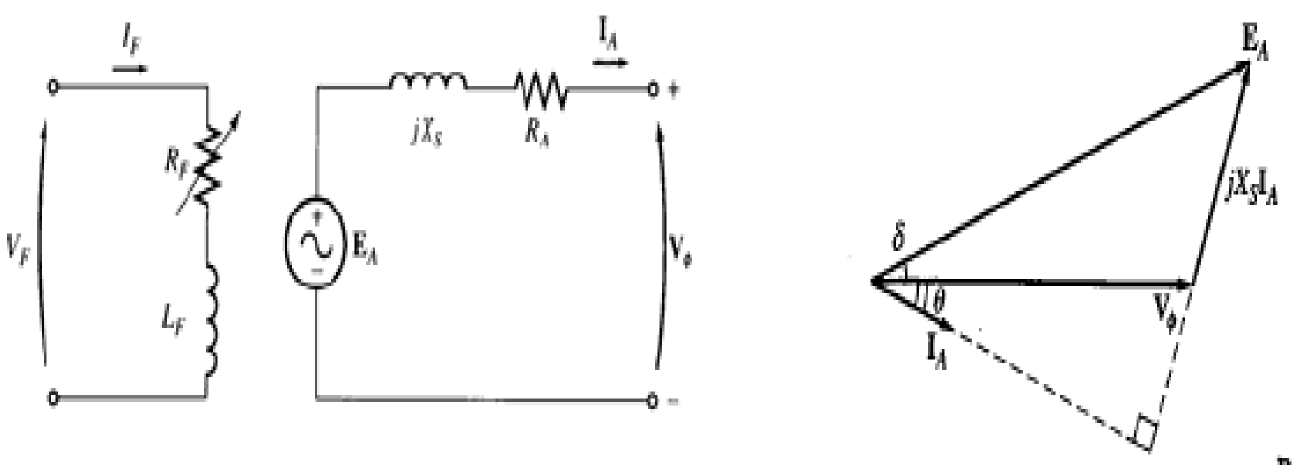
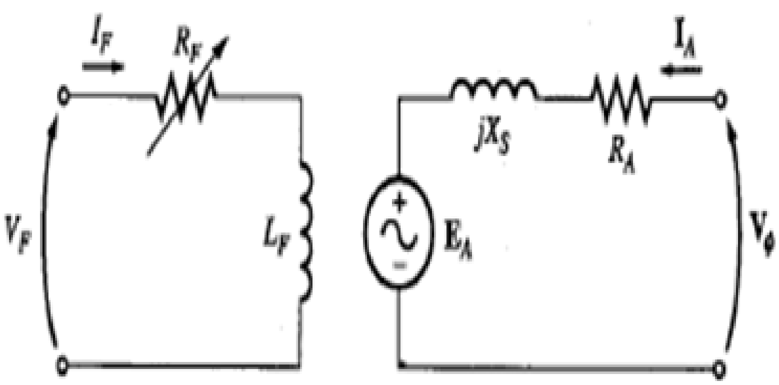


Figure 1: Synchronous generator

Equivalent circuit and phasor diagram of a synchronous motor per phase



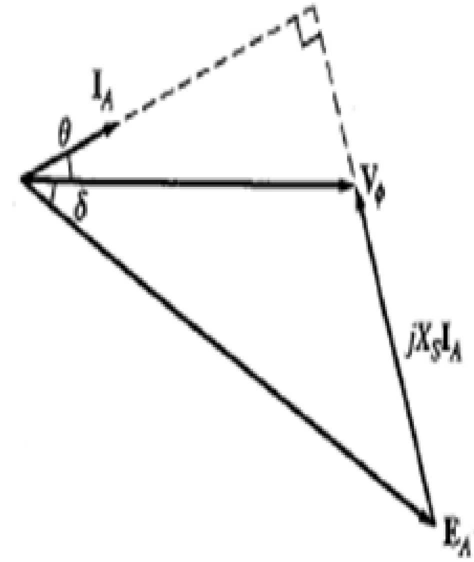


Figure 2: Synchronous motor

The circuit equation for a synchronous motor is thus

$$\boldsymbol{V_{\emptyset} = E_A + jX_s I_a + R_a I_a}$$
$$\boldsymbol{E_A = V_{\emptyset} - jX_s I_a - R_a I_a}$$

This is exactly the same as the equation for a generator, except that the sign on the current term has been reversed.

In order to satisfy the above circuit equation, the phasor $\boldsymbol{E_A}$ (often regarded as the back emf of the motor) must lag the terminal voltage $\boldsymbol{V_{\emptyset}}$ by the load angle δ.

Example: A 1492 kW ,unity power factor,3-phase ,star-connected ,2300 V, 50 Hz, synchronous motor has a synchronous reactance of 1.95 ohm/phase. Compute the max. torque in N-m which this motor can deliver if it is supplied from a constant frequency source and if the field excitation is constant at the value which would result in unity power factor at rated load. Assume that the motor is of cylindrical rotor type. Neglect all losses.

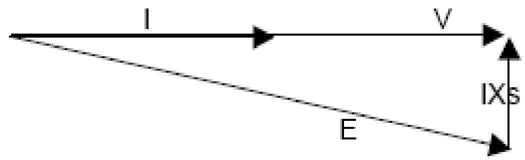
Solution: Rated kVA, 3-phase= S = 1492

Rated kVA per phase = $\frac{1492}{3} = 497.333$

Rated Voltage/phase = V =$\frac{2300}{\sqrt{3}} = 1327.906$

Rated current, I $= \frac{KVA\times1000}{V} = \frac{497.333\times1000}{1327.906} = 374.524A$

Phasor diagram:



$$E = \sqrt{V^2 + (IX_s)^2} = 1515.489\ Volts$$

$$P_{max} = \frac{EV}{X_s} = \frac{1515.489 \times 1327.906}{1.95} = 1032.014\ KW/phase$$

$$\omega = 2\pi f = 2\pi \times 50 = 314.159$$

$$Max.Torque, T_{max} = \frac{P_{max}}{\omega} = \frac{1032.014 \times 1000}{314.159} = 3285\ N \cdot m/phase$$

$$3 - phase\ max.Torque = 9855\ N \cdot m$$

Effect of Field Excitation: V-curves

Assume that a synchronous motor is driving a constant torque load. The active power converted by the machine is constant, since the power, the voltage and the motor speed are constant. Thus,

$$T = \frac{3V_a E_a}{\omega_{syn} X_s} \sin\delta = constant$$

or $$E_a \sin\delta = constant$$

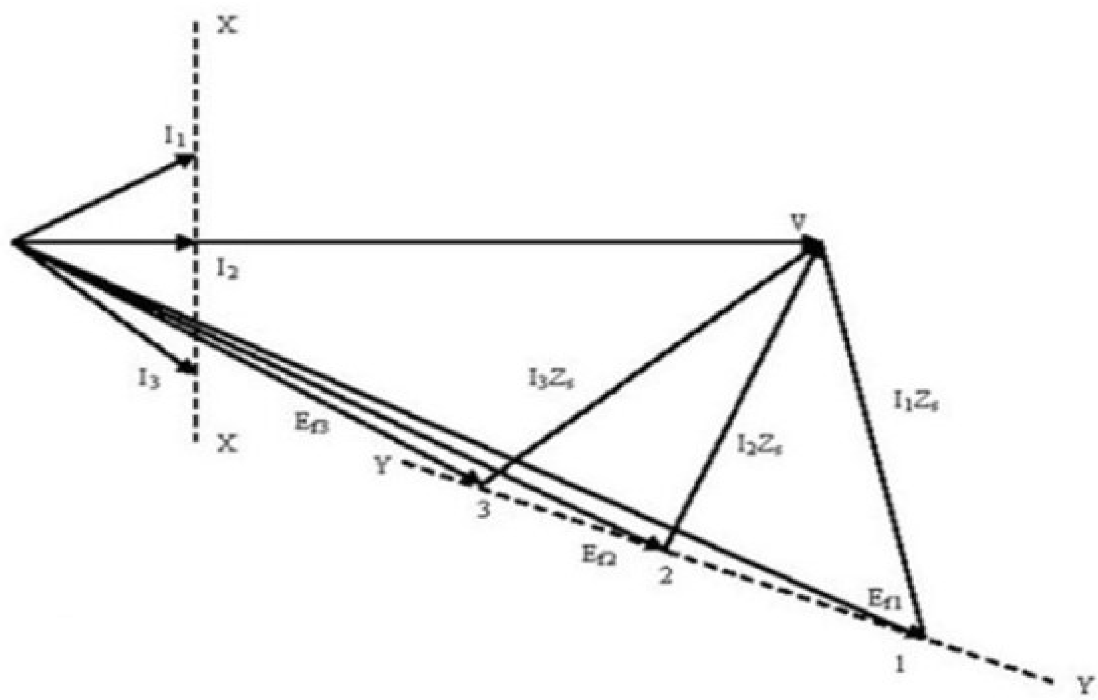
and

$$P_{em} = 3V_a I_a \cos\varphi = constant$$

or $$I_a \cos\varphi = constant$$

Figure 3 shows the effect of change in field excitation on the operation of the synchronous motor. As the field current is changed, the tip of armature current phasor ***I*** will follow the locus **XX** (a line perpendicular to ***V***), while the tip of the back emf phasor E_f will follow the locus **YY** (a line perpendicular to $I_2.X_s$, where I_2 is the in-phase component of armature current).

Suppose the synchronous motor is initially overexcited (in other words, excited with a large field current) and is operating at point **1**, as shown in Figure 3. The corresponding armature current I_1 is leading ***V***, and hence the input power factor is leading. Reduction of field current causes the tip of E_f phasor to move towards



point **2**: the armature current decreases to a minimum (I_2) and the motor input power factor increases to unity. Further reduction of field current causes E_f to move to point **3**: The armature current increases to I_3 and the input power factor becomes lagging.

Figure 3: Effect of field excitation on performance of a synchronous motor XX – locus of armature current at constant power; YY – locus of open-circuit voltage at constant power.

When the synchronous motor operates with constant power input, the variation of armature current with field current is thus a ***V-shaped curve***, as illustrated in Figure 4. In general, overexcitation will cause the synchronous motor to operate at a leading power factor, while underexcitation will cause the motor to operate at a lagging power factor. The synchronous motor thus possesses a variable-power-factor characteristic.

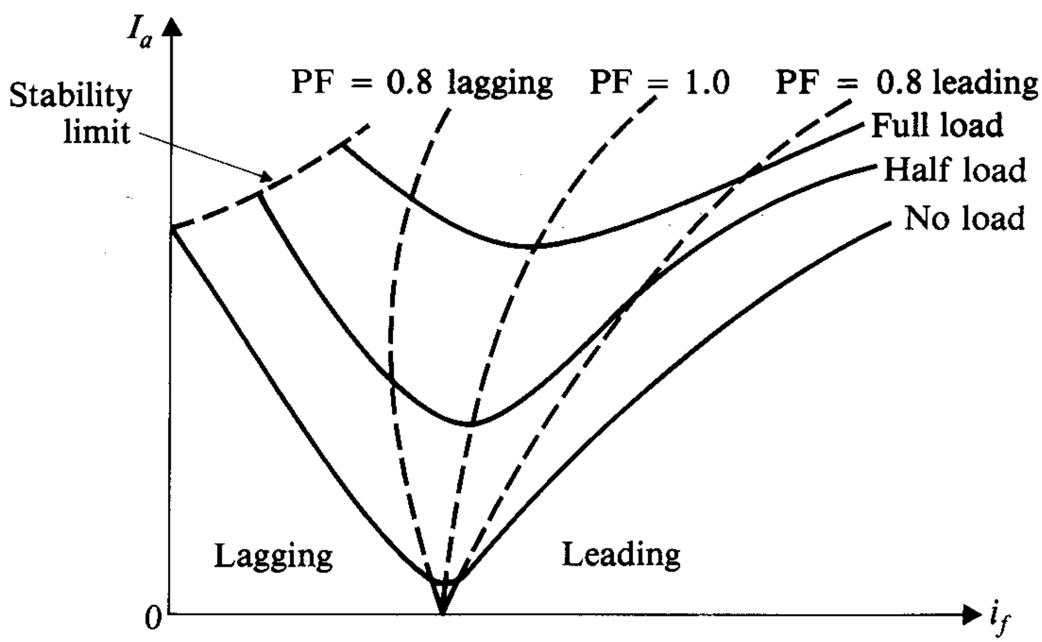
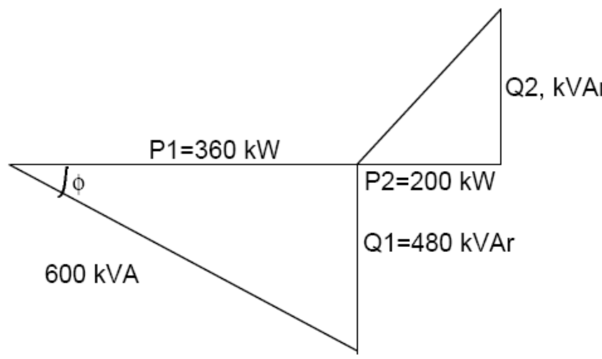


Figure 4: Synchronous motor V-curves

Example: A factory takes 600 kVA at a lagging power factor of 0.6. A synchronous motor is to be installed to raise the power factor to 0.9 lagging when the motor is taking 200 kW. Calculate the corresponding apparent power (in kVA) taken by the motor and the power factor at which it operates.

Solution:



Load power factor, Cos ϕ= 0.6

Sin $\phi = 0.8$

Load kVA = 600

P1, Load power = load kVA*cos ϕ = 360 kW

Q1, Load reactive power = kVA*Sin ϕ = 480 kVAr

P2, Motor power = 200 kW

Overall P.F., Cos α= 0.9 lag

tan $\alpha = 0.484$

Since, $\tan \propto = \frac{(Q_1 - Q_2)}{P_1 + P_2}$,

$$Q_2 = Q_1 - (P_1 + P_2) \tan \propto = 208.78 \, KVAr$$

S2, Apparent power of the motor = $\sqrt{{P_2}^2 + {Q_2}^2} = 289.118 \, KVA$

Motor P.F. =P2/S2= 0.692 lead

Applications of Synchronous motors

Synchronous motors are used for constant speed, steady loads. High power factor operations these motors are sometimes exclusively used for power factor improvement. These motors find application in driving low speed compressors, slow speed fans, pumps, ball mills, metal rolling mills and process industries.

Methods of starting

(1) by using a starting motor. This motor is directly coupled to the motor. It'may be an induction motor which can run on a synchronous speed closer to the synchronous speed of the main motor.

(2) Starting as an induction motor. This is the most usual method in which the motor is provided with a special damper winding on rotor poles. The stator is switched on to supply either directly or by star delta/reduced voltage starting. When the rotor reaches more than 95% of the synchronous speed, the dc circuit breaker for field excitation is switched on and the field current is gradually increased. The rotor pulls into synchronism
(A) Pull-in torque. It is the maximum constant load torque under which the motor will pull into synchronism at the rated rotor supply voltage and rated frequency, when the rated field current is applied

(B) Nominal pull in torque. It is the value of pull in torque at 95 percent of ,the synchronous speed with the rated voltage and frequency applied *to* the stator when the motor is running with the winding current.

(C) Pull out torque. It is the maximum sustained torque which the motor will develop at synchronous speed for I minute with rated frequency and with rated field current.

(D) Pull up torque. It is the minimum torque developed between standstill and .pull in point. This torque must exceed the load torque by sufficient margin to ensure satisfactory acceleration of the load during starting.

(E) Reluctance torque. It is fraction of the total torque with the motor operating synchronously. It results from saliency of the poles. It is approximately 30% of the pull-out torque.

(F) Locked rotor torque. It is the maximum torque which a synchronous motor will-develop at rest, for any angular positions of the rotor at the rated voltage and frequency.

Lossess
Various losses occurring in the motor are:

(1) Armature copper loss $I_a^2 R_a$
(2) Iron and friction losses.

Difference between induction motor and synchronous motor

INDUCTION MOTOR	SYNCHRONOUS MOTOR
(1) These motors have wound rotor with slip rings or a squirrel cage rotor	(1) These motors have dc poles on rotor energised by excitation system
(2) Rotor current is ac and is induced by magnetic induction	(2) The field current can be changed to vary the power factor
(3) These motors run at less than synchronous speed. Full load slip is about 4Hz..	(3)These motors always run at synchronous speed without slip.
(4) These motors take lagging power factor current.	(4)These motors take different p.f currents
(5) These motors have inherent starting torque.	(5)These motors do not have any inherent starting torque
(6) These motors start unaided	(6) These motors have to be started by suitable means and brought to synchronous speed and then synchronised.
(7) These motors are useful for variable speed and variable load drives.	(7)These motors are used for constant speed and constant load drives

Examples

AMPLE *A 1000 kVA, 11000 V, 3-phase star-connected synchronous motor armature resistance and reactance per phase of 3.5 Ω and 40 Ω respectively. the induced e.m.f. and angular retardation of the rotor when fully loaded at unity power factor,* **(b)** *0.8 power factor lagging, (c) 0.8 power factor leading.*

SOLUTION. $V = \frac{11000}{\sqrt{3}} = 6351$ V

$R_a = 3.5$ Ω $X_s = 40$ Ω

$(kVA)_{3\phi} = \frac{\sqrt{3}}{}$

$1000 = \frac{\sqrt{3}}{}$

(a) Unity power factor

$\cos\phi = 1.0$

$E_f = V$

$= 6$

$E_f\angle\delta = 6$

E_f

δ

$$= (6351 - 52.49 \times 3.5 \times 0.8 - 52.49 \times 40 \times 0.6)$$

$$- j\,(52.49 \times 40 \times 0.8 - 52.49 \times 3.5 \times 0.6)$$

$$E_f\angle\delta = 4944 - j\,1569.5 = 5187\,\underline{/-17.6^\circ}\text{ V}$$

$\therefore$ $E_f = 5187$ per phase, $\delta = -17.6^\circ$

Induced line voltage

$$= \sqrt{3} \times 5187 = 8984\text{ V}$$

(c) 0.8 power factor leading

$$\mathbf{I}_a = I_a\angle + \phi$$

$$\mathbf{E}_f = \mathbf{V} - \mathbf{I}_a\,\mathbf{Z}_s = V - (I_a\angle + \phi)\,(R_a + jX_s)$$

$$= (V - I_aR_a\cos\phi + I_aX_s\sin\phi) - j\,(I_a\,X_s\cos\phi + I_a\,R_a\sin\phi)$$

$$= (6351 - 52.49 \times 3.5 \times 0.8 + 52.49 \times 40 \times 0.6)$$

$$- j\,(52.49 \times 40 \times 0.8 + 52.49 \times 3.5 \times 0.6)$$

$$E_f\angle\delta = 7463.8 - j1790 = 7675\,\underline{/-13.48^\circ}\text{ V}$$

$E_f = 7675$ V per phase

$\delta = -13.48^\circ$

Induced line voltage $= \sqrt{3} \times 7675 = 13293$ V

$$\mathbf{I}_a = I_a\angle - \phi$$

$$\mathbf{E}_f = \mathbf{V} - \mathbf{I}_a\,\mathbf{Z}_s$$

$$= V - (I_a\,\underline{/-\phi})\,(R_a + jX_s) = V - (I_a\cos\phi - j\,I_a\sin\phi)\,(R_a + jX_s)$$

$$= (V - I_a\,R_a\cos\phi - I_a\,X_s\sin\phi) - j\,(I_aX_s\cos\phi - I_a\,R_a\sin\phi)$$

EXAMPLE . *A 2000 V, 3-phase, star-connected synchronous motor has an effective resistance and synchronous reactance of* 0.2 Ω *and* 2.2 Ω *per phase respectively. The input is 800 kW at normal voltage and the induced line e.m.f. is 2500 V. Calculate the line current and power factor.*

SOLUTION. Supply voltage per phase

$$V = \frac{2000}{\sqrt{3}} = 1154.7 \text{ V}$$

Induced e.m.f. per phase

$$E_f = \frac{2500}{\sqrt{3}} = 1443.4 \text{ V}$$

Since the induced e.m.f. is greater than the supply voltage, the motor is operating with a leading power factor cos ϕ.

If **V** is taken as refe

$\therefore \quad \mathbf{V} = V\angle 0°$

$$= V - [(I_a \cos\phi + jI_a \sin\phi)(R_a + jX_s)]$$

$$= V - [(I_aR_a \cos\phi - I_aX_s \sin\phi) + j(I_aX_s \cos\phi + I_aR_a \sin\phi)]$$

$$= (V - I_aR_a \cos\phi + I_aX_s \sin\phi) - j(I_aX_s \cos\phi + I_aR_a \sin\phi)$$

$$E_f^2 = (V - I_aR_a \cos\phi + I_aX_s \sin\phi)^2 + (I_aX_s \cos\phi + I_aR_a \sin\phi)^2$$

$$1443.4^2 = (1154.7 - 0.2 \times 231 + 2.2\, I_a \sin\phi)^2 + (231 \times 2.2 + 0.2\, I_a \sin\phi)^2$$

$$= (1108.5 + 2.2\, I_a \sin\phi)^2 + (508.2 + 0.2\, I_a \sin\phi)^2$$

$$2083404 = 1228772 + 4877.4\, I_a \sin\phi + 4.84\, I_a^2 \sin^2\phi + 258267$$
$$+ 203.3\, I_a \sin\phi + 0.04\, I_a^2 \sin^2\phi$$

$$4.88\, I_a^2 \sin^2\phi + 5080.7\, I_a \sin\phi - 596365 = 0$$

$$I_a^2 \sin^2\phi + 1041\, I_a \sin\phi - 122206 = 0$$

$$I_a \sin\phi = \frac{-1041 \pm \sqrt{1041^2 + 4 \times 122206}}{2} = \frac{1}{2}(-1041 + 1254) = 106.5$$

$$\therefore \quad \mathbf{I}_a = I_a \cos\phi + j\, I_a \sin\phi$$

$$= 231 + j\,106.5 = 254.4\,\angle 24.75° \text{ A}$$

$\therefore$ Line current $I_L = I_a = 254.4$ A

Power factor $= \cos 24.75° = 0.9081$ (leading)

EXAMPLE . *A 6600 V, 3-phase, star-connected synchronous motor draws a full-load current of 80 A at 0.8 p.f. leading. The armature resistance is 2.2 Ω and synchronous reactance 22 Ω per phase. If the stray losses of the machine are 3200 W, determine : (a) the e.m.f. induced ; (b) the output power ; (c) the efficiency.*

SOLUTION. $V_p = \frac{6600}{\sqrt{3}} = 3810.6$ V

$I_a = 80$ A, $\cos\phi = 0.8$, $\sin\phi = 0.6$

$R_a = 2.2\ \Omega$, $X_s = 22\ \Omega$

For leading power factor

$$E_{fp} = (V_p - I_a R_a \cos\phi + I_a X_s \sin\phi) - j\,(I_a X_s \cos\phi + I_a R_a \sin\phi)$$
$$= (3810.6 - 80 \times 2.2 \times 0.8 + 80 \times 22 \times 0.6) - j\,(80 \times 22 \times 0.8 + 80 \times 2.2 \times 0.6)$$
$$= 4725.8 - j\,1513.6 = 4962\ \angle -17.76^\circ \text{ V}$$

Induced line e.m.f. $= \sqrt{3} \times 4962 = 8594$ V

Power input $= \sqrt{3}\, V_L I_a \cos\phi = \sqrt{3} \times 6600 \times 80 \times 0.8 = 731618$ W

Total copper loss $= 3\, I_a^2 R_a = 3 \times 80^2 \times 2.2 = 42240$ W

Stray loss $= 3200$ W

Power output = power input − copper losses − stray loss

$= 731618 - 42240 - 3200 = 686178$ W

Efficiency $= \frac{\text{output}}{\text{input}} = \frac{686178}{731618} = 0.9379$ p.u.

EXAMPLE . *The efficiency of a 3-phase, 400 V, star-connected synchronous motor is 95% and it takes 24 A at full load and unity power factor. What will be the induced e.m.f. and total mechanical power developed at full load and 0.9 p.f. leading ? The synchronous impedance per phase is* $(0.2 + j2)\ \Omega$.

SOLUTION. $V_p = \frac{400}{\sqrt{3}} = 231$ V

$\cos\phi = 0.9$, $\sin\phi = 0.4359$

$R_a = 0.2\ \Omega$, $X_s = 2\ \Omega$

Current at 0.9 power factor

$$I_a = \frac{24}{0.9} = 26.66 \text{ A}$$

For leading power factor

$$E_{fp} = (V_p - I_a R_a \cos\phi + I_a X_s \sin\phi) - j\,(I_a X_s \cos\phi + I_a R_a \sin\phi)$$
$$= (231 - 26.66 \times 0.2 \times 0.9 + 26.66 \times 2 \times 0.4359)$$
$$- j\,(26.66 \times 2 \times 0.9 + 26.66 \times 0.2 \times 0.4359)$$
$$= 249.44 - j50.31 = 254.46\ \angle -11.4^\circ \text{ V}$$

Induced line e.m.f. $= \sqrt{3} \times 254.46 = 440.7$ V

Total copper loss $= 3\,I_a^2\,R_a = 3 \times \left(\frac{24}{0.9}\right)^2 \times 0.2 = 426.67$ W

Input power $P_i = \sqrt{3}\,V_L\,I_a \cos\phi = \sqrt{3} \times 400 \times \frac{24}{0.9} \times 0.9 = 16627.68$ W

Mechanical power developed

$$= \text{input power} - \text{copper loss}$$

$$= 16627.68 - 426.67 = 16201 \text{ W} = 16.201 \text{ kW}$$

EXAMPLE 5. *A 6.6 kV, 3-phase, star-connected synchronous motor is running in parallel with an infinite bus. Its direct-and quadrature-axis synchronous reactances are 10 Ω and 5 Ω respectively. If the field current is reduced to zero, find the maximum load that can be put on the synchronous motor. Also calculate the armature current and the maximum power. Neglect armature resistance.*

SOLUTION. $P = \frac{E_f V}{X_d} \sin\delta + \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$

When the field current becomes zero, $E_f = 0$

$$\therefore \quad P = \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

For maximum reluctance power,

$\sin 2\delta = 1, \quad \delta = 45°$

$$\therefore \quad P_{max} = \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)$$

$$= \frac{1}{2}\left(\frac{6.6 \times 10^3}{\sqrt{3}}\right)^2\left(\frac{1}{5} - \frac{1}{10}\right) = 726 \times 10^3 \text{ W per phase}$$

Total maximum power for all the three phases

$$= 3 \times 726 \times 10^3 \text{ W} = 2178 \text{ kW}$$

For maximum power, $\delta = 45°$ and

$$I_d = \frac{V\cos\delta}{X_d} = \frac{6.6 \times 10^3}{\sqrt{3}} \times \frac{\cos 45°}{10} = 269.45 \text{ A}$$

$$I_q = \frac{V\sin\delta}{X_q} = \frac{6.6 \times 10^3}{\sqrt{3}} \times \frac{\sin 45°}{10} = 538.90 \text{ A}$$

Armature current at maximum power

$$I_a = \sqrt{I_d^2 + I_q^2} = \sqrt{(269.45)^2 + (538.90)^2} = 602.5 \text{ A}$$