Chapter -5

Synchronous Motors

Introduction of Synchronous Motors

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 ($N_s = 120f/P$) 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. However, synchronous motors are not used so much because they run at constant speed (i.e., synchronous speed).

synchronous motors are rated between 150 kW and 15 MW and run at speeds ranging from 150 to 1800 r.p.m.

Characteristic of Synchronous Motors :

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.

Construction of Synchronous Motor .:

11.1 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:

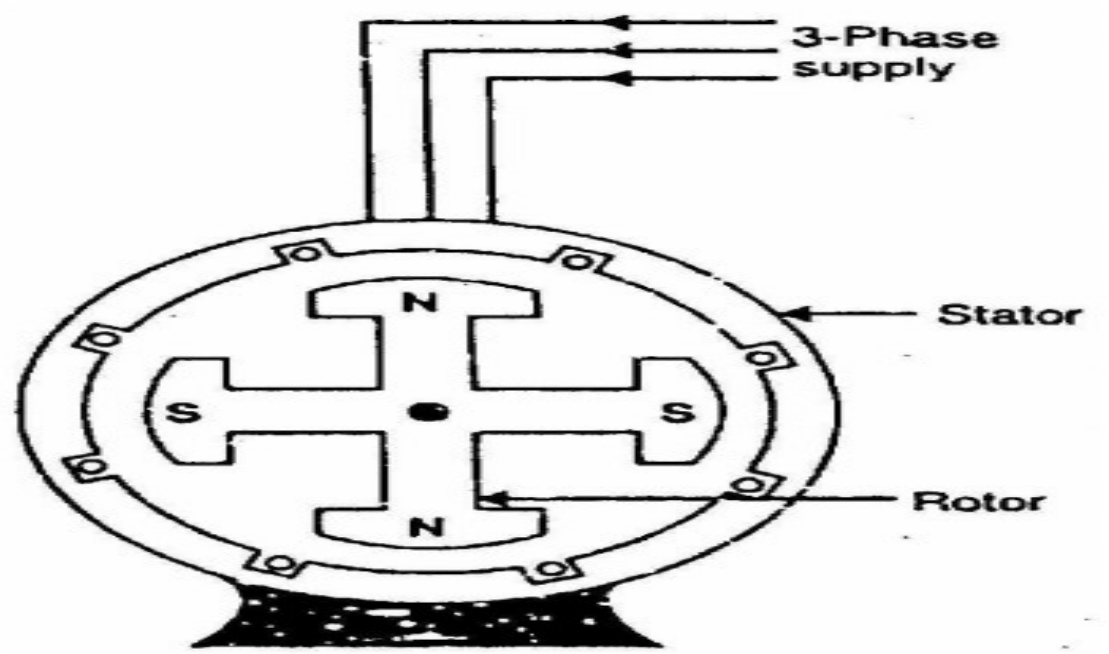


Fig.(11.1)

(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. (11.1)].

(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:

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

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 of Synchronous Motor :

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.

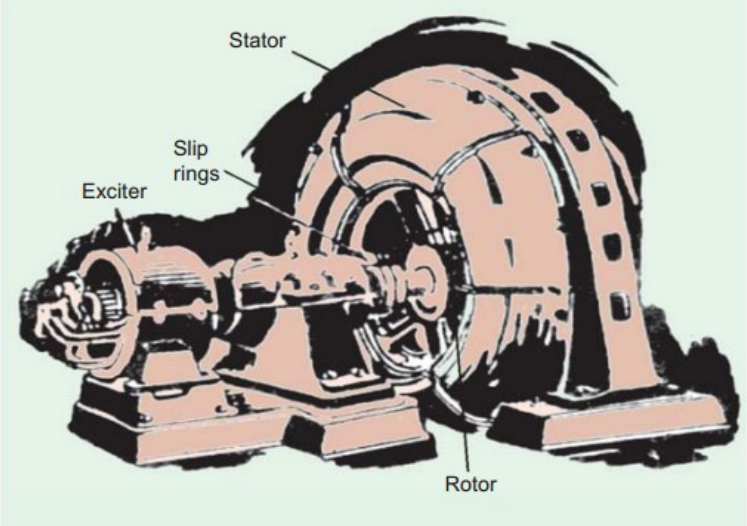


Fig. 38.1

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.

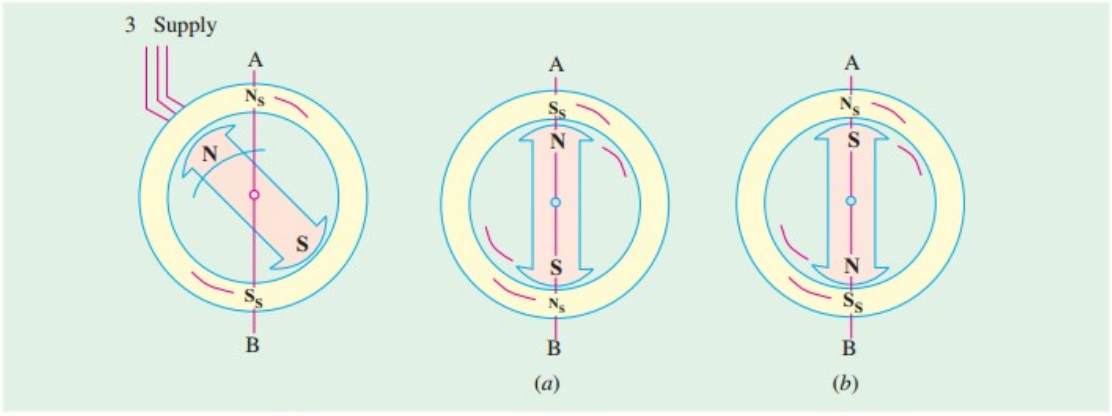


Fig. 38.2 Fig. 38.3 Fig. 38.3

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.

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. (11.3 (i)). 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. (11.3 (ii)). 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.

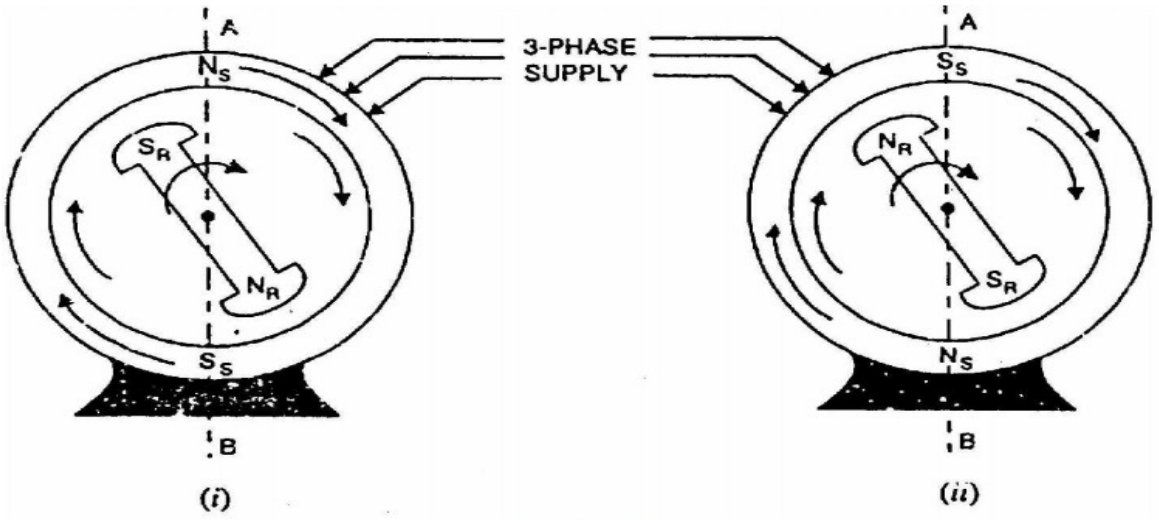


Fig.(11.3)

11.4 Making Synchronous Motor Self-Starting

A synchronous motor cannot start by itself. In order to make the motor self-starting, a squirrel cage winding (also called damper winding) is provided on the rotor. The damper winding consists of copper bars embedded in the pole faces of the salient poles of the rotor as shown in Fig. (11.4). The bars are short-circuited at the ends to form in effect a partial squirrel cage winding. The damper winding serves to start the motor.

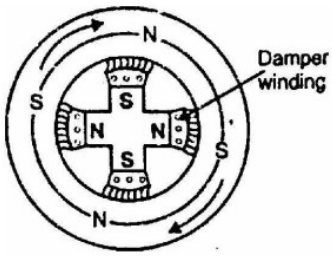


Fig.(11.4)

Equivalent Circuit Diagram of a Synchronous Motor :

Fig. 38.9 (*a*) shows the equivalent circuit model for one armature phase of a cylindrical rotor synchronous motor.

It is seen from Fig. 38.9 (*b*) that the phase applied voltage V is the vector sum of reversed back e.m.f. *i.e.*, $-E_b$ and the impedance drop $I_a Z_S$. In other words, $V = (-E_b + I_a Z_S)$. The angle α* between the phasor for V and E_b is called the load angle or power angle of the synchronous motor.

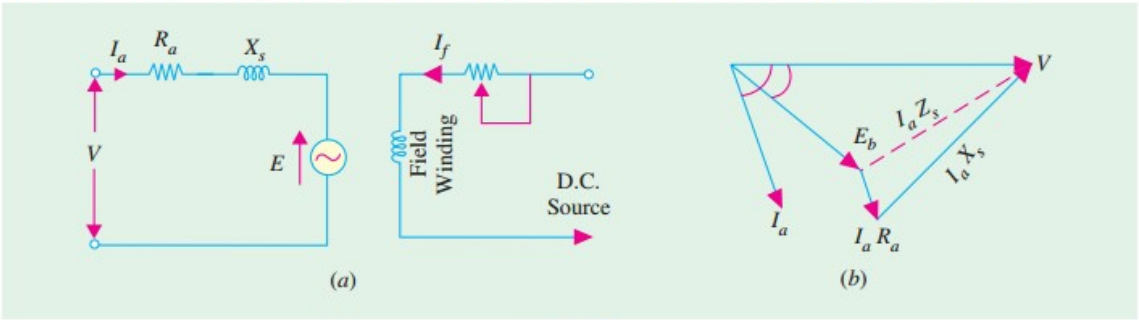


Fig. 38.9

Net voltage/phase in stator winding is

$$E_r = V - E_b$$ phasor difference

Armature current/phase, $I_a = \dfrac{E_r}{Z_s}$

where $Z_s = \sqrt{R_a^2 + X_s^2}$

This equivalent circuit helps considerably in understanding the operation of a synchronous motor.

A synchronous motor is said to be normally excited if the field excitation is such that $E_b = V$. If the field excitation is such that $E_b < V$, the motor is said to be under-excited. The motor is said to be over-excited if the field excitation is such that $E_b > V$. As we shall see, for both normal and under excitation, the motor has lagging power factor. However, for over-excitation, the motor has leading power factor.

Power Flow within a Synchronous Motor :

Let R_a = armature resistance / phase ; X_S = synchronous reactance / phase

then $\mathbf{Z_S} = \mathbf{R}_a + j X_S$; $\mathbf{I}_a = \dfrac{\mathbf{E_R}}{\mathbf{Z_S}} = \dfrac{\mathbf{V} - \mathbf{E_b}}{\mathbf{Z_S}}$; Obviously, $\mathbf{V} = \mathbf{E}_b + \mathbf{I}_a \mathbf{Z_S}$

The angle θ (known as internal angle) by which I_a lags behind E_R is given by $\tan \theta = X_S / R_a$.

If R_a is negligible, then $\theta = 90°$. Motor input = $V I_a \cos \phi$ —per phase

Here, V is applied voltage / phase.

Total input for a star-connected, 3-phase machine is, $P = \sqrt{3}\, V_L \,.\, I_L \cos \phi$.

The mechanical power developed in the rotor is

P_m = back e.m.f. × armature current × cosine of the angle between the two *i.e.*, angle between I_a and E_b reversed.

$= E_b I_a \cos (\alpha - \phi)$ per phase ...Fig. 38.8

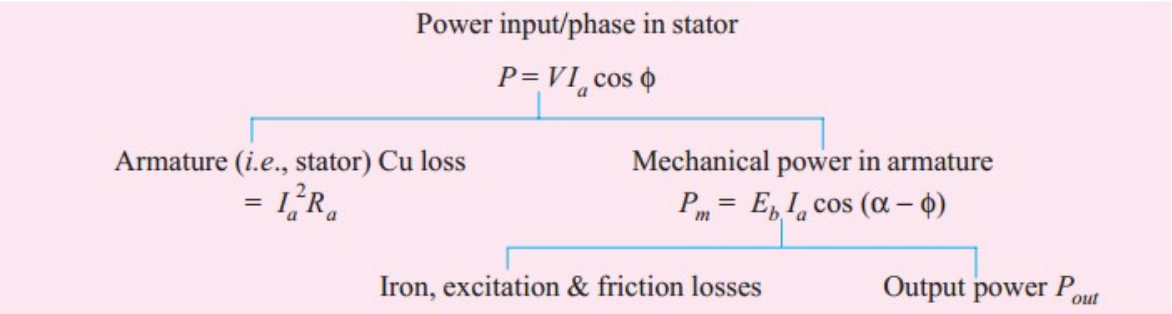
Out of this power developed, some would go to meet iron and friction and excitation losses. Hence, the power available at the shaft would be less than the developed power by this amount.

Out of the input power / phase $V I_a \cos \phi$, and amount $I_a^2 R_a$ is wasted in armature***, the rest ($V . I_a \cos \phi - I_a^2 R_a$) appears as mechanical power in rotor; out of it, iron, friction and excitation losses are met and the rest is available at the shaft. If power input / phase of the motor is P, then

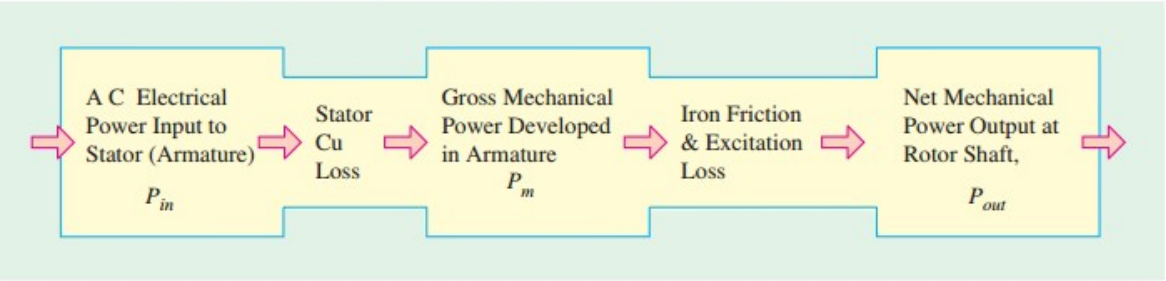
$$P = P_m + I_a^2 R_a$$

or mechanical power in rotor $P_m = P - I_a^2 R_a$ —per phase

For three phases $P_m = \sqrt{3}\, V_L I_L \cos \phi - 3 I_a^2 R_a$



Different power stages in a synchronous motor are as under :



11.12 Motor Torque

$$\text{Gross torque, } T_g = 9.55\frac{P_m}{N_s} \text{ N - m}$$

where P_m = Gross motor output in watts = $E_b I_a \cos(\delta - \phi)$
N_s = Synchronous speed in r.p.m.

$$\text{Shaft torque, } T_{sh} = 9.55\frac{P_{out}}{N_s} \text{ N - m}$$

It may be seen that torque is directly proportional to the mechanical power because rotor speed (i.e., N_s) is fixed.

11.13 Mechanical Power Developed By Motor

(Armature resistance neglected)

Fig. (11.13) shows the phasor diagram of an under-excited synchronous motor driving a mechanical load. Since armature resistance R_a is assumed zero. $\tan\theta = X_s/R_a = \infty$ and hence $\theta = 90°$.

Input power/phase = $V I_a \cos\phi$

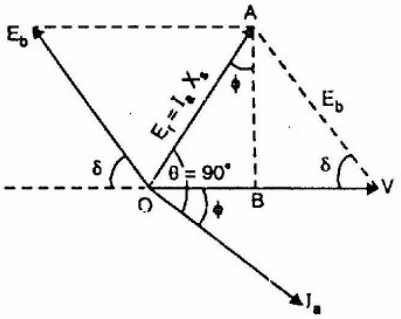


Fig.(11.13)

Since R_a is assumed zero, stator Cu loss ($I_a^2 R_a$) will be zero. Hence input power is equal to the mechanical power P_m developed by the motor.

Mech. power developed/ phase, $P_m = V I_a \cos\phi$ (i)

Referring to the phasor diagram in Fig. (11.13),

$$AB = E_r \cos\phi = I_a X_s \cos\phi$$

Also $$AB = E_b \sin\delta$$

$$\therefore \quad E_b \sin\delta = I_a X_s \cos\phi$$

or $$I_a \cos\phi = \frac{E_b \sin\delta}{X_s}$$

$$P_{max} = \frac{V E_b}{X_s} \quad \text{per phase}$$

11.12 Motor Torque

$$\text{Gross torque, } T_g = 9.55\frac{P_m}{N_s} \text{ N - m}$$

where P_m = Gross motor output in watts = $E_b I_a \cos(\delta - \phi)$
N_s = Synchronous speed in r.p.m.

$$\text{Shaft torque, } T_{sh} = 9.55\frac{P_{out}}{N_s} \text{ N - m}$$

It may be seen that torque is directly proportional to the mechanical power because rotor speed (i.e., N_s) is fixed.

11.16 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.

(*b*) Constant-speed applications

Because of their high efficiency and high-speed, synchronous motors (above 600 r.p.m.) are well-suited for loads where constant speed is required such as centrifugal pumps, belt-driven reciprocating compressors, blowers, line shafts, rubber and paper mills etc.

Low-speed synchronous motors (below 600 r.p.m.) are used for drives such as centrifugal and screw-type pumps, ball and tube mills, vacuum pumps, chippers and metal rolling mills etc.