Three-Phase Synchronous Motor

1. Introduction:

The same synchronous machine can be used as a generator or as a motor. When it converts mechanical power or energy into electric power or energy, it is called a synchronous generator. On the other hand, when it converts electric power or energy into mechanical power or energy, it is called a synchronous motor.

2. Principle of Operation:

When a three-phase supply is given to the stator of a three-phase wound synchronous motor, a revolving field is set up (say in anticlockwise) which rotates at a synchronous speed (**N_S =120 f / P**).

This field is represented by the imaginary stator poles. At an instant as shown in Figure 1(*a*), the opposite poles of stator and rotor are facing each other (for simplicity two-pole machine is considered). As there is a force of attraction between them, an anticlockwise torque is produced in the rotor as the rotor poles are dragged by the stator revolving poles or field. After half a cycle, polarity of the stator poles is reversed whereas the rotor poles could not change their position due to inertia. Thus, like poles are facing each other and due to force of repulsion a clockwise torque is produced in the rotor as shown in Figure 1(*b*).

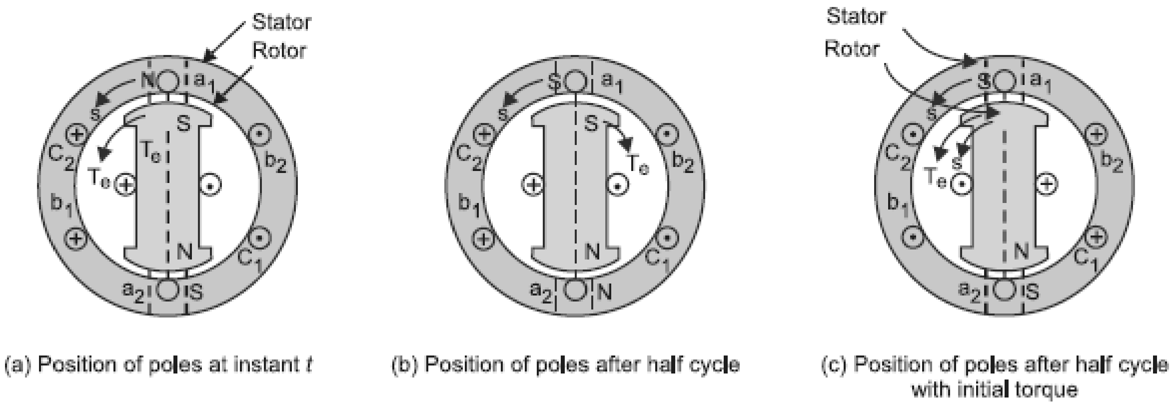


Figure 1 Representing Working Principle

Hence, the torque produced in a three-phase synchronous motor is not unidirectional and as such this motor is **not self-starting**.

However, if rotor of synchronous motor is rotated by some external means (Initial torque) at starting so that it also reverses its polarity as the polarity of stator poles is reversed after half a cycle as shown in Figure 1(c). A continuous force of attraction between stator and rotor poles exists. This is called magnetic locking. Once the magnetic locking is obtained, the rotor poles are dragged by the stator revolving field (imaginary poles) and a continuous torque is obtained. As the rotor poles are dragged by the stator revolving field, hence the rotor rotates at the same speed as that of stator revolving field, i.e., synchronous speed. Thus, a synchronous motor only runs at a constant speed called synchronous speed.

3. The Equivalent Circuit:

The equivalent circuit of a synchronous motor is the same, in all respects, as that of a synchronous generator, the only difference is that the direction of power flow is reversed in this case, as shown in Figure 2.

In the equivalent circuit:

V = Terminal voltage to the armature (phase value),

I = Armature current (phase value),

R = Effective armature resistance per phase,

X_S = Synchronous reactance per phase,

Z_S = **R + j X_s** Synchronous impedance per phase,

E = Excitation voltage (phase value),

I_f = Exciting or field current.

For Synchronous Motor:

$$\overline{V} = \overline{E} + \overline{I}\overline{Z}_s = \overline{E} + \overline{I}(R + jX_S)$$

$$\overline{E} = \overline{V} - \overline{I}\overline{Z}_s = \overline{V} - \overline{I}(R + jX_S)$$

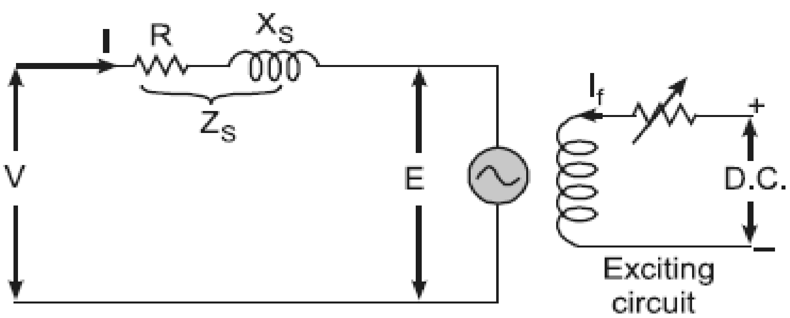


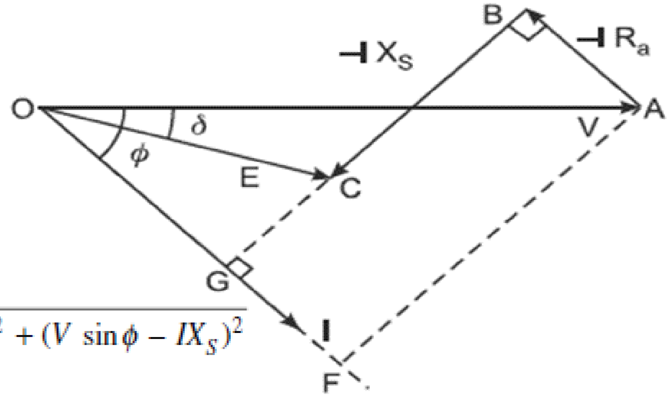
Figure 2 Per Phase Equivalent Circuit of Synchronous Motor

4. Phasor Diagram of Non-Salient Pole Synchronous Motor:

A three-phase non-salient pole synchronous motor (cylindrical rotor) may operate at different power factors i.e., lagging, unity or leading. Accordingly, its phasor diagram is drawn with the help of above equations.

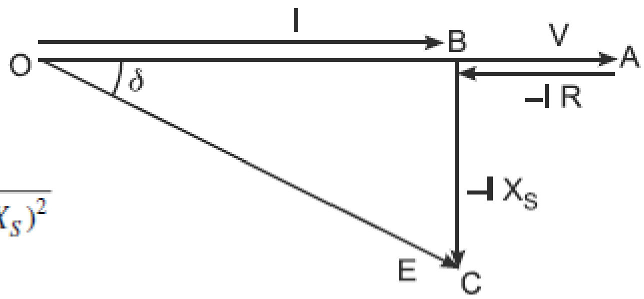
I. Phasor Diagram for lagging power factor:

$$E = \sqrt{(V\cos\phi - IR)^2 + (V\sin\phi - IX_S)^2}$$



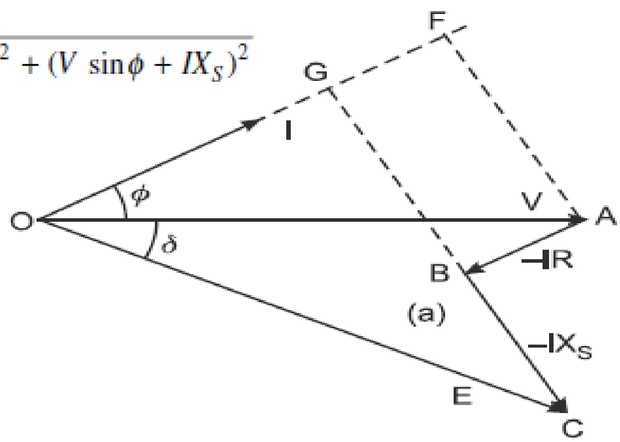
II. Phasor Diagram for unity power factor:

$$E = \sqrt{(V - IR)^2 + (IX_S)^2}$$



III. Phasor Diagram for leading power factor:

$$E = \sqrt{(V\cos\phi - IR)^2 + (V\sin\phi + IX_S)^2}$$



5. Power Developed in Non-Salient Pole Synchronous Motor:

For developed power calculation and specially in large machines, usually the value of armature resistances R is so small than the synchronous reactance (X_s) that it is neglected (R=0). Return to the phasor diagram of non-salient pole rotor type synchronous motor with neglected armature resistance**, the final expression for the developed power in the motor for three-phase is as below:**

$$P_d = 3\frac{VE}{X_S}\sin\delta$$

While, the maximum developed power in the motor will be:

$$P_{max} = 3\frac{VE}{X_S}$$

The power available at the shaft (output power) will be:

Power at the shaft (P_{shaft}) = Power Developed – Rotational Losses

Where, Rotational losses include friction, windage and core losses.

6. Power Flow in Synchronous Motor:

The power flow diagram for synchronous machine working as a motor is shown in figure 3.

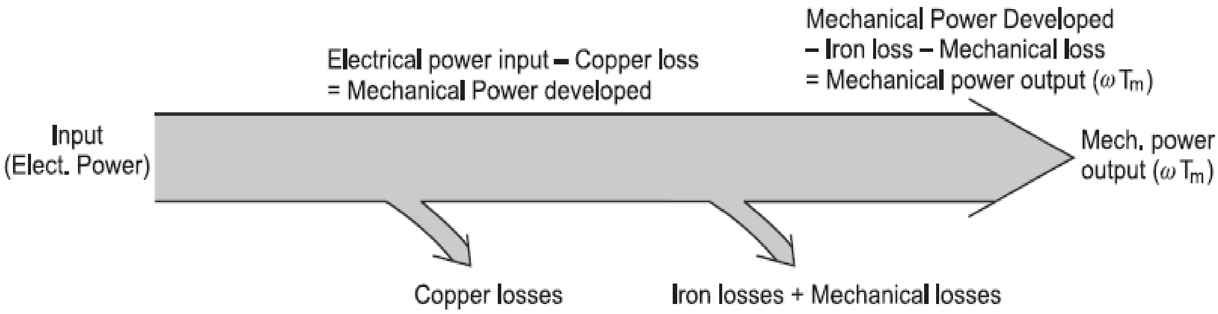


Figure 3 Power Flow Diagram of Synchronous Motor

7. V-Curves and Inverted V-Curves:

While changing the excitation of a three-phase synchronous motor, keeping the load constant, the curve plotted between field current (**I_f**) and armature or load current (**I**) is called V-curve. It is named as V-curve because its shape resembles with the shape of English alphabet 'V'. When the excitation of a three-phase synchronous motor taking constant power is varied, it changes the operating power factor of the motor.

Let: **P = 3 V I cos θ**

Where, **P** = Power input to motor, **V** = Terminal voltage (phase value), **I** = Armature current (phase value) and **cos θ** = Power factor.

Then for constant power input (**P**) and terminal voltage (**V**), only increase in power factor (**cos θ**) causes decrease in armature current (**I**) and vice versa. Armature current will be minimum at unity power factor and increases when the power factor decreases on either side (lagging or leading). Hence variation in excitation (field current) causes the variation in armature current (**I**). If we plot a curve taking field current (**I_f**) on X-axis and the armature current (**I**) on Y-axis, the curve obtained is called V-curve because of its shape. The V-curve at different power inputs are shown in Figure 4.

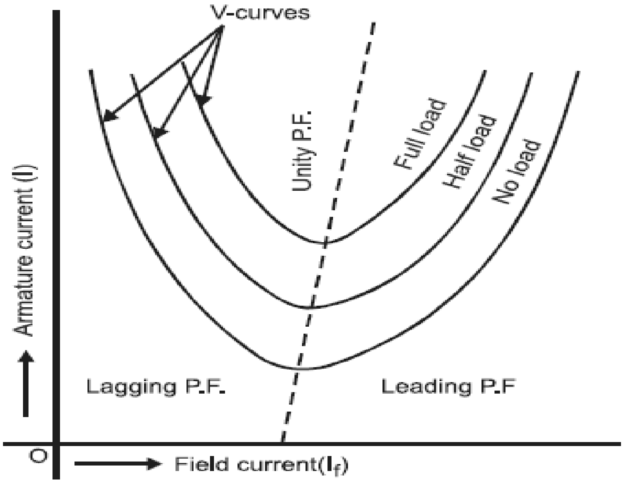


Figure 4, V-Curves at Different Loading Conditions

V-curves give a clear expectation about the relationship between adjusted field current and the withdrawn armature current of the motor. By increasing the field current (**I_f**) beyond the level of minimum armature current (**I**), we can obtain leading power factor. On the other hand, by decreasing the field current (**I_f**) below the level of minimum armature current (**I**), we can obtain lagging power factor. Therefore, by controlling the field current of a synchronous motor, the reactive power supplied to or consumed from the power system can be controlled.

Thus, by changing the field current (or excitation), a synchronous motor can be used as a **condenser** (supplying reactive power at leading power factor), or **inductor** (consuming reactive power at lagging power factor).

8. Inverted V-Curves:

If we plot a family of curves between power factor and field current (**I_f**), the curves so obtained are called inverted V-curves, as shown in Figure 5, because of their shape (like inverted V-letter). These curves reveal that:

- The highest point on each of these curves indicate unity P.F.
- The field current for unity P.F. at full load is more than the field current for unity P.F. at no-load.
- If the synchronous motor at full load is operating at unity P.F., then the removal of shaft load causes the motor to operate at leading P.F.

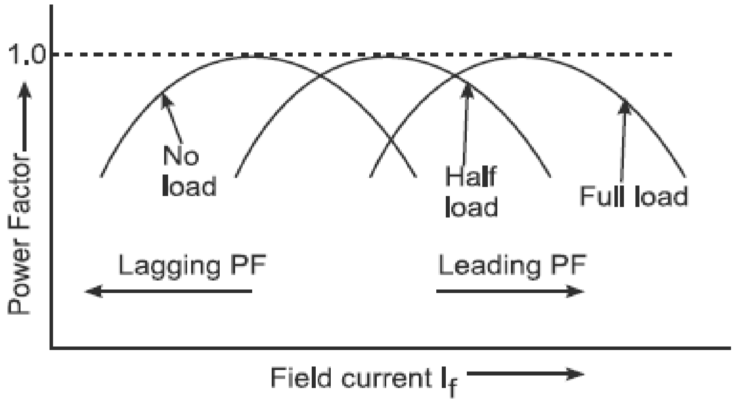


Figure 5, Inverted V-Curves at Different Loading Conditions

9. Synchronous Condenser:

The power factor of a synchronous motor can be controlled over a wide range by adjusting its excitation. At no-load, when the motor is over-excited it may draw the current from mains which leads the voltage by large angle nearly 90°. Hence, the motor acts like a static capacitor and is known as a synchronous condenser. Thus, an over excited synchronous motor operating at no-load is called a **synchronous condenser**.

When an over excited motor is operated on the same electrical system to which some industrial load (induction motors, induction furnaces, arc furnaces, etc.) is operating at lagging power factor, the leading reactive power supplied by the synchronous motor compensates for the lagging reactive power of industrial load and improves the overall power factor of the system. In large industrial plants, which have a low lagging power factor load, it is often found economical to install an over excited synchronous motor (synchronous condenser), even though the motor is not required to drive a load. Consider an industrial load (**P_L**)operating at a power factor (**$\cos \theta_1$**). When an over excited motor drawing power (**P_m**) is connected in parallel with the existing load as shown in Figure 6 (a), some of the lagging reactive power of the industrial load in compensated by the leading reactive power of the motor (i.e., $\mathbf{Q_m}$) which improves the over-all power factor to ($\mathbf{\cos \theta_2}$) as shown in Figure 6 (b).

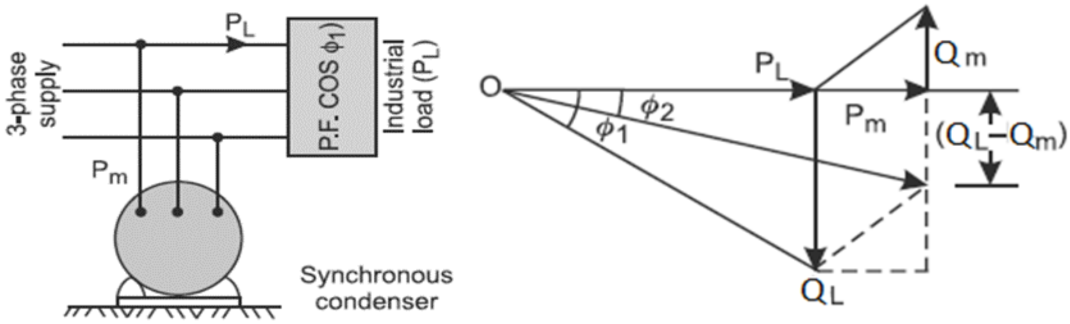


Figure 6 (a) Synchronous Motor as Synchronous Condenser (b) Phasor Diagram

Example:

The excitation of a three-phase synchronous motor connected in parallel with a load of 500 kW operating at 0·8 p.f. lagging is adjusted to improve the overall p.f. of the system to 0.9 lagging. If the mechanical load on the motor including losses is 125 kW, calculate the kVA input to the synchronous motor and its p.f.

Sol:

Industrial load: Active power, $\mathbf{P_L}$ = 500 kW, Load p.f., $\cos \theta_L = 0.8$ lagging

Reactive power of industrial load, $\mathbf{Q_L} = P_L \tan \theta_L = 500 \times 0{\cdot}75 = 375$ kVAR

Motor load: $\mathbf{P_m}$ = 125 kW

Total active power, $\mathbf{P_T = P_L + P_m} = 500 + 125 = 625$ kW

Power factor of total load, $\cos \theta_T = 0{\cdot}9$ lag

$\tan \theta_T = \tan \cos^{-1} 0{\cdot}9 = 0{\cdot}4843$

Total reactive power, $\mathbf{Q_T = P_T \tan \theta_T} = 625 \times 0{\cdot}4843 = 302{\cdot}7$ kVAR

Reactive power supplied by synchronous motor,

$\mathbf{Q_m = Q_T - Q_L} = 302{\cdot}7 - 375 = -72{\cdot}3$ kVAR

Input of the motor in kVA,

$\mathbf{S_m = Sqrt\ [P_m^2 + Q_m^2]}$

$\mathbf{S_m} = 144{\cdot}4$ kVA

Power factor of the motor,

$\mathbf{\cos \theta_m = P_m / S_m = 125 / 144.4 = 0.8656}$ Leading P.F.

10.Characteristics of Synchronous Motor:

A synchronous motor has the following important characteristics:

- It is inherently not a self-starting motor.
- For a given frequency, it operates only at one speed called synchronous speed given by the expression NS = 120 f / P.

- It can be operated under a wide range of power factors both lagging and leading.
- In addition to the motor being used for mechanical load, it is also used as a power factor improvement equipment and is known as synchronous condenser.
- At no-load it draws a very small current from the mains to meet the internal losses of the motor. With the increase in load, the torque angle δ increases due to which motor draws more current from the mains. After the input current reaches maximum (torque angle δ in nearly 90°) no further increase in load is possible. If the motor is further loaded it goes out of synchronism and stops.

11.Methods of Starting of Synchronous Motor:

Since a synchronous motor is inherently not self-starting, the following methods are generally adopted to start the synchronous motor:

I. **By Means of an Auxiliary Motor:** A small induction motor called the pony motor (auxiliary motor) is mounted on the same shaft or coupled to synchronous motor as shown in Figure 7. The auxiliary motor should have the same number of poles as that of synchronous motor or preferably one pole pair less so that it can rotate the motor nearly at synchronous speed. First, supply is given to the pony motor.

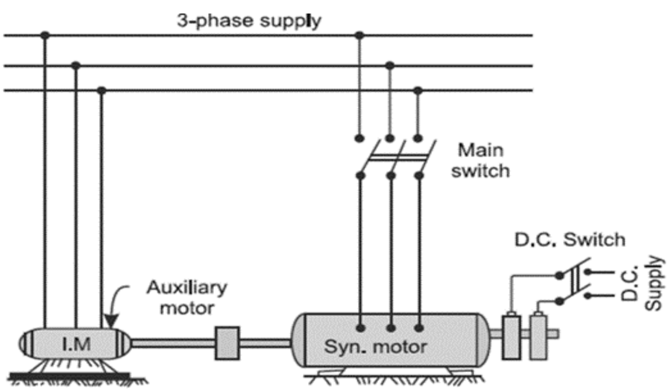


Figure 7, Starting of SM by means of Auxiliary Motor

When it rotates the rotor of the synchronous motor near to the synchronous speed the main switch and DC switch of the main synchronous motor are closed. The rotor poles are pulled into synchronism with the rotating field (poles) of the armature (stator) of the main motor. Then supply to the auxiliary motor is disconnected, and it acts as a load on the main motor.

II. **By Providing Damper Winding:**

This is a most common method of starting a synchronous motor. In this method, the motor is first started as a squirrel cage induction motor by providing a special winding on the rotor poles, known as damper or squirrel cage winding.

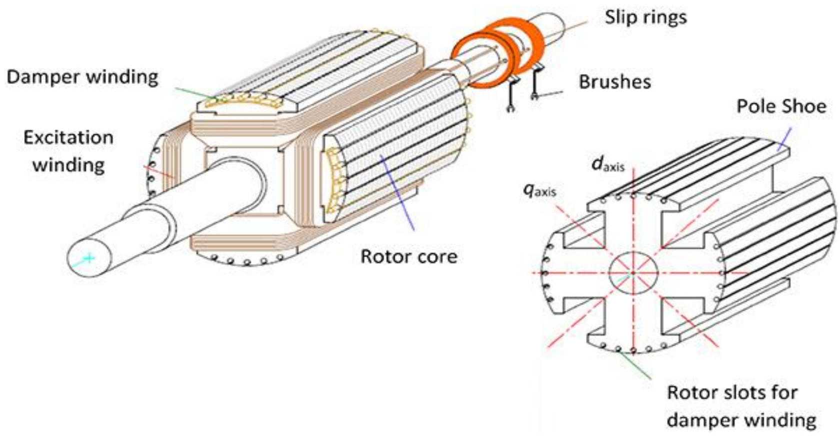


Figure 8, Starting of SM by Providing Damper Winding

This damper winding consists of number of copper bars embedded into the slots or holes provided on the outer periphery of the pole shoes, where salient poles are employed, and then short circuiting these bars by brazing them to end rings as shown in Figure 8. In a non-salient pole machine, the damper winding conductors are placed in the rotor slots above the main field winding and short circuited by the end rings. When the synchronous motor is connected to three-phase supply mains, a revolving field is set up which causes the rotor to rotate as a squirrel cage induction motor. As soon as motor attains about 65% synchronous speed, the rotor winding is connected to DC exciter and the rotor field is magnetically locked with the stator rotating field and the starts running as a synchronous motor.

12.Hunting:

When a synchronous motor is loaded, the rotor poles slightly fall back in position with respect to the stator field (poles) by an angle δ known as power angle or torque angle or retarding angle. As the load is gradually increased, this angle δ also increases gradually so as to produce more torque for coping with the increased load and the motor remains in equilibrium. If the load is suddenly changed (large decrease, or increase in applied load), angle δ decreases suddenly and the rotor poles are pulled into almost exact opposition to the stator poles, but due to inertia of rotor and rotor poles travel too far. They are then pulled back again, and so on, thus oscillations are set up around the equilibrium position, corresponding to new load. If these oscillations are too large, they may throw the motor out of synchronism and stops.

The oscillation of the rotor about its equilibrium position is known as hunting. The hunting may also occur when the machine is operating as an alternator. In this case also because of sudden change in electrical output or mechanical input oscillations are set up in the rotor called hunting. From the above discussions, the following factors are evolved:

I. Causes of Hunting

- Sudden change in the load.
- Sudden change in the field current.
- Cyclic variation of the load torque.
- Faults occurring in the system.

II. Effects of Hunting

- The machine (generator or motor) may go out of synchronism.
- Large mechanical stresses may develop in the rotor shaft.
- It increases the machine losses which may overheat the machine.
- It may cause variations in supply voltage (at generator operation).

III. Reduction of Hunting

- By using damper winding: The eddy currents developed in the damper winding, damped down the oscillations.
- By using flywheels: The prime-mover is provided with a large and heavy flywheel which increases the inertia of the prime-mover and helps in maintaining the motor speed constant.

13.Applications of Synchronous Motors:

The following are the important applications of synchronous motors:

- Improving the power factor of large industries and substations.
- These motors are mostly used to drive equipment which are operated at constant speed continuously such as centrifugal pumps, centrifugal fans, air compressors, motor-generator sets, blowers, etc.