Unit-V
Synchronous Motors

Objectives:

- To familiarize the students with the operation of synchronous motor
- To understand the concepts of V & inverted V curves of a synchronous motor

Syllabus:

Principle of operation – Phasor diagrams – Variation of current & p.f with excitation – Excitation circles and power circles – Synchronous condenser – Hunting and its suppression – Methods of starting, Auxiliary motor starting, starting by damper winding

Outcomes:

Students will be able to

- understand the principle of operation of synchronous motor and various starting methods
- draw the phasor diagrams of synchronous motor
- understand the concept of variation of current and p.f with excitation
- understand the excitation and power circles of synchronous motor

Introduction

It may be recalled that a d.c. generator can be run as a d.c. motor. In like manner, an alternator may operate as a motor by connecting its armature winding to a 3-phase supply. It is then called a synchronous motor. As the name implies, a synchronous motor runs at synchronous speed ($N_s = \frac{120f}{P}$) i.e., in synchronism with the revolving field produced by the 3-phase supply. The speed of rotation is, therefore, tied to the frequency of the source. Since the frequency is fixed, the motor speed stays constant irrespective of the load or voltage of 3-phase supply. In this chapter, we shall discuss the working and characteristics of synchronous motors.

Construction

A synchronous motor is a machine that operates at synchronous speed and converts electrical energy into mechanical energy. It is fundamentally an alternator operated as a motor. Like an alternator, a synchronous motor has the following two parts:

(i) A stator which houses 3-phase armature winding in the slots of the stator core and receives power from a 3-phase supply [See Fig: 6.1].

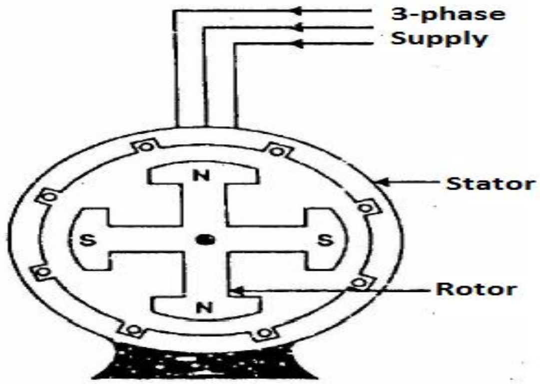


Fig: 6.1

ii) A rotor that has a set of salient poles excited by direct current to form alternate N and S poles. The exciting coils are connected in series to two slip rings and direct current is fed into the winding from an external exciter mounted on the rotor shaft.

The stator is wound for the same number of poles as the rotor poles. As in the case of an induction motor, the number of poles determines the synchronous speed of the motor:

Synchronous speed, $N_s = \frac{120f}{P}$

Where f = frequency of supply in Hz

P = number of poles

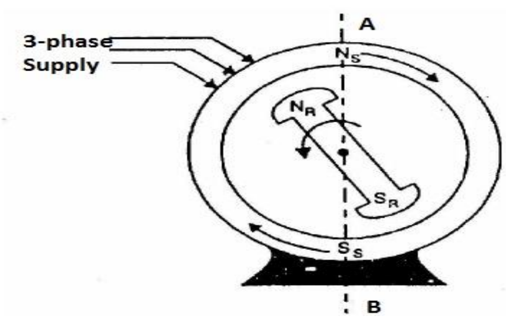
An important drawback of a synchronous motor is that it is not self-starting and auxiliary means have to be used for starting it.

Operating Principle

The fact that a synchronous motor has no starting torque can be easily explained.

(i) Consider a 3-phase synchronous motor having two rotor poles N_R and S_R. Then the stator will also be wound for two poles N_S and S_S. The motor has direct voltage applied to the rotor winding and a 3-phase voltage applied to the stator winding. The stator winding produces a rotating field which revolves round the stator at synchronous speed Ns= (120 f/P). The direct (or zero frequency) current sets up a two-pole field which is stationary so long as the rotor is not turning. Thus, we have a situation in which there exists a pair of revolving armature poles (i.e., N_S - S_S) and a pair of stationary rotor poles (i.e., N_R - S_R).

(ii) Suppose at any instant, the stator poles are at positions A and B as shown in Fig 6.2 (a). It is clear that poles N_S and N_R repel each other and so do the poles S_S and S_R. Therefore, the rotor tends to move in the anticlockwise direction. After a period of half-cycle (or ½ f = 1/100 second), the polarities of the stator poles are reversed but the polarities of the rotor poles remain the same as shown in Fig 6.2 (b). Now S_S and N_R attract each other and so do N_S and S_R. Therefore, the rotor tends to move in the clockwise direction. Since the stator poles change their polarities rapidly, they tend to pull the rotor first in one directi on and then after a period of half-cycle in the other. Due to high inertia of the rotor, the motor fails to start.



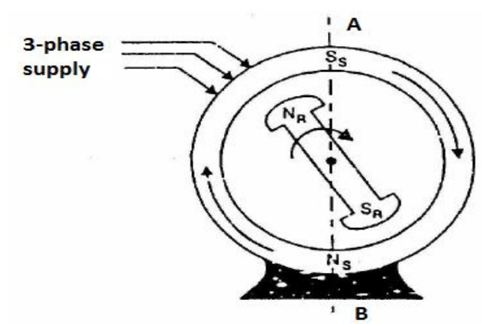


Fig: 6.2 (a)

Fig: 6.2 (b)

Hence, a synchronous motor has no self-starting torque i.e., a synchronous motor cannot start by itself.

How to get continuous unidirectional torque?

If the rotor poles are rotated by some external means at such a speed that they interchange their positions along with the stator poles, then the rotor will experience a continuous unidirectional torque. This can be understood from the following discussion:

(i) Suppose the stator field is rotating in the clockwise direction and the rotor is also rotated clockwise by some external means at such a speed that the rotor poles interchange their positions along with the stator poles.

(ii) Suppose at any instant the stator and rotor poles are in the position shown in Fig 6.3(a). It is clear that torque on the rotor will be clockwise. After a period of half-cycle, the stator poles reverse their polarities and at the same time rotor poles also interchange their positions as shown in Fig 6.3 (b). The result is that again the torque on the rotor is clockwise. Hence a continuous unidirectional torque acts on the rotor and moves it in the clockwise direction. Under this condition, poles on the rotor always face poles of opposite polarity on the stator and a strong magnetic attraction is set up between them. This mutual attraction locks the rotor and stator together and the rotor is virtually pulled into step with the speed of revolving flux (i.e., synchronous speed).

(iii) If now the external prime mover driving the rotor is removed, the rotor will continue to rotate at synchronous speed in the clockwise direction because the rotor poles are magnetically locked up with the stator poles. It is due to this magnetic interlocking between stator and rotor poles that a synchronous motor runs at the speed of revolving flux i.e., synchronous speed.

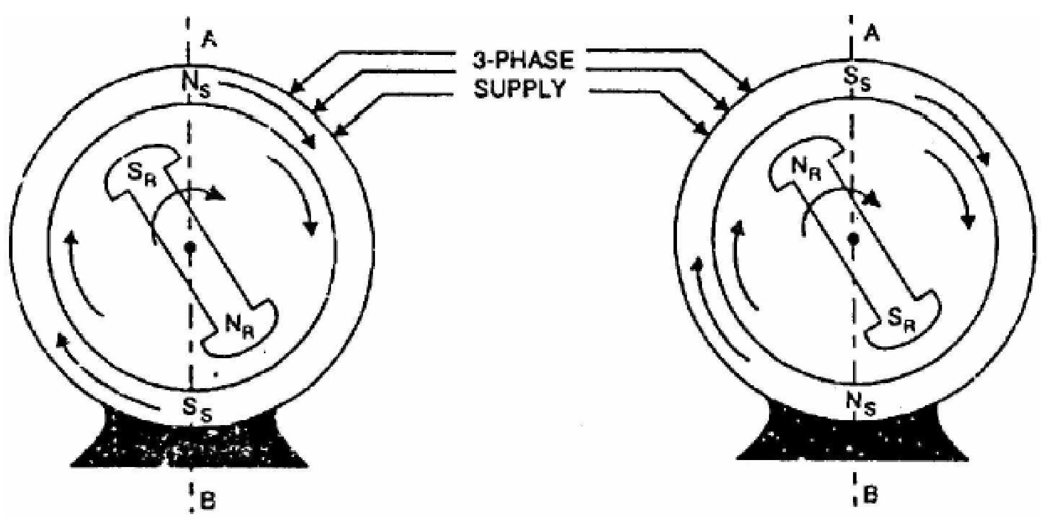


Fig: 6.3 (a) **Fig**: 6.3 (b)

Synchronous Motor on Load

In d.c. motors and induction motors, an addition of load causes the motor speed to decrease. The decrease in speed reduces the counter e.m.f. enough so that additional current is drawn from the source to carry the increased load at a reduced speed. This action cannot take place in a synchronous motor because it runs at a constant speed (i.e., synchronous speed) at all loads.

What happens when we apply mechanical load to a synchronous motor? The rotor poles fall slightly behind the stator poles while continuing to run at synchronous speed. The angular displacement between stator and rotor poles (called torque angle α) causes the phase of back e.m.f. E_f to change w.r.t. supply voltage V_t. This increases the net e.m.f. E_r in the stator winding. Consequently, stator current $I_a = \frac{E_r}{Z_s}$ increases to carry the load.

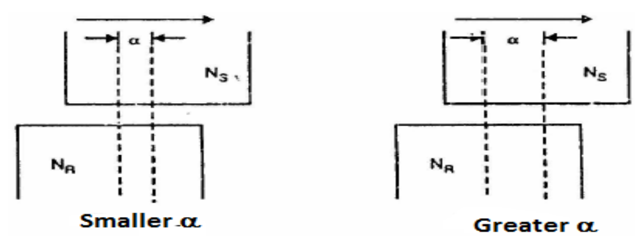


Fig: 6.4

The following points may be noted in synchronous motor operation:

(i) A synchronous motor runs at synchronous speed at all loads. It meets the increased load not by a decrease in speed but by the relative shift between stator and rotor poles i.e., by the adjustment of torque angle α.

(ii) If the load on the motor increases, the torque angle α also increases (i.e., rotor poles lag behind the stator poles by a greater angle) but the motor continues to run at synchronous speed. The increase in torque angle α causes a greater phase shift of back e.m.f. E_f w.r.t. supply voltage V_t. This increases the net voltage E_r in the stator winding.

Consequently, armature current $I_a = \frac{E_r}{Z_s}$ increases to meet the load demand.

(iii) If the load on the motor decreases, the torque angle α also decreases. This causes a smaller phase shift of E_f w.r.t. V_t. Consequently, the net voltage E_r in the stator winding decreases and so does the armature current $I_a = \frac{E_r}{Z_s}$

Pull-Out Torque

There is a limit to the mechanical load that can be applied to a synchronous motor. As the load increases, the torque angle a also increases so that a stage is reached when the rotor is pulled out of synchronism and the motor comes to a standstill. This load torque at which the motor pulls out of synchronism is called pull-out or breakdown torque. Its value varies from 1.5 to 3.5 times the full-load torque.

When a synchronous motor pulls out of synchronism, there is a major disturbance on the line and the circuit breakers immediately trip. This protects the motor because both rotor and stator winding heat up rapidly when the machine ceases to run at synchronous speed.

Motor Phasor Diagram

We will discuss here the simplest way of drawing the **phasor diagram for synchronous motor**

Before we draw phasor diagram, let us write the various notations for each quantity at one place. Here we will use:

E_f to represent the excitation voltage
V_t to represent the terminal voltage
I_a to represent the armature current
θ to represent the angle between terminal voltage and armature current
ψ to represent the angle between the excitation voltage and armature current
δ to represent the angle between the excitation voltage and terminal voltage
r_a to represent the armature per phase resistance.

We will take V_t as the reference phasor in order to **phasor diagram for synchronous motor**. In order to draw the phasor diagram one should know these two important points which are written below:

(1) We know that if a machine is made to work as a synchronous motor then direction of armature current will in phase opposition to that of the excitation emf.

(2) Phasor excitation emf is always behind the phasor terminal voltage. Above two points are sufficient for drawing the phasor diagram for synchronous motor.

The phasor diagram for the synchronous motor is given below:

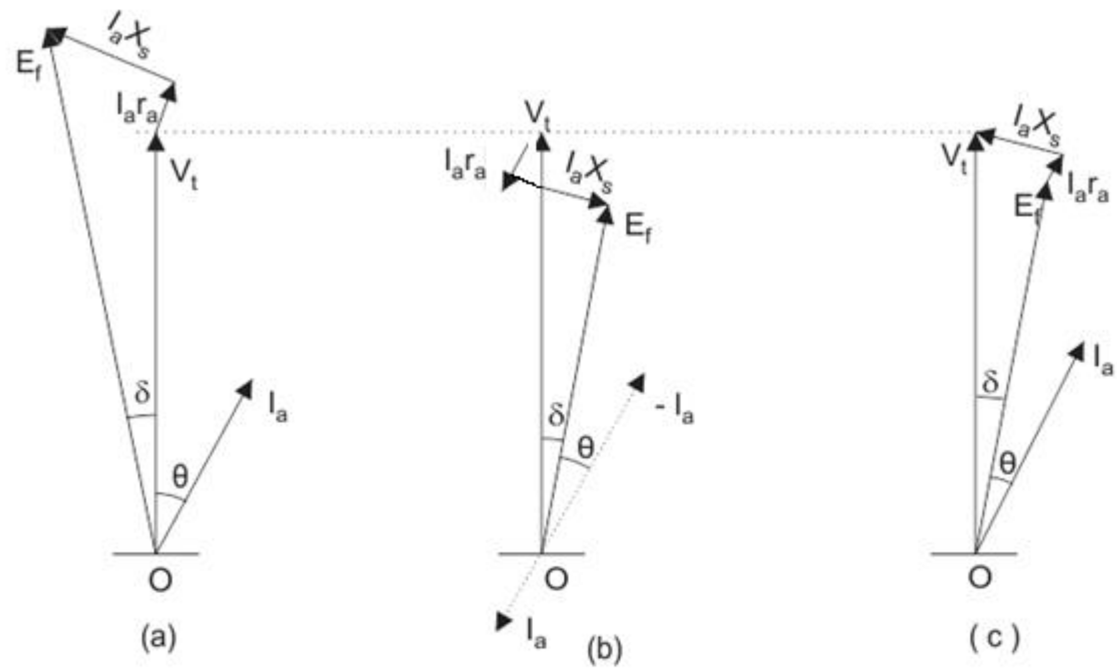


Fig.6.5 (a) Alternator voltage phasor diagram. (b) & (c) synchronous motor voltage phasor diagram

In the phasor the direction of the armature current is opposite in phase to that of the excitation emf. It is usually customary to omit the negative sign of the armature current in the phasor of the synchronous motor so in the phasor two we have omitted the negative sign of the armature current. Now we will draw complete phasor diagram for the synchronous motor and also derive expression for the excitation emf in each case. We have three cases that are written below:

(a) Motoring operation at lagging power factor.

(b) Motoring operation at unity power factor.

(c) Motoring operation at leading power factor.

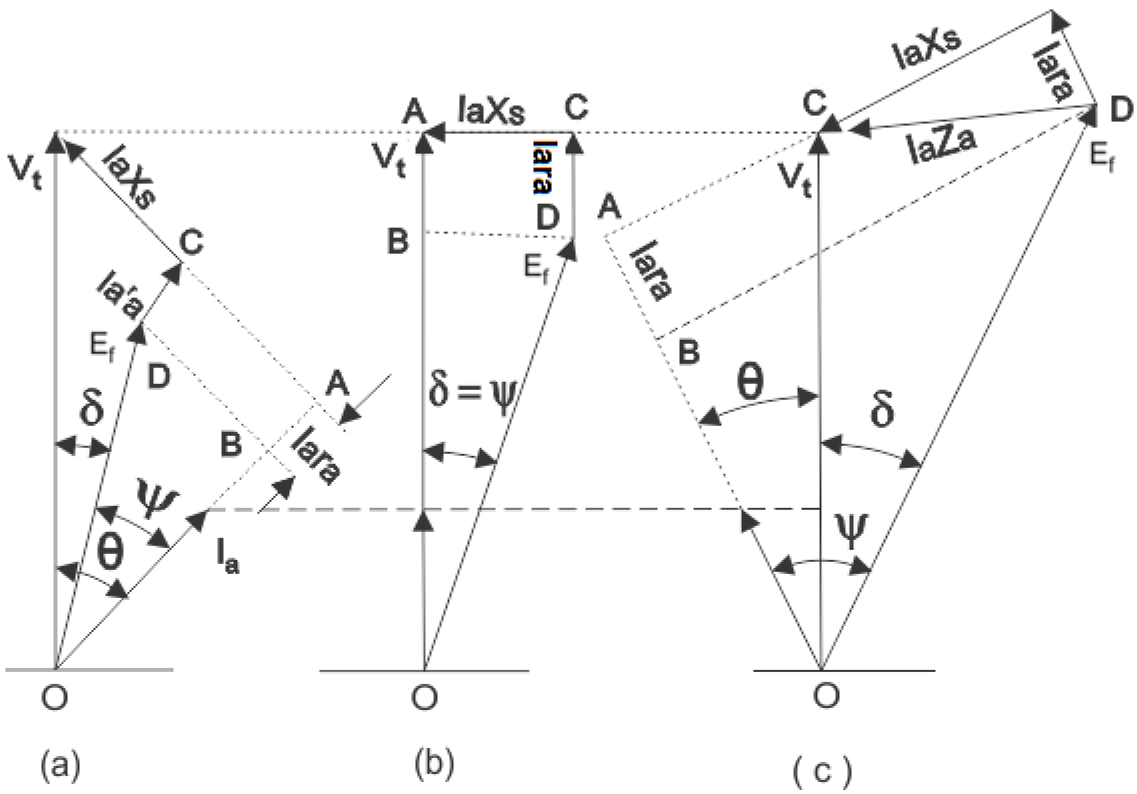


Fig. 6.6 Synchronous motor phasor diagrams for (a) lagging p.f load (b) upf load (c) leading p.f load

(a) Motoring operation at lagging power factor: In order to derive the expression for the excitation emf for the lagging operation we first take the component of the terminal voltage in the direction of armature current I_a. Component in the direction of armature current is $V_t\cos\theta$. As the direction of armature current is opposite to that of the terminal voltage therefore voltage drop will be $-I_a r_a$ hence the total voltage drop is $(V_t\cos\theta - I_a r_a)$ along the armature current. Similarly we can calculate the voltage drop along the direction perpendicular to armature current. The total voltage drop comes out to be $(V_t\sin\theta - I_a X_s)$. From the triangle BOD in the first phasor diagram we can write the expression for excitation emf as

$$E_f^2 = (V_t cos\theta - I_a \times r_a)^2 + (V_t sin\theta - I_a \times X_s)^2$$

(b) Motoring operation at unity power factor: In order to derive the expression for the excitation emf for the unity power factor operation we again first take the component of the terminal voltage in the direction of armature current Ia. But here the value of theta is zero and hence we have ψ = δ. From the triangle BOD in the second phasor diagram we can directly write the expression for excitation emf as

$$E_f^2 = (V_t - I_a \times r_a)^2 + (I_a \times X_s)^2$$

(c) Motoring operation at leading power factor: In order to derive the expression for the excitation emf for the leading power factor operation we again first take the component of the terminal voltage in the direction of armature current Ia. Component in the direction of armature current is $V_t\cos\theta$. As the direction of armature is opposite to that of the terminal voltage therefore voltage drop will be ($-I_ar_a$) hence the total voltage drop is ($V_t\cos\theta$ - I_ar_a) along the armature current. Similarly we can calculate the voltage drop along the direction perpendicular to armature current. The total voltage drop comes out to be ($V_t\sin\theta+I_aX_s$). From the triangle BOD in the first phasor diagram we can write the expression for excitation emf as

$$E_f^2 = (V_t cos\theta - I_a \times r_a)^2 + (V_t sin\theta + I_a \times X_s)^2$$

Effect of Changing Field Excitation at Constant Load

One of the most important features of a synchronous motor is that by changing the field excitation, it can be made to operate from lagging to leading power factor. Consider a synchronous motor having a fixed supply voltage and driving a constant mechanical load. Since the mechanical load as well as the speed is constant, the power input to the motor ($3\ V_tI_a cos\Phi$) is also constant. This means that the in-phase component V_tI_a□cosΦ drawn from the supply will remain constant. If the field excitation is changed, Excitation e.m.f E_f also changes. This results in the change of phase position of I_a w.r.t. V_t and hence the power factor $\cos\phi$ of the motor changes. Fig: 5.7 shows the phasor diagram of the synchronous motor for different values of field excitation. Note that extremities of current phasor I_a lie on the straight line AB.

(i) Normal excitation

The motor is said to be normally excited if the field excitation is such that Ef = Vt. This is shown in Fig: 6.7(b). Note that the effect of increasing excitation (i.e., increasing Ef) is to turn the phasor and hence Ia in the anti-clockwise direction i.e., Ia phasor has come closer to phasor Vt. Therefore, power factor increases though still lagging. Since input power (3 Vt Ia cos Φ) is unchanged, the stator current Ia must decrease with increase in power factor.

(ii) Under excitation

The motor is said to be under-excited if the field excitation is such that $E_f < V_t$. Under such conditions, the current I_a lags behind V_t so that motor power factor is lagging as shown in Fig: 6.7 (a).This can be easily explained. Since $E_f < V_t$, the net voltage E_r is decreased and turns clockwise. As angle θ(= 90°) between E_r and I_a is constant, therefore, phasor I_a also turns clockwise i.e., current I_a lags behind the supply voltage. Consequently, the motor has a lagging power factor.

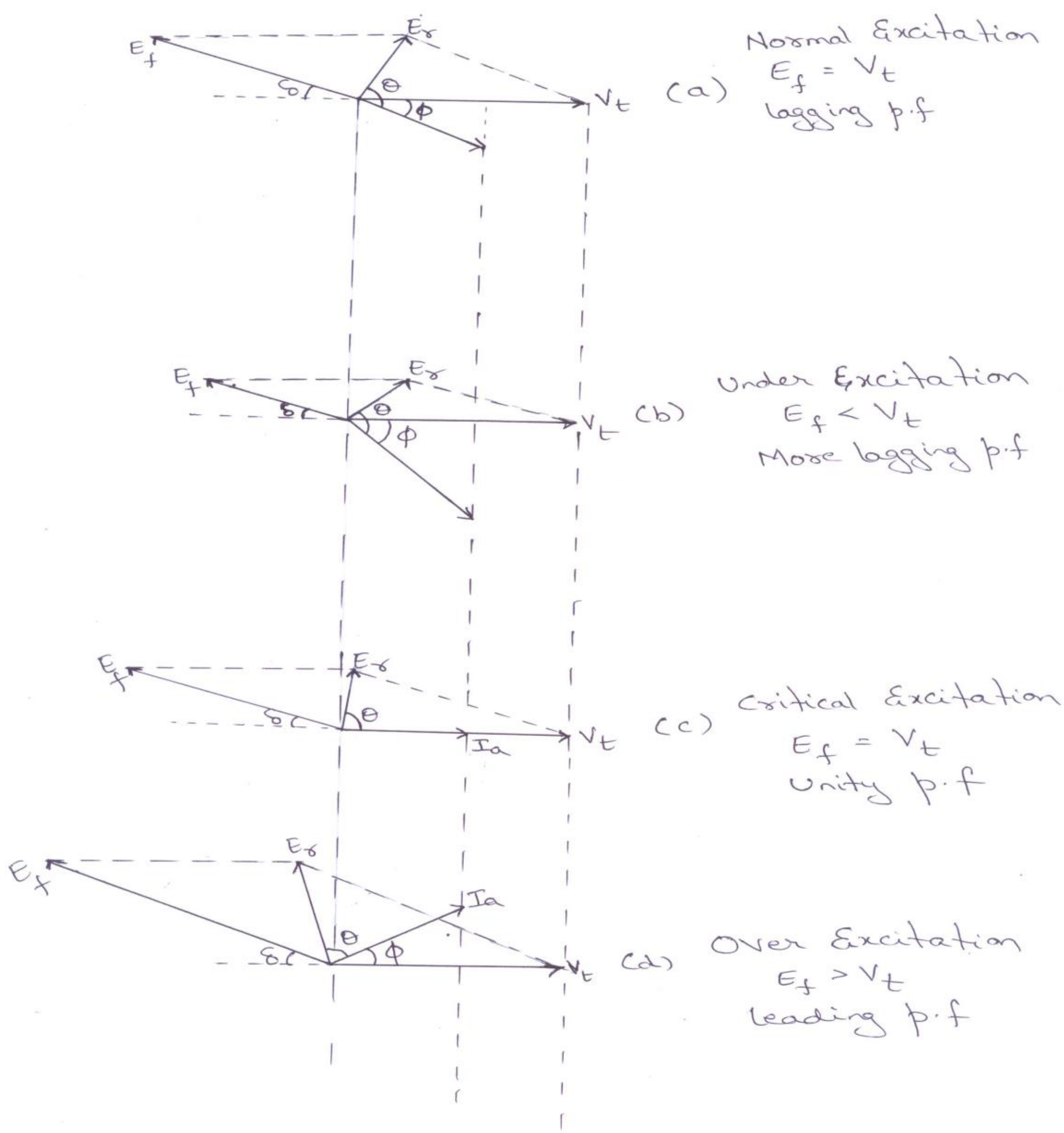


Fig: 6.7:

Suppose the field excitation is increased until the current is in phase with the applied voltage V_t, making the power factor of the synchronous motor unity [see Fig: 6.7 (c))]. For a given load, at unity power factor, the resultant E_r and, therefore, I_a are minimum.

(iii) Over excitation

The motor is said to be overexcited if the field excitation is such that $E_f > V_t$. Under-such conditions, current I_a leads V_t and the motor power factor is leading as shown in Fig: 6.7 (d)). Note that E_r and hence I_a further turn anti-clockwise from the normal excitation position. Consequently, I_a leads V_t.

From the above discussion, it is concluded that if the synchronous motor is under-excited, it has a lagging power factor. As the excitation is increased, the power factor improves till it becomes unity at normal excitation. Under such conditions, the current drawn from the supply is minimum. If the excitation is further increased (i.e., over excitation), the motor power factor becomes leading.

Note. The armature current (I_a) is minimum at unity power factor and increases as the power factor becomes poor, either leading or lagging.

Circle Diagrams of synchronous Machines:

The steady state behavior of a synchronous machine can easily be obtained from its circle diagrams. These diagrams offer quick graphical solution to many synchronous machine problems, though the results are a little less accurate from those obtained analytically.

Synchronous Motor Circle Diagrams:

Here the excitation-circle and power-circle diagrams for a cylindrical-rotor synchronous motor are developed.

(a) The excitation circles:

The excitation circle diagram gives the locus of armature current I_a , as the excitation voltage E_f and load angle δ are varied. This circle diagram for a synchronous motor is based on its voltage equation,

$$\bar{V}_t = \bar{E}_f + \bar{I}_a \bar{Z}_s$$

or

$$\bar{I}_a = \frac{\bar{V}_t}{\bar{Z}_s} - \frac{\bar{E}_f}{\bar{Z}_s} \qquad (1)$$

The current phasors = $\frac{\bar{V}_t}{\bar{Z}_s}$ = (OC) and $\frac{\bar{E}_f}{\bar{Z}_s}$ (=OB) lag behind their corresponding voltage phasors by angle θ_z and armature current I_a = OA, is obtained by taking their difference as per equation (1). Note that the angle between $\frac{\bar{V}_t}{\bar{Z}_s}$ and $-\frac{\bar{E}_f}{\bar{Z}_s}$ is the power angle δ, as shown in Fig:6.8 (a). Phasor CA is parallel to OB and in magnitude CA=OB= $\frac{E_f}{Z_s}$. The orientation of phasor V_t is deliberate so that $\frac{V_t}{Z_s}$ becomes horizontal.

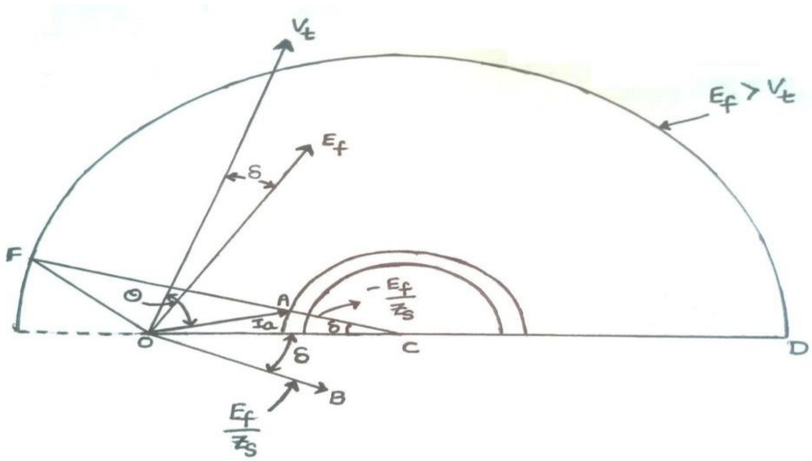


Fig: 6.8 (a) Excitation-circle diagram illustarting the locus of armature current as E_f and δ are varied in a synchronous motor.

Alternatively, the same result can also be obtained as follows. With V_t as reference phasor, equation (1) can be re-written as

$$\bar{I_a} = \frac{V_t\angle 0}{Z_s\angle\theta_Z} - \frac{E_f\angle -\delta}{Z_s\angle\theta_Z} = \frac{V_t}{Z_s}\angle -\theta_Z - \frac{E_f}{Z_s}\angle -\delta - \theta_Z$$

In expanded form $\bar{I_a} = \left[\frac{V_t}{Z_s}\cos\theta_Z - \frac{E_f}{Z_s}\cos(\delta+\theta_Z)\right] + j\left[-\frac{V_t}{Z_s}\sin\theta_Z + \frac{E_f}{Z_s}\sin(\delta+\theta_Z)\right]$

The magnitude of I_a^2 is

$$I_a^2 = \left[\frac{V_t}{Z_s}\cos\theta_Z - \frac{E_f}{Z_s}\cos(\delta+\theta_Z)\right]^2 + \left[-\frac{V_t}{Z_s}\sin\theta_Z + \frac{E_f}{Z_s}\sin(\delta+\theta_Z)\right]^2$$

$$= \left(\frac{V_t}{Z_s}\right)^2 + \left(\frac{E_f}{Z_s}\right)^2 - 2\frac{V_t}{Z_s}\frac{E_f}{Z_s}\left[\cos(\delta+\theta_Z)\cos\theta_Z + \sin(\delta+\theta_Z)\sin\theta_Z\right]$$

$$I_a^2 = \left(\frac{V_t}{Z_s}\right)^2 + \left(\frac{E_f}{Z_s}\right)^2 - 2\frac{V_t}{Z_s}\frac{E_f}{Z_s}\cos\delta \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ (2)}$$

Equation (2) states that I_a =(OA) is one side of a triangle (ΔOCA), whose other two sides, include between them a variable angle $\delta(=\angle ACO)$, the two sides being of magnitude.

$\frac{V_t}{Z_s}(=OC)$ and $\frac{E_f}{Z_s}(=CA)$ both of which are of the nature of currents.

If V_t is assumed constant, $\frac{V_t}{Z_s} = OC$ is constant. For a fixed excitation voltage E_f, the extremities of phasors $\frac{E_f}{Z_s}$ and I_a follow the path of a circle as load is changed on the motor. This locus, known as the *excitation circle*, defines the magnitude and power factor of I_a and the load angle δ, for different shaft loads.

For $E_f > V_t$, the armature current I_a, for the same load angle δ, is equal to OF, fig: 6.1 (a) and it leads V_t. Thus for $E_f < V_t$, the motor operates at a lagging power factor and for $E_f > V_t$, the motor may operate at a leading power factor.

The maximum value of load angle ACO can be equal to θ_z.

(b) The Power circles:

A power circle gives the locus of the armature current I_a, as mechanical power developed and power factor angle θ are varied.

The power output per phase in case of a synchronous motor is

$$P = V_t I_a \cos\theta - I_a^2 r_a \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_ (3)}$$

Where $V_t I_a \cos\theta$ is the per phase power input to a synchronous motor and P is the mechanical power developed including both the iron and mechanical losses. In other words,

P=Shaft power + Iron and mechanical losses

Equation (3) can be re-written as

$$I_a^2 - \frac{V_t}{r_a} I_a \cos\theta + \frac{P}{r_a} = 0 \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_ (4)}$$

or

$$I_a^2 \cos^2\theta + I_a^2 \sin^2\theta - \frac{V_t}{r_a} I_a \cos\theta + \frac{P}{r_a} = 0 \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_ (5)}$$

Let $x = I_a \sin\theta$ and $y = I_a \cos\theta$. With this substitution, equation (5) becomes,

$$x^2 + y^2 - \frac{V_t}{r_a} y + \frac{P}{r_a} = 0 \quad \text{\_\_\_\_\_\_\_\_\_\_ (6)}$$

Equation (6) is the equation of a circle with its centre at $\left(0, \frac{V_t}{2r_a}\right)$ and radius $= \sqrt{\left(\left(\frac{V_t}{2r_a}\right)^2 - \frac{P}{r_a}\right)}$

as shown in fig: 6.1(b). The co-ordinates of any point on the circle, such as point A, are (x, y) or $(I_a \sin\theta, I_a \cos\theta)$. It is seen from fig: 6.1(b) that

$AO = \sqrt{(I_a \sin\theta)^2 + (I_a \cos\theta)^2} = I_a$ and $\angle COA = \theta$.

Therefore a line joining the origin O [x=0, y=0] and any point on the power circle, gives the armature current I_a and its power factor angle θ with V_t, as shown in Fig. 5.8 (b)

Equation (4) can be treated in an alternative manner also. Addition of $\left(\frac{V_t}{2r_a}\right)^2$ to each side of Equation (4) gives

$$I_a^2 + \left(\frac{V_t}{2r_a}\right)^2 - 2\frac{V_t}{2r_a} I_a \cos\theta = \left(\frac{V_t}{2r_a}\right)^2 - \frac{P}{r_a}.$$

This equation shows that $\sqrt{\left(\left(\frac{V_t}{2r_a}\right)^2 - \frac{P}{r_a}\right)}$, is one side of a triangle whose other two sides are I_a and $\frac{V_t}{2r_a}$, with angle θ in between them, see Fig: 6.8 (b).Note that $\frac{V_t}{2r_a}$ and V_t are in the same phase.

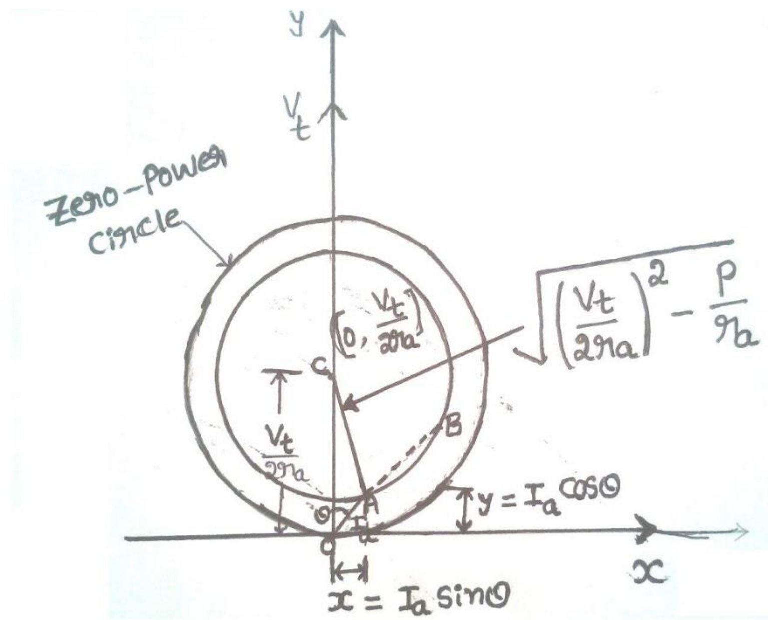


Fig: 6.8 (b) Power-circle diagram illustrating the locus of armature current for constant mechanical power developed.

When P=0, the radius of the power circle= $\frac{V_t}{2r_a}$ showing thereby that the zero-power circle passes through origin, marked O in Fig: 5.8 (b). As the power developed P, goes on increasing, the radius of the power circle goes on reducing and maximum power would occur when the radius of power circle is zero, i.e. when

$$\sqrt{\left(\left(\frac{V_t}{2r_a}\right)^2 - \frac{P_{max}}{r_a}\right)} = 0$$

$$\frac{P_{max}}{r_a} = \frac{V_t^2}{4r_a^2}$$

$$P_{max} = \frac{V_t^2}{4r_a}$$

Corresponding to the maximum power P_{max}, the power circle of zero radius is the point C itself and the armature current is $\frac{V_t}{2r_a}$ in phase with V_t, i.e. power factor is unity.

Maximum power input $= V_t I_a \cos\theta = V_t . \frac{V_t}{2r_a} . 1 = \frac{V_t^2}{2r_a}$

And maximum power output, $P_{max} = \frac{V_t^2}{4r_a}$

Therefore, efficiency at maximum output= 50%

An efficiency of 50% is too low a value for a synchronous motor. At this efficiency, losses would be about half of the input and temperature rise would be far above the permissible temperature of the motor. As such, maximum power output of $\frac{V_t^2}{4r_a}$ can never be obtained in practice from a synchronous motor.

Equation (5) when solved for I_a, for given values of power and power factor gives two currents, which are also indicated as OA and OB in the power-circle diagram of Fig: 6.8 (b).

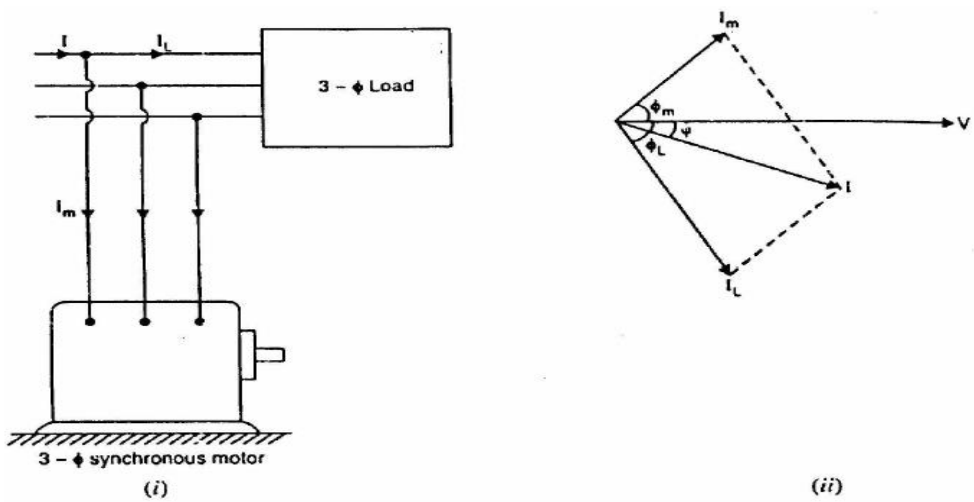
Synchronous Condenser

A synchronous motor takes a leading current when over-excited and, therefore, behaves as a capacitor.

An over-excited synchronous motor running on no-load in known as synchronous condenser.

When such a machine is connected in parallel with induction motors or other devices that operate at low lagging power factor, the leading KVAR supplied by the synchronous condenser partly neutralizes the lagging reactive KVAR of the loads. Consequently, the power factor of the system is improved.

Fig: 6.9 show the power factor improvement by synchronous condenser method. The 3-phase load takes current I_L at low lagging power factor $\cos\phi_L$. The synchronous condenser takes a current I_m which leads the voltage by an angle ϕ_m .The resultant current I is the vector sum of I_m and I_L and lags behind the voltage by an angle Φ. It is clear that Φ □is less than ϕ_L so that $\cos\phi$ is greater than $\cos\phi_L$. Thus the power factor is increased from $\cos\phi_L$ to $\cos\phi$.



Synchronous condensers are generally used at major bulk supply substations for power factor improvement.

Advantages

(i) By varying the field excitation, the magnitude of current drawn by the motor can be changed by any amount. This helps in achieving step less control of power factor.
(ii) The motor windings have high thermal stability to short circuit currents.
(iii) The faults can be removed easily.

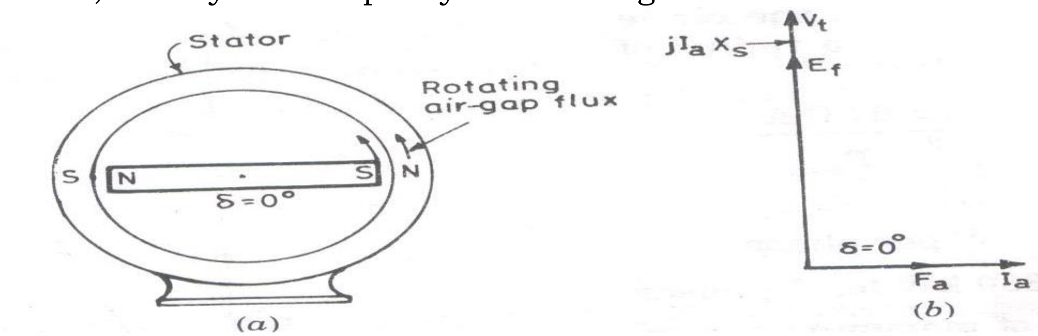
Disadvantages

(i) There are considerable losses in the motor.
(ii) The maintenance cost is high.
(iii) It produces noise.
(iv) Except in sizes above 500 KVA, the cost is greater than that of static capacitors of the same rating.
(v) As a synchronous motor has no self-starting torque, then-fore, an auxiliary equipment has to be provided for this purpose.

Hunting:

A synchronous machine operates satisfactorily, if the mechanical speed of the rotor is equal to the stator field speed, i.e., if the relative speed between the rotor and stator fields is zero. Any departure from these conditions, gives rise synchronizing forces, which tend to maintin this equality.

Unloaded synchronous motor operation is illustrated in Fig. 6.10 (a) and (b), where all the losses are neglected and load angle δ is assumed zero at no load. The rotor structure in Fig. 6.10(a) is shown different from its actual construction, merely for simplicity in showing the rotor oscillations. In the



phasor diagram of 6.10 (b), X_d and X_q are assumed equal for convenience.

Fig. 6.10. Unloaded synchronous motor operation (a) its physical interpretation and (b) its phasor diagram

If the shaft load is put on the synchronous motor in small steps, the load angle would increase gradually from zero. For any shaft load P_1, the load angle δ_1(say), armature current would be I_{a1}, this is illustrated in Fig. 6.11 (a), (b), and (c). Under steady state, $P_1 = \frac{E_f V_t}{X_s} sin\delta_1 = P_m sin\delta_1$ and the operating point is 'a' as indicated in Fig. 6.11 (a), (b) and (c). This operating point travels from 'o' to 'a' as the load is gradually increased to P_1.

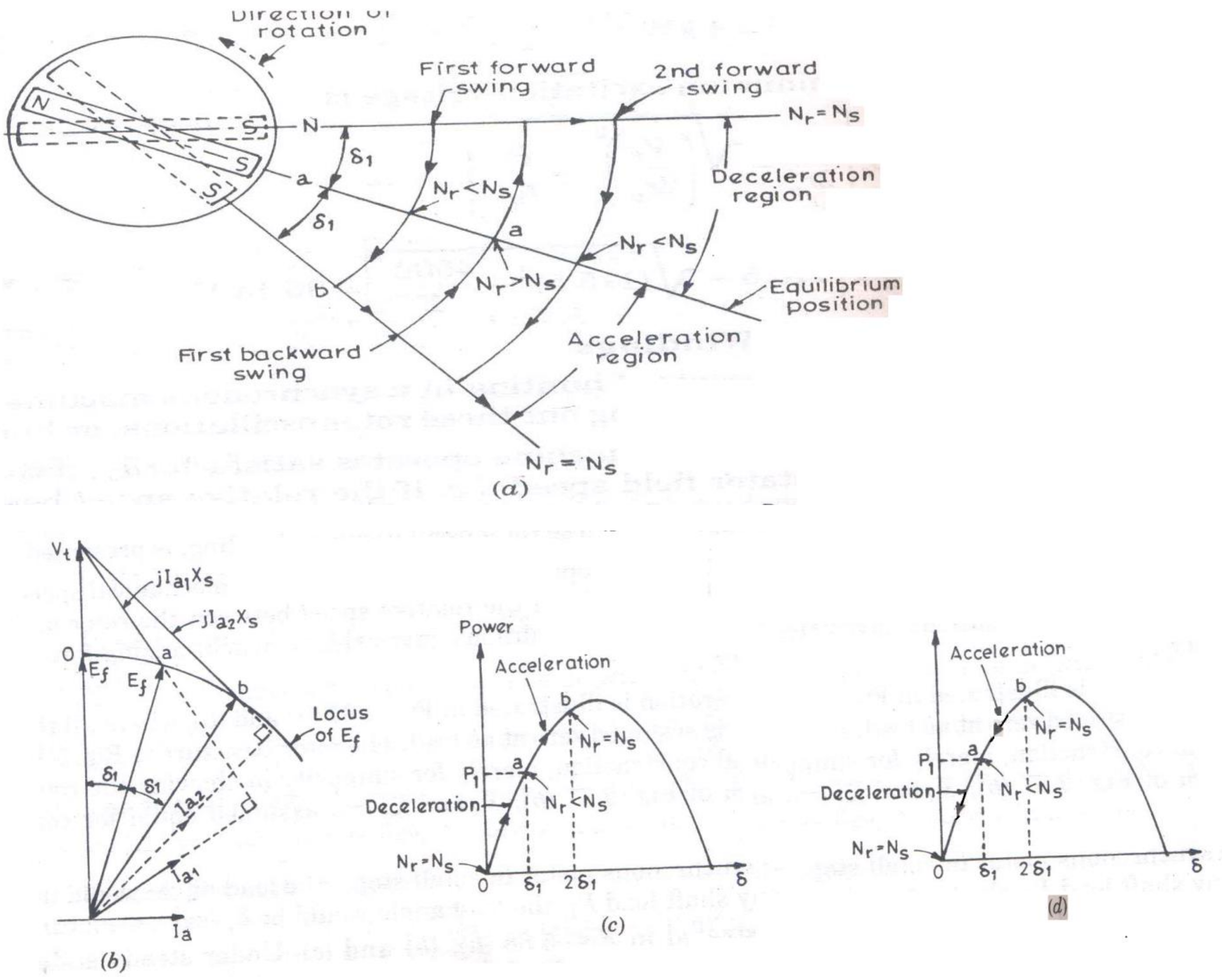
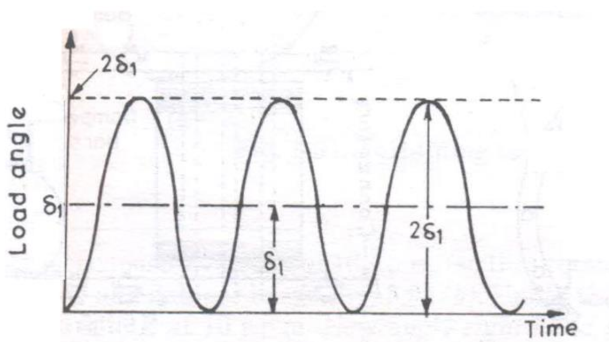


Fig. 6.11. Illustrating the rotor hunting in a synchronous motor

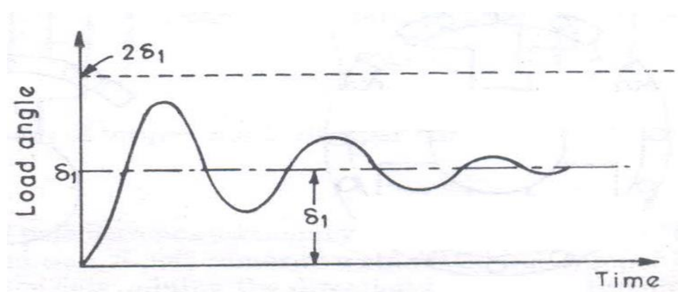
Now suppose the load P_1 is applied suddenly to the unloaded motor shaft, instead of gradually. Now the motor must slow down momentarily (i.e., the rotor speed must become less than synchronous speed) in order to supply the load P_1. As a result, load angle starts building up from zero degree. As soon as δ_1 is first reached during its forward swing, electrical power developed $P_m \sin\delta_1$ becomes equal to shaft load P_1, but equilibrium is not established, since the rotor speed is less than synchronous speed, i.e., $N_r < N_s$. In order to boost the rotor speed to N_s, the rotor swings further. As soon as load angle exceeds δ_1, $P_m \sin \delta > P_1$. In other words, now the electrical power input $P_m \sin\delta_1$ has exceeded the shaft load P_1, therefore the rotor gets accelerated. At some angle $\delta_2 = 2\ \delta_1$, the rotor attains synchronous speed and the current increases to $I_{a2} = \frac{V_t - E_f}{jX_s}$.

The operation at load angle $2\delta_1$ is indicated by point 'b' in Fig. 6.11(a), (b) and (c). Note that for the rotor travel from 'o' to 'a', the rotor decelerates (P_m sin $\delta < P_1$) and from 'a' to 'b', the rotor accelerates (P_m sin $\delta > P_1$). At load angle 2 δ_1, $N_r = N_s$ but P_m sin δ is still greater than P_1, the rotor therefore continues to accelerate even above synchronous speed. The effect of rotor speeding up above synchronous speed causes the load angle to decrease from 2 δ_1. After some time, load angle decreases to δ_1, though P_m sinδ_1 = P_1 at this angle, the equilibrium is not yet established, because now the rotor speed is more than synchronous speed i.e., $N_r > N_s$. This operating point at angle δ_1 during the first backward swing is indicated by point 'a' in Fig. 6.11 (a), (b) and (d). As the rotor speed is above N_s, the rotor continues its first backward swing below δ_1. As soon as load angle becomes less than δ_1, P_1 > Pm sinδ, rotor therefore gets decelerated. Under the assumption of no losses and no damping, the rotor would attain synchronous speed during its first backward swing only at $\delta = 0$ as indicated by point 'o' in Fig. 6.11 (a), (b) and (d0. At zero angle $I_a = \frac{V_t - E_f}{jX_s}$ as shown in Fig. 6.10(b) and 6.11 (b).

At zero load angle, P_m sin δ is zero, as a result shaft load P_1 slows down the rotor, the load angle begins to rise during its second forward swing from zero to δ_1 and then from δ_1 to $2\delta_1$ as before if there were no damping. In this manner, the rotor swings or oscillates first to one side and then to the other side of the new equilibrium position or new space – phase position of δ_1 as shown in Fig. 6.11 (a). Note that the new equilibrium position of load angle is given by $\delta_1 = \sin^{-1}(P_1/P_m)$. This phenomenon, involving the oscillation of the rotor about its final equilibrium position is called ***hunting***. Fig 6.11 (b) reveals that during the rotor oscillations or hunting, the orientation of phasor E_f changes relative to fixed voltage V_t and because of this reason, hunting is also called ***phase – swinging***. Fig. 6.11 (a) depicts the internal happenings of how rotor hunting occurs and how load angle δ varies from zero degree to $2\delta_1$ and back.



(a)



(b)

Fig. 6.12. Variation of load angle δ, after sudden loading of an unloaded synchronous motor with (a) no damping and (b) damping present.

In Fig. 6.12 (a) is shown the variation of load angle δ with time in case the motor system has no damping. Fig. 6.12 (b) shows the variation of load angle δ with time when damping is present in the system. A physical system does possess inherent damping. As a result, the rotor of synchronous motor eventually settles down to stable operating point with a load angle δ_1. The word ***"hunting"*** has been used here, because after sudden application of load, the rotor has to search for, or hunt for, its new equilibrium space position.

From the phasor diagram of Fig. 6.11 (b), it is seen that hunting is associated with power and current pulsations, which can be observed in the laboratory with the help of wattmeter and ammeter. The rotor hunting can also be observed in the laboratory by means of a stroboscope light falling on the rotor shaft. At normal synchronous speed the rotor appears stationary.

In an alternator synchronized with infinite bus, if the gate opening in case of hydroelectric power stations (or steam valve opening in case of thermal power stations) is decreases suddenly, the alternator will slow down momentarily thereby decreasing the load angle. Rotor oscillations or hunting will follow before the final equilibrium space position is reached.

Causes of Hunting in Synchronous Motor:

- Sudden change in load.
- Sudden change in field current.
- A load containing harmonic torque.
- Fault in supply system.

Effects of Hunting in Synchronous Motor:

Hunting is objectionable, particularly when the synchronous machine is coupled with a system whose torque variations contain harmonics, e.g. air-compressor, reciprocating engine etc. If frequency of the torque component happens to be equal to that of the frequency of free oscillations of synchronous machine the latter may fall out of step. The other bad effects of hunting are as follows:

- It produces severe mechanical stress and fatigue in the shaft.
- It causes great surges in current and power flow.
- It increases machine losses and thus the temperature rise of the machine.

Reduction of Hunting in Synchronous Motor:

The undesirable phenomenon of hunting, can be guarded against in three ways:

- By using a flywheel
- By designing the synchronous machine with suitable synchronizing power coefficient or stiffness factor
- By the employment of damper or amortisseur windings

Use of Damper Winding

Damper windings consist of low – resistance copper, brass or aluminium bars, embedded in slots in the pole faces of salient pole machines. The projecting ends of the bars are connected to short – circuiting strips of the same material as used for the bars. Sometimes interpolar connectors are omitted to form incomplete type of damper winding as shown in Fig. 6.13 (a). When strips on both sides of the pole shoes are joined by interpolar connectors as in Fig. 6.13(b), complete type of damper winding is obtained. Fig. 6.13 (c) shows how strips are interconnected by interpolar connectors.

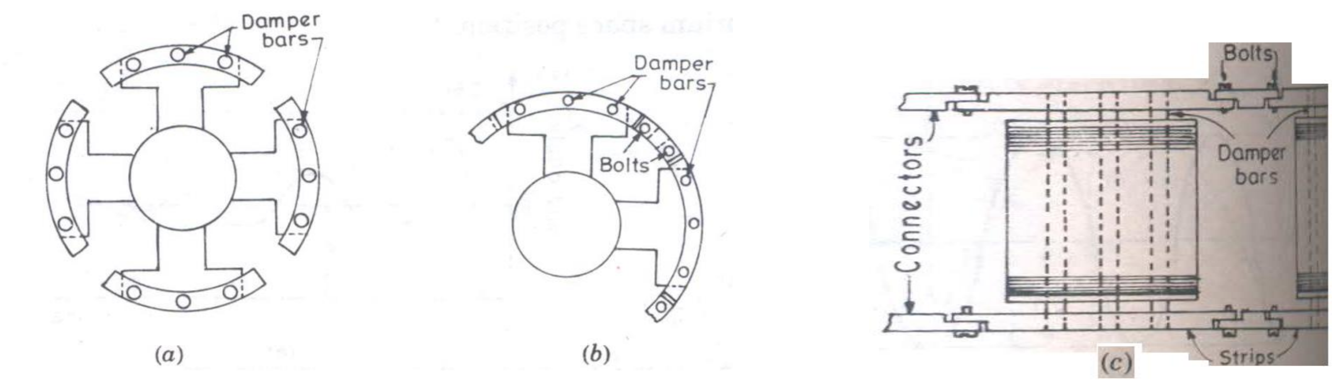


Fig. 6. 13: Damper winding (a) incomplete type, (b) and (c) complete type

It is seen from above that damper windings are of two types:

- Incomplete, non – connected, or open type, Fig. 6.13 (a),
- Complete, or connected type, Fig. 6.13 (b).

An additional equivalent rotor circuit, providing the damping effect, may be formed by the bolts and iron of the salient pole structure. The salient pole circuit which takes part in damping out the rotor hunting is called amortisseur circuit. In view of this, damper winding is also called ***amortisseur winding***.

Damper windings are not used on turbo – generators. But the solid – steel rotor cores of such machines, provide path for eddy currents, especially in the quadrature axis, where the iron may form an equivalent rotor circuit, thus producing the same effects as those of damper bars.

Damper bars may form the starting winding for synchronous motors of the salient pole type. For good starting torque, damper bars should have high resistance. But for large damping effect near synchronous speed, the damper bars should have low resistance. Therefore, a compromise between good starting torque and good damping effect should be made, for obtaining satisfactory operation of the synchronous motor. However, such a problem does exist in alternators, because the purpose of damper bars in them is merely to damp out rotor oscillations, i.e., hunting. Therefore, low – resistance damper winding can be used in alternators.

It should be noted that when the rotor is running at synchronous speed, the relative speed between damper bars and rotating air – gap flux is zero. Because of zero relative speed, no flux cutting action takes place and e.m.f. generated in damper bars is zero, consequently no damping torque is developed. The damper winding comes into play only during rotor hunting, when rotor speed departs from synchronous speed.

In order to understand how the damper bars damp out hunting, assume the rotor speed become 10 r.p.m less than the synchronous speed of 1500 r.p.m.(say), Fig. 6.14 (a). Under this assumption, the relative velocity between rotor and air – gap field is 10 r.p.m., Fig. 6.14 (b). If S pole is assumed on the stator near the damper bar, an e.m.f. shown by a dot is induced in the bar, Fig. 6.14 (b). This bar current sets up its own flux lines which interact with the S pole to produce a torque in the direction of rotation as shown in Fig. 6.14 (c).

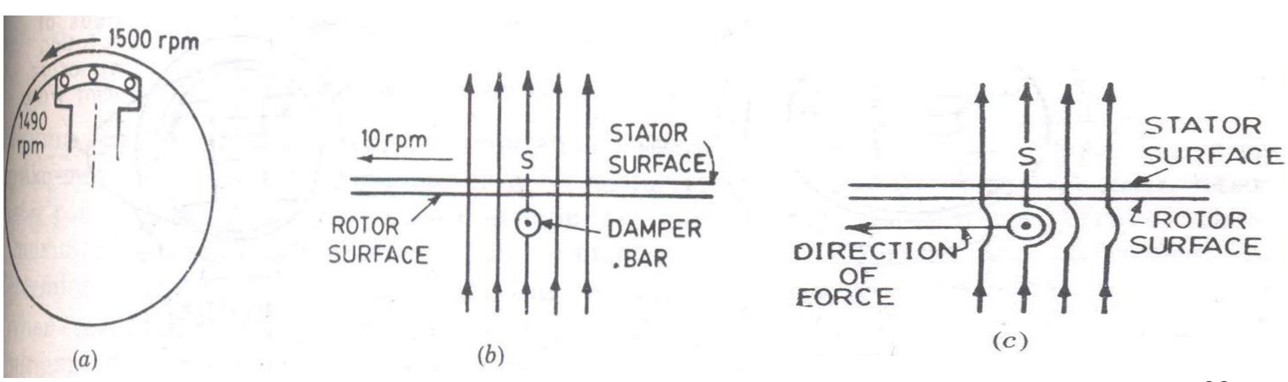


Fig. 6. 14. Pertaining to the production of torque due to damper bars

The effect of this torque is to accelerate the rotor, tending to make the two speeds equal. This torque in the direction of rotation is known as induction motor torque and is produced whenever the rotor speed falls below the synchronous speed.

Likewise, when the rotor speed becomes greater than synchronous speed, induction generator torque (against the direction of rotation) is produced, which tends to retard the rotor and make the two speeds equal. In other words, when the rotor speed falls below the synchronous speed, the slip becomes temporarily positive, induction motor action comes into play and rotor is accelerated – when the rotor speed exceeds synchronous speed, the slip becomes temporarily negative, induction generator action takes place and rotor is retarded.

Thus, when the rotor speed departs from the synchronous speed, the damping torques are brought into play to make the relative speed between rotor and stator fields as zero. The magnitude of these damping torques is approximately proportional to the slip speed, provided the slip is small.

Starting of Synchronous Motors:

The rotor of a synchronous motor must be brought up to a speed equal to the rotating stator field speed for the production of steady – state electromagnetic torque. This can be accomplished by two methods, namely:

- Auxiliary motor starting
- Induction motor starting.

(a) Auxiliary motor starting

The purpose of the auxiliary motor is to bring the synchronous motor speed, near to its synchronous speed. The auxiliary motor may be an induction motor or a D.C motor.

If 3 – phase induction motor is used as an auxiliary motor, then it is mechanically coupled with synchronous motor. Both the motors have the same number of poles and are energized from the same 3 – phase supply. The auxiliary 3 – phase induction motor brings the main motor speed almost equal to its synchronous speed. At this time, the armature winding of the synchronous motor is also energized from 3 – phase supply. Now when the field winding of main motor is connected to D.C source, the field poles get locked with those produced by armature winding. As a result of this, main motor starts running as a synchronous motor at synchronous speed. The auxiliary induction motor can now be disconnected from three – phase supply.

Sometimes an induction motor with two poles, fewer than the synchronous motor poles, is used as an auxiliary motor. This induction motor runs the main motor above its synchronous speed. After this, the induction motor is switched off and the synchronous motor armature is switched on to 3 – phase A.C supply. When the speed of the set is just above synchronous speed of the main motor, the field winding is energized from D.C supply. By the time the field current rises to its constant value, the set attains synchronous speed.

If the synchronous motor is coupled with D.C. machine, as it is usual in the laboratories, then D.C. machine is first run as a D.C motor. The main motor, now made to operate as a synchronous generator, is synchronized with the 3 – phase supply system in the usual manner. If the D.C motor is now switched off, the mian motor starts running as a synchronous motor.

The disadvantage of this method of starting is that the motor can't be started under load, in case it is desired to do so, the auxiliary motor rating will be large, thus increasing the cost of the set. In view of this, the auxiliary motor starting is used only for unloaded synchronous motors. At the same time, the auxiliary motor has to overcome primarily the inertia of the unloaded synchronous motor, its rating is therefore much lower than the rating of the synchronous motor.

(b) Starting by Damper winding (or induction – motor starting):

In order to make the motor a self – starting synchronous motor, the amortisseur or damper winding is embedded in the slots in the rotor pole faces. This winding is short circuited at both ends by metal rings. Thus the damper winding is exactly similar to the squirrel cage winding of 3 – phase induction motors.

When armature is excited from 3 – phase supply, a rotating magnetic field is established. This rotating field and the damper winding develop induction motor torque, rotor is therefore accelerated up to about synchronous speed. Note that the synchronous motor with damper bars in its rotor pole shoes, runs as a squirrel cage induction motor, from standstill up to near its synchronous speed. If the field winding is now energised from D.C source, the rotor and stator poles will lock together provided the rotor poles just approaching the stator poles are of opposite polarity as shown in Fig. 6.15.

In all other cases (e.g. rotor S pole ahead of stator N pole, rotor N pole near stator N pole etc.,), the rotor and stator poles will not lock together immediately after the instant of closing the field circuit. In view of this, the synchronous motor torque is not constant nut consists of induction motor torque plus a sinusoidally time – varying torque of very low frequency, equal to the slip frequency. This pulsating torque causes violent disturbances in the supply current. In case the load torque required is not too great, the positive half cycle of the synchronous motor torque pulls the rotor into synchronism under favourable conditions.

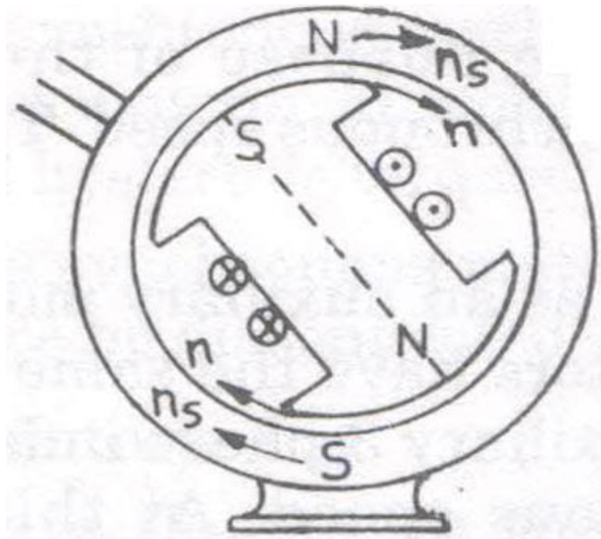


Fig. 6.15: Pertaining to the starting of synchronous motor

Instead of direct – on – line starting, the synchronous motor is sometimes started by star delta starting, reactor starting or auto – transformer starting, in order to limit the starting current.

The field winding has usually a large number of turns as compared to the stator turns. At the time of starting very high voltage may be induced in the field winding. The stator may be thought of as the primary winding and the field winding as the secondary winding of a transformer. On starting, rotating magnetic field cuts the field winding at synchronous speed and, therefore, high values of e.m.fs are induced in it. This high value of induced e.m.f may cause breakdown of the field winding insulation. The voltage induced in the field winding can be limited by short – circuiting the field winding or by connecting it to a resistance whose value is about 7 to 10 times the field winding resistance itself. As rotor speeds up, the induced e.m.f. in the field winding decreases, therefore, the external resistance in the field circuit should be gradually reduced. When the rotor reaches normal speed, external resistance in the field circuit is reduced to zero and field winding is opened; after this the field winding is connected to a D.C source. Another advantage of short – circuiting the field winding or of connecting it in series with external resistance during synchronous motor starting is that additional torque is developed due to interaction between rotating field and field – circuit m.m.fs. This additional torque adds to the induction motor torque developed by damper bars and in this manner, starting torque is increased. Star – delta starting, reactor – starting or the auto transformer starting also helps in reducing the voltage induced in the field winding.

Applications of Synchronous Motors

(i) Synchronous motors are particularly attractive for low speeds (<300 r.p.m.) because the power factor can always be adjusted to unity and efficiency is high.

(ii) Overexcited synchronous motors can be used to improve the power factor of a plant while carrying their rated loads.

(iii) They are used to improve the voltage regulation of transmission lines.

(iv) High-power electronic converters generating very low frequencies enable us to run synchronous motors at ultra-low speeds. Thus huge motors in the 10 MW range drive crushers, rotary kilns and variable-speed ball mills.