Chapter 38
Synchronous Motor

Md. Omar Faruque
Lecturer
Department of Electrical and Electronic Engineering
City University
Email – write2faruque@gmail.com

Characteristics Features

38.1. Synchronous Motor—General

A synchronous motor (Fig. 38.1) is electrically identical with an alternator or a.c. generator. In fact, a given synchronous machine may be used, at least theoretically, as an alternator, when driven mechanically or as a motor, when driven electrically, just as in the case of d.c. machines. Most synchronous motors are rated between 150 kW and 15 MW and run at speeds ranging from 150 to 1800 r.p.m.


Synchronous motor

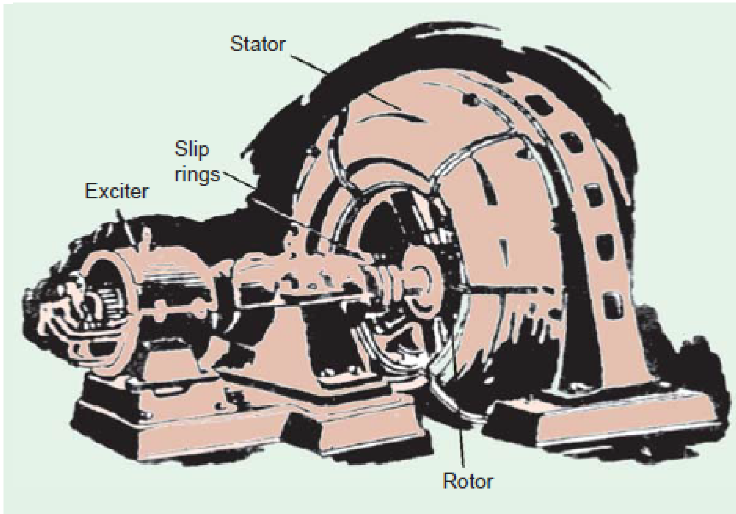
Some characteristic features of a synchronous motor are worth noting :

1. It runs either at synchronous speed or not at all *i.e.* while running it maintains a constant speed. The only way to change its speed is to vary the supply frequency (because $Ns = 120\, f / P$).
2. It is not inherently self-starting. It has to be run upto synchronous (or near synchronous) speed by some means, before it can be synchronized to the supply.
3. It is capable of being operated under a wide range of power factors, both lagging and leading. Hence, it can be used for power correction purposes, in addition to supplying torque to drive loads.

Working Principle

38.2. Principle of Operation

As shown in Art. 34.7, when a 3-ϕ winding is fed by a 3-ϕ supply, then a magnetic flux of constant magnitude but *rotating* at synchronous speed, is produced. Consider a two-pole stator of Fig. 38.2, in which are shown two stator poles (marked N_S and S_S) rotating at synchronous speed, say, in clockwise direction. With the rotor position as shown, suppose the stator poles are at that instant situated at points A and B. The two similar poles, N (of rotor) and N_S (of stator) as well as S and S_S will repel each other, with the result that the rotor tends to rotate in the anticlockwise direction.



But half a period later, stator poles, having rotated around, interchange their positions *i.e.* N_S is at point B and S_S at point A. Under these conditions, N_S attracts S and S_S attracts N. Hence, rotor tends to rotate clockwise (which is just the reverse of the first direction). Hence, we find that due to continuous and rapid rotation of stator poles, the rotor is subjected to a torque which is rapidly reversing *i.e.*, in quick succession, the rotor is subjected to torque which tends to move it first in one direction and then in the opposite direction. Owing to its large inertia, the rotor cannot instantaneously respond to such quickly-reversing torque, with the result that it remains stationary.

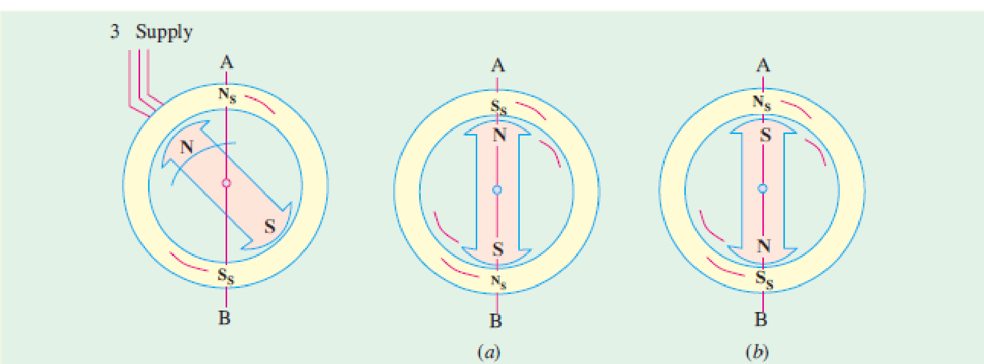
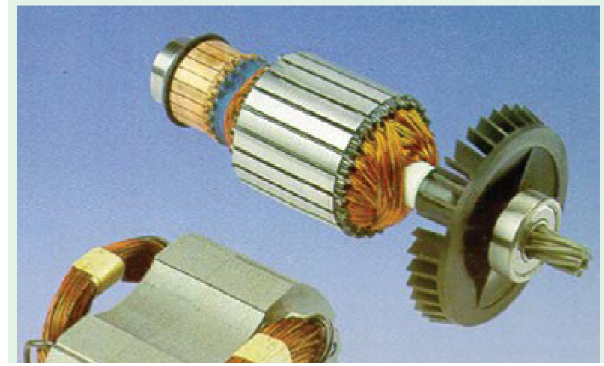


Fig. 38.2 **Fig. 38.3** **Fig. 38.3**

Now, consider the condition shown in Fig. 38.3 (*a*). The stator and rotor poles are attracting each other. Suppose that the rotor is not stationary, but is rotating clockwise, with such a speed that it turns through one pole-pitch by the time the stator poles interchange their positions, as shown in Fig. 38.3 (*b*). Here, again the stator and rotor poles attract each other. It means that if the rotor poles also shift their positions along with the stator poles, then they will continuously experience a unidirectional torque *i.e.*, clockwise torque, as shown in Fig. 38.3.



Starting of Synchronous Motor

Synchronous motors have lots of advantages but being not self-starting unlike 3 phase induction motors, is a major disadvantage. In synchronous motors, the stator has 3 phase windings and is excited by 3 phase supply whereas the rotor is excited by DC supply. The 3 phase windings provide rotating flux whereas the DC supply provides constant flux.

1. Starting a Synchronous Motor Using an Induction Motor

We need to bring the rotor of the synchronous motor to synchronous speed before we switch on the motor. For that reason, we directly couple a small induction motor (pony motor) with the synchronous motor. After the rotor of the synchronous motor is brought to the synchronous speed, we switch on the DC supply to the rotor. After that, we simply de-couple the induction motor from the synchronous motor shaft.

2. Starting a Synchronous Motor Using Damper Windings

In this method, the motor is first started as an induction motor and then starts running as a synchronous motor after achieving synchronous speed. For this, damper windings are used. Damper windings are additional windings consisting of copper bars placed in the slots in the pole faces. The ends of the copper bars are short-circuited. These windings behave as the rotor of an induction motor. When 3 phase power is supplied to the motor, the motor starts running as an induction motor at a speed below synchronous speed. After some time DC supply is given to the rotor. The motor gets pulled into synchronism after some instant and starts running as a synchronous motor. When the motor reaches synchronous speed, there is no induced emf in the damper windings anymore and hence they don't have any effect now on the working of the motor. This is the most commonly used technique for **starting synchronous motors**.

Motor on Load with constant Excitation

38.4. Motor on Load with Constant Excitation

Before considering as to what goes on inside a synchronous motor, it is worthwhile to refer briefly to the d.c. motors. We have seen (Art. 29.3) that when a d.c. motor is running on a supply of, say, V volts then, on rotating, a back e.m.f. E_b is set up in its armature conductors. The resultant voltage across the armature is $(V - E_b)$ and it causes an armature current $I_a = (V - E_b)/ R_a$ to flow where R_a is armature circuit resistance. The value of E_b depends, among other factors, on the speed of the rotating armature. The mechanical power developed in armature depends on $E_b I_a$ (E_b and I_a being in opposition to each other).

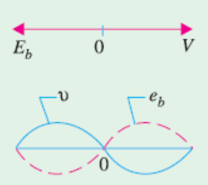


Fig. 38.6

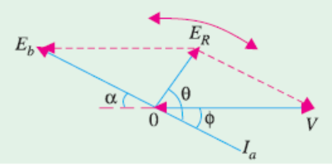


Fig. 38.7

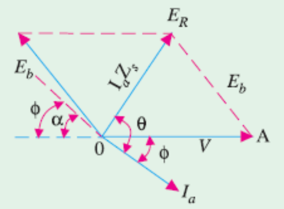
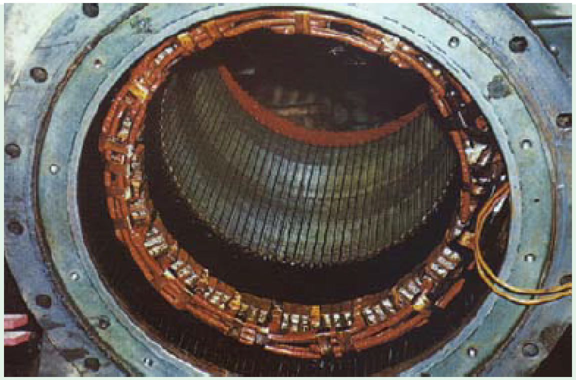


Fig. 38.8

Similarly, in a synchronous machine, a back e.m.f. E_b is set up in the armature (stator) by the rotor flux which opposes the applied voltage V. This back e.m.f. depends on rotor excitation only (and not on speed, as in d.c. motors). The net voltage in armature (stator) is the *vector difference* (not arithmetical, as in d.c. motors) of V and E_b. Armature current is obtained by dividing this *vector* difference of voltages by armature impedance (not resistance as in d.c. machines).



Stator of synchronous motor

Fig. 38.6 shows the condition when the motor (properly synchronized to the supply) is running on ***no-load*** and has ***no losses***.* and is having field excitation which makes $E_b = V$. It is seen that vector difference of E_b and V is zero and so is the armature current. Motor intake is zero, as there is neither load nor losses to be met by it. In other words, the motor just floats.

If motor is on no-load, but it has losses, then the vector for E_b falls back (vectors are rotating anti-clockwise) by a certain small angle α (Fig. 38.7), so that a resultant voltage E_R and hence current I_a is brought into existence, which supplies losses.**

If, now, the motor is loaded, then its rotor will further fall back ***in phase*** by a greater value of angle α – called the load angle or coupling angle (corresponding to the twist in the shaft of the pulleys). The resultant voltage E_R is increased and motor draws an increased armature current (Fig. 38.8), though at a slightly decreased power factor.

MATH

Example 38.6. *The input to an 11000-V, 3-phase, star-connected synchronous motor is 60 A. The effective resistance and synchronous reactance per phase are respectively 1 ohm and 30 ohm. Find (i) the power supplied to the motor (ii) mechanical power developed and (iii) induced emf for a power factor of 0.8 leading.* **(Elect. Engg. AMIETE (New Scheme) June 1990)**

Solution. (*i*) Motor power input = $\sqrt{3} \times 11000 \times 60 \times 0.8 = 915$ kW

(*ii*) stator Cu loss/phase = $60^2 \times 1 = 3600$ W; Cu loss for three phases = $3 \times 3600 = 10.8$ kW

$$P_m = P_2 - \text{rotor Cu loss} = 915 - 10.8 = 904.2 \text{ kW}$$

$$V_p = 11000/\sqrt{3} = 6350 \text{ V}; \quad \phi = \cos^{-1} 0.8 = 36.9° ;$$

$$\theta = \tan^{-1}(30/1) = 88.1°$$

$$Z_S \cong 30\ \Omega; \text{ stator impedance drop / phase} = I_a Z_S$$

$$= 60 \times 30 = 1800 \text{ V}$$

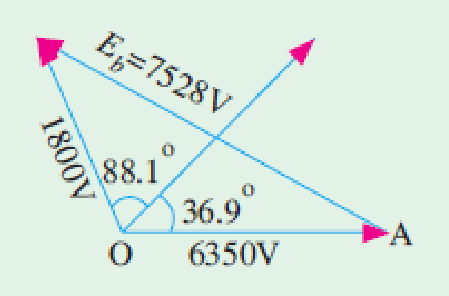


Fig. 38.25

As seen from Fig. 38.25,

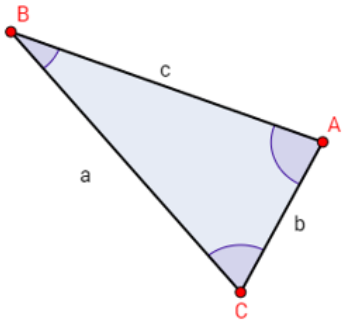
$$E_b^2 = 6350^2 + 1800^2 - 2 \times 6350 \times 1800 \times \cos(88.1° + 36.9°)$$

$$= 6350^2 + 1800^2 - 2 \times 6350 \times 1800 \times -0.572$$

$$\therefore \quad E_b = 7528 \text{ V}; \text{ line value of } E_b = 7528 \times \sqrt{3} = \mathbf{13042}$$

$$\boxed{\tan\Phi = \frac{x_s}{R_a}}$$

Law of Cosines



$a^2 = b^2 + c^2 - 2bcCosA$
$b^2 = a^2 + c^2 - 2acCosB$
$c^2 = a^2 + b^2 - 2abCosC$

MATH

Example 38.9. *A 2,300-V, 3-phase, star-connected synchronous motor has a resistance of 0.2 ohm per phase and a synchronous reactance of 2.2 ohm per phase. The motor is operating at 0.5 power factor leading with a line current of 200 A. Determine the value of the generated e.m.f. per phase.* **(Elect. Engg.-I, Nagpur Univ. 1993)**

Solution. Here,

$$\phi = \cos^{-1}(0.5) = 60° \text{ (lead)}$$

$$\theta = \tan^{-1}(2.2/0.2) = 84.8°$$

$$\therefore \quad (\theta + \phi) = 84.8° + 60° = 144.8°$$

$$\cos 144.8° = -\cos 35.2°$$

$$V = 2300/\sqrt{3} = 1328 \text{ volt}$$

$$Z_S = \sqrt{0.2^2 + 2.2^2} = 2.209\ \Omega$$

$$IZ_S = 200 \times 2.209 = 442 \text{ V}$$

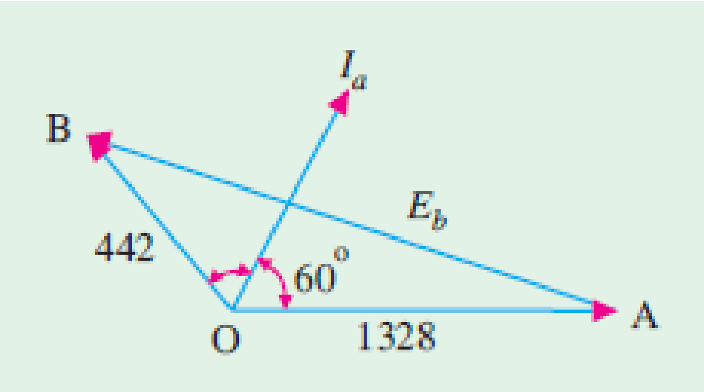


Fig. 38.27

The vector diagram is shown in Fig. 38.27.

$$E_b = \sqrt{V^2 + E_{R^2} - 2V \cdot E_R \cos(\theta + \phi)}$$

$$= \sqrt{1328^2 + 442^2 + 2 \times 1328 \times 442 \times \cos 35.2°} = \textbf{1708 Volt / Phase}$$

Power developed by a Synchronous Motor

38.12. Power Developed by a Synchronous Motor

In Fig. 38.21, OA represents supply voltage/phase and $I_a = I$ is the armature current, AB is back e.m.f. at a load angle of α. OB gives the resultant voltage $E_R = IZ_S$ (or IX_S if R_a is negligible). I leads V by ϕ and lags behind E_R by an angle $\theta = \tan^{-1}(X_S / R_a)$. Line CD is drawn at an angle of θ to AB. AC and ED are $\perp$ to CD (and hence to AE also).

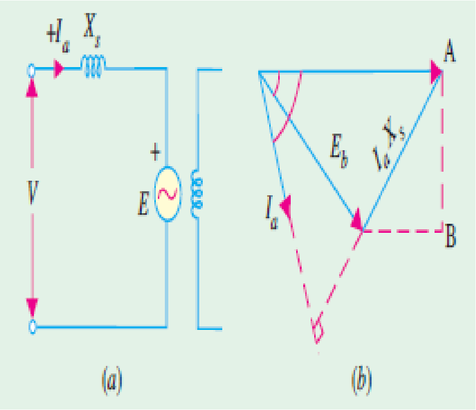


Fig. 38.21

Mechanical power per phase developed in the rotor is

$$P_m = E_b I \cos\psi \qquad ...(i)$$

In $\Delta\, OBD$, $BD = I Z_S \cos\psi$

Now, $BD = CD - BC = AE - BC$

$$I Z_S \cos\psi = V\cos(\theta - \alpha) - E_b \cos\theta$$

$$\therefore \quad I\cos\psi = \frac{V}{Z_S}\cos(\theta-\alpha) - \frac{E_b}{Z_S}\cos\theta$$

Substituting this value in (i), we get

$$P_m \text{ per phase} = E_b\left[\frac{V}{Z_S}\cos(\theta-\alpha) - \frac{E_b}{Z_S}\cos\theta\right] = \frac{E_b V}{Z_S}\cos(\theta-\alpha) - \frac{E_b^2}{Z_S}\cos\theta^{*} \qquad ...(ii)$$

This is the expression for the mechanical power developed in terms of the load angle (α) and the internal angle (θ) of the motor for a constant voltage V and E_b (or excitation because E_b depends on excitation only).

If T_g is the gross armature torque developed by the motor, then

$$T_g \times 2\pi N_S = P_m \text{ or } T_g = P_m/\omega_s = P_m / 2\pi N_S \qquad -N_S \text{ in rps}$$

$$T_g = \frac{P_m}{2\pi N_S/60} = \frac{60}{2\pi}\cdot\frac{P_m}{N_S} = 9.55\,\frac{P_m}{N_S} \qquad -N_S \text{ in rpm}$$

Condition for maximum power developed can be found by differentiating the above expression with respect to load angle and then equating it to zero.

$$\therefore \quad \frac{dP_m}{d\alpha} = -\frac{E_b V}{Z_S}\sin(\theta-\alpha) = 0 \quad \text{or} \quad \sin(\theta-\alpha) = 0 \qquad \therefore \quad \theta = \alpha$$

$\therefore$ value of maximum power $(P_m)_{max} = \dfrac{E_b V}{Z_S} - \dfrac{E_b^2}{Z_S}\cos\alpha$ or $(P_m)_{max} = \dfrac{E_b V}{Z_S} - \dfrac{E_b^2}{Z_S}\cos\theta$. ...($iii$)

This shows that the maximum power and hence torque ($\because$ speed is constant) depends on V and E_b *i.e.*, excitation. Maximum value of θ (and hence α) is 90°. For all values of V and E_b, this limiting value of α is the same but maximum torque will be proportional to the maximum power developed as given in equation (iii). Equation (ii) is plotted in Fig. 38.22.

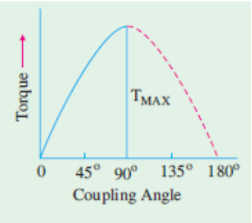


Fig. 38.22

If R_a is neglected, then $Z_S \equiv X_S$ and $\theta = 90°$ $\therefore \cos\theta = 0$

$$P_m = \frac{E_b V}{X_S}\sin\alpha \quad ...(iv) \qquad (P_m)_{max} = \frac{E_b V}{X_S} \text{ ... from equation}$$

(iii)* The same value can be otained by putting $\alpha = 90°$ in equation (iv). This corresponds to the 'pull-out' torque.

MATH

Example 38.5. *A 3300-V, 1.5-MW, 3-ϕ, Y-connected synchronous motor has $X_d = 4\Omega$ / phase and $X_q = 3\ \Omega$ / phase. Neglecting all losses, calculate the excitation e.m.f. when motor supplies rated load at unity p.f. Calculate the maximum mechanical power which the motor would develop for this field excitation.* **(Similar Example, Swami Ramanand Teertha Marathwada Univ. Nanded 2001)**

Solution.

$$V = 3300/\sqrt{3} = 1905 \text{ V}; \ \cos\phi = 1; \ \sin\phi = 0; \ \phi = 0°$$

$$I_a = 1.5 \times 10^6/\sqrt{3} \times 3300 \times 1 = 262 \text{ A}$$

$$\tan\psi = \frac{V\sin\phi - I_a X_q}{V\cos\phi} = \frac{1905 \times 0 - 262 \times 3}{1905} = -0.4125; \ \psi = -22.4°$$

$$\alpha = \phi - \psi = 0 - (-22.4°) = 22.4°$$

$$I_d = 262 \times \sin(-22.4°) = -100 \text{ A}; \ I_q = 262\cos(-22.4°) = 242 \text{ A}$$

$$E_b = V\cos\alpha - I_d X_d = 1905\cos(-22.4°) - (-100 \times 4) = 2160 \text{ V}$$

$$= 1029 \sin\alpha + 151 \sin 2\alpha$$

$$P_m = \frac{E_b V}{X_d}\sin\alpha + \frac{V^2 (X_d - X_q)}{2 X_d X_q}\sin 2\alpha \quad \text{... per phase}$$

$$= \frac{2160 \times 1905}{4 \times 1000} + \frac{1905^2 (4-3)}{2 \times 4 \times 3 \times 1000}\sin 2\alpha \quad \text{...kW/phase}$$

$$= 1029 \sin\alpha + 151 \sin 2\alpha \quad \text{...kW/phase}$$

If developed power has to achieve maximum value, then

$$\frac{dP_m}{d\alpha} = 1029\cos\alpha + 2 \times 151 \cos 2\alpha = 0$$

$$\therefore \quad 1029\cos\alpha + 302(2\cos^2\alpha - 1) = 0 \quad \text{or} \quad 604\cos^2\alpha + 1029\cos\alpha - 302 = 0$$

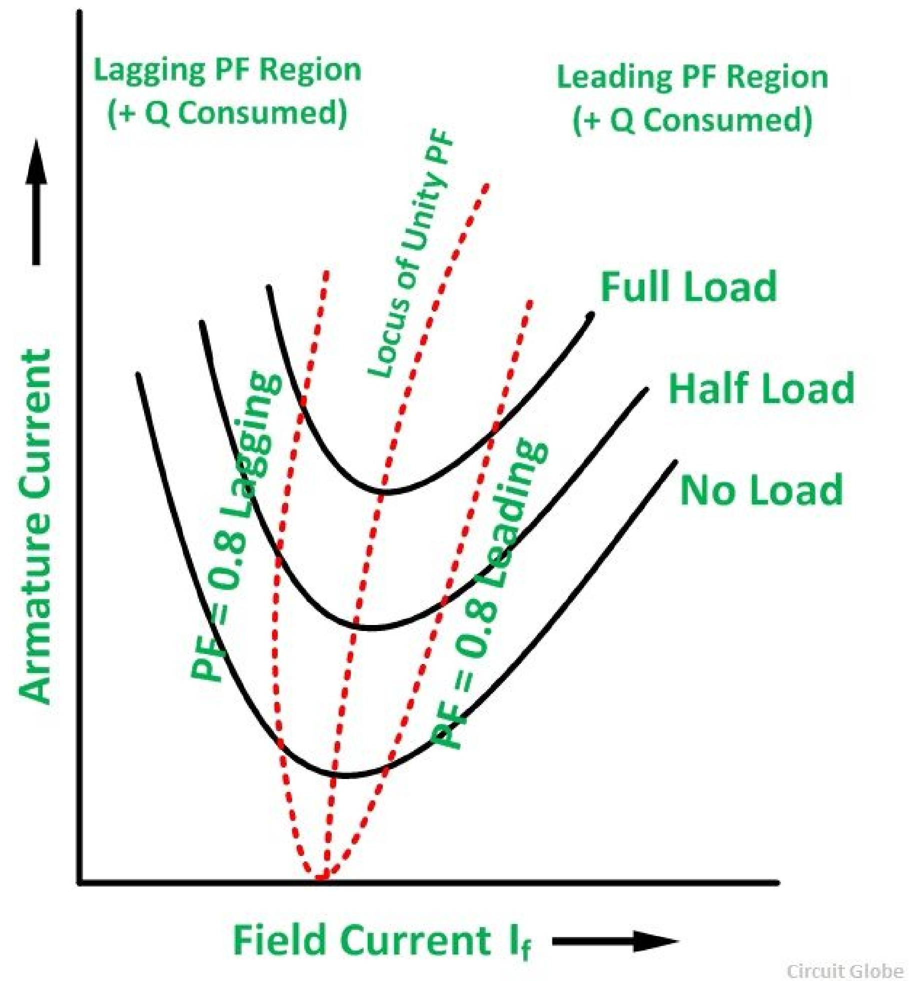
$$\therefore \quad \cos\alpha = \frac{-1029 \pm \sqrt{1029^2 + 4 \times 604 \times 302}}{2 \times 604} = 0.285; \ \alpha = 73.4°$$

$$\therefore \quad \text{maximum } P_m = 1029 \sin 73.4° + 151 \sin 2 \times 73.4° = 1070 \text{ kW/phase}$$

Hence, maximum power developed for three phases = 3 × 1070 = **3210 kW**

V Curve of a Synchronous Motor

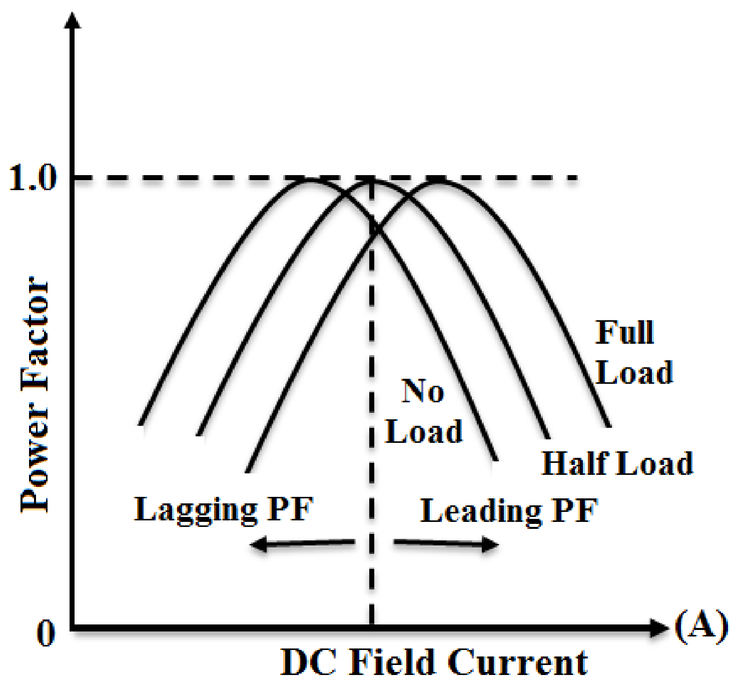
V curve is a plot of the stator current versus fiel current for different constant loads. Since the shape of these curves is similar to the letter "V", thus they are called V curve of synchronous motor.
The power factor of the synchronous motor can be controlled by varying the field current I_f. As w know that the armature current I_a changes with the change in the field current I_f. Let us assume that the motor is running at NO load. If the field current is increased from this small value, the armature current Ia decreases until the armature current becomes minimum. At this minimum point, the motor is operating at unity power factor. The motor operates at lagging power factor until it reaches up to this point of operation.
If now, the field current is increased further, the armature current increases and the motor start operating as a leading power factor. If this procedure is repeated for various increased loads, a family of curves is obtained.
The **V curves** of a synchronous motor are shown below.



Inverted V-Curves of Synchronous Motor

If the power factor is plotted against excitation for various load conditions, we obtain a set of curves known as ' Inverted V-Curves '.

The inverted V-Curves of synchronous motor shows how the power factor varies with excitation. From inverted V-curves it is observed that, the power factor is lagging when the motor is under excited and leading when it is over excited. In between, the power factor is unity.



Inverted V-curve of Synchronous Motor

Electrical Deck

Synchronous Motor with different excitations

38.8. Synchronous Motor with Different Excitations

A synchronous motor is said to have normal excitation when its $E_b = V$. If field excitation is such that $E_b < V$, the motor is said to be *under-excited*. In both these conditions, it has a lagging power factor as shown in Fig. 38.12.

On the other hand, if d.c. field excitation is such that $E_b > V$, then motor is said to be *over-excited* and draws a leading current, as shown in Fig. 38.13 (*a*). There will be some value of excitation for which armature current will be in phase with V, so that power factor will become unity, as shown in Fig. 38.13 (*b*).

The value of α and back e.m.f. E_b can be found with the help of vector diagrams for various power factors, shown in Fig. 38.14.

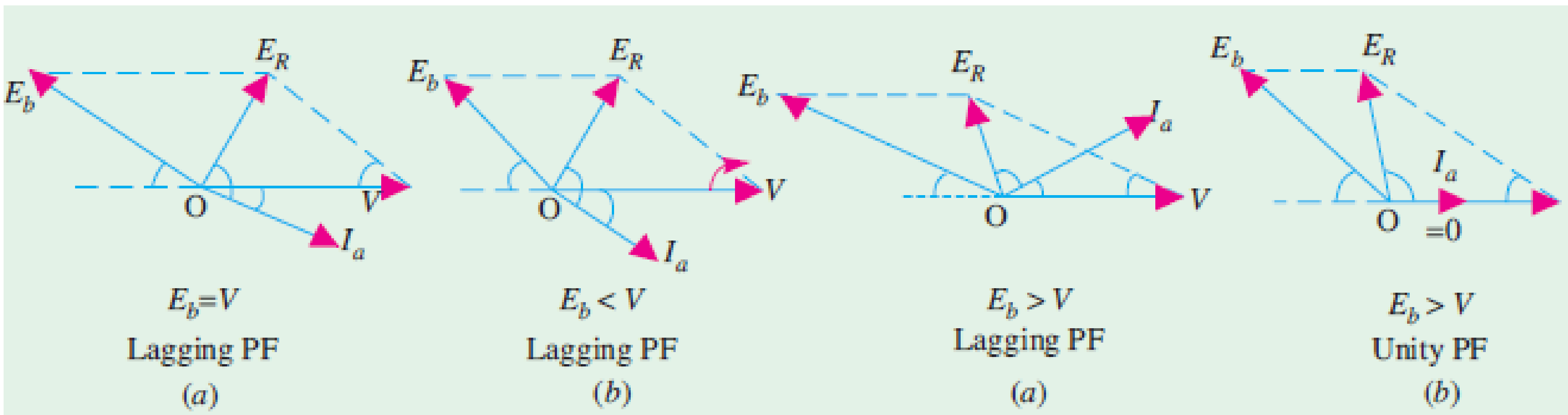


Fig. 38.12

Fig. 38.13