Synchronous Motor

Exciter
Slip Rings
Stator
Rotor

Fig. 36.1
Synchronous Motor-General

A synchronous motor is electrically identical with an alternator or AC generator.

A given alternator (or synchronous machine) can be used as a motor, when driven electrically.

Some characteristic features of a synchronous motor are as follows:

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 $N_S=120f/P$).

2. **It is not inherently self-starting.** It has to be run up to 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.
Principle of Operation

When a 3-phase winding is fed by a 3-phase supply, then a magnetic flux of constant magnitude but rotating at synchronous speed, is produced.

Consider a two-pole stator of Fig. 36.2, in which are shown two stator poles (marked $N_S$ and $S_S$) rotating at synchronous speed say, in clockwise direction.

Since the two similar poles, $N$ (of rotor) and $N_S$ (of stator) as well as $S$ and $S_S$ will repel each other, the rotor tends to rotate in the anti-clockwise direction.

But half a period latter, stator poles, having rotated around, interchange their position i.e. $N_S$ is at position B and $S_S$ at point A. under these conditions, $N_S$ attracts $S$ and $S_S$ attracts $N$ and rotor tends to rotate clockwise.

Hence, we find that due to continuous and rapid rotation of stator poles, 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.
Now, consider the condition shown in Fig. 36.3(a) where the stator and rotor poles are attracting each other.

Suppose that the rotor is not stationary, but it is rotating clockwise, with such a speed that turns through one pole-pitch by the time the stator poles interchange their positions, as shown in Fig. 36.3(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 \textit{i.e.} clockwise torque, as shown in Fig. 36.3.
Method of Starting

There are several methods to start the synchronous motor such as:

(a) Auxiliary drive (induction motor or dc motor),
(b) Induction start (using damper winding), etc

General Starting Procedure: The rotor (which is as yet unexcited) is speeded up to synchronous or near synchronous speed by some arrangement and then excited by the DC source.

The moment this (near) synchronously rotating rotor is excited, it is magnetically locked into position with the stator i.e. the rotor poles are engaged with the stator poles and both run synchronously in the same direction.

It is because of this inter-locking of stator and rotor poles that the motor has either to run synchronously or not at all.

However, it is important to understand that the arrangement between the stator and rotor poles is not an absolutely rigid one.
As the load on the motor is increase, the rotor progressively tends to fall back *in phase* (but *not* in speed as in DC motors) by some angle *(Fig. 36.4)* *but it still continuous to run synchronously*.

![Diagram](image)

The value of this load angle or coupling angle (as it is called) depends on the amount of load to be met by the motor.

In other words, the torque developed by the motor depends on this angle, say, $\alpha$. This angle is referred as *load angle* or *coupling angle*. This is also the angle between rotor and stator fields.
Procedure for Starting a Synchronous Motor Using the Damper Winding

While starting a modern synchronous motor provided with damper windings, following procedure is adopted.

1. First, main field winding is short circuited.
2. Reduced voltage with the help of auto-transformers is applied across stator terminals. The motor starts up.
3. When it reaches a steady state speed (as judge by its sound), a weak DC excitation is applied by removing the short-circuit on the main field winding. If excitation is sufficient, then the machine will be pulled into synchronism.
4. Full supply voltage is applied across stator terminals by cutting out the auto-transformers.
5. The motor may be operated at any desired power factor by changing the DC excitation.
Motor on Load With Constant Excitation

In a synchronous machine, a back emf $E_b$ (as like DC motor) is set up in the armature (stator) by the rotor flux which opposes the applied voltage $V$.

This back emf depends on rotor excitation only (and not on speed as in DC motors).

The net voltage in armature (stator) is the *vector difference* (not arithmetical, as in DC motors) of $V$ and $E_b$.

Armature current is obtained by dividing this vector difference of voltages by armature impedance (not resistance as in DC machines).

**Fig. 36.6** shows the condition when the motor (properly synchronized to the supply) is running on *no-load* and has *no losses* and is having fixed 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 angle $\alpha$ (Fig. 36.7), 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 $\alpha$-called the load angle or coupling angle.

The resultant voltage $E_R$ is increased and motor draws an increased armature current (Fig. 36.8), though at a slightly decreased power factor.
Fig. 36.9(a) shows the equivalent circuit model for one armature phase of a cylindrical rotor synchronous motor.

It is seen from Fig. 36.9(b) that the phase applied voltage $V$ is the vector sum of reversed back emf $-E_b$ and the impedance drop $I_a Z_s$.

In other words, $V = (-E_b + I_a Z_s)$.

The angle $\alpha$ between the phasor for $V$ and $E_b$ is called the load angle or power angle of the synchronous motor.
Power Flow within a Synchronous Motor

Let \( R_a = \text{armature resistance/phase}; \)
\( X_S = \text{synchronous reactance/phase} \)

Then, \( Z_s = R_a + jX_s \);

\[
I_a = \frac{E_R}{Z_s} = \frac{V - E_b}{Z_s}
\]

Obviously, \( V = E_b - I_a Z_S \)

The angle \( \theta \) (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 \( \theta = 90^\circ \).

Motor input = \( VI_a \cos \phi \)-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, some would go to meet iron and fraction 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 \( VI_a \cos \phi \), and amount \( I_a^2 R_a \) is wasted in armature, the rest \( (VI_a \cos \phi - I_a^2 R_a) \) appears as mechanical power in rotor; out of it, iron, friction and excitation losses are meet 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 \( P_m = \sqrt{3} V_L I_L \cos \phi - 3I_a^2 R_a \).
The per phase power development in a synchronous machine is as under:

\[ P = V I_a \cos \phi \]

- Armature (i.e. stator) Cu loss: \[ I_a^2 R_a \]
- Mechanical power in armature: \[ P_m = E_b I_a \cos(\alpha - \phi) \]
- Iron, excitation & friction losses

Different power stages in a synchronous motor are as under:

1. **A C Electrical Power Input to Stator (Armature)**: \( P_{in} \)
2. **Stator Cu Loss**: \( P_{Cu} \)
3. **Gross Mechanical Power Developed in Armature**: \( P_m \)
4. **Iron Friction & Excitation Loss**: \( P_{loss} \)
5. **Net Mechanical Power Output at Rotor Shaft**: \( P_{out} \)
Power Developed by a Synchronous Motor

The armature resistance of a synchronous motor is negligible as compared to its synchronous reactance.

Hence the equivalent circuit for the motor becomes as shown in Fig. 36.10 (a).

From the phasor diagram of Fig. 36.10(b), it is seen that

\[ AB = E_b \sin \alpha = I_a X_S \cos \phi \]

Or, \( VI_a X_S \cos \phi = E_b V \sin \alpha \)

Now, \( VI_a \cos \phi = \) motor power input/phase

\[ \therefore P_{in} = \frac{E_b V}{X_S} \sin \alpha \quad \text{– per phase} \]

\[ \therefore P_{in} = \frac{3E_b V}{X_S} \sin \alpha \quad \text{– for three phase} \]

Since Stator Cu losses have been neglected, \( P_{in} \) also represents the gross mechanical power \( (P_m) \) developed by the motor.

The gross torque developed by the motor is \( T_g = 9.55 \frac{P_m}{N_S} \) N-m \( - \) \( N_S \) in rpm.

\[ \therefore T_g = 9.55 \frac{P_m}{N_S} = \frac{9.55 \times 3E_b V}{N_S X_S} \sin \alpha = 28.65 \frac{E_b V \sin \alpha}{N_S X_S} \quad \text{N–m} \]
Example 38.1 A 75 kW, 3-phase, Y-connected, 50 Hz, 440 V cylindrical rotor synchronous motor operates at rated condition with 0.8 power factor leading. The motor efficiency excluding field and stator losses, is 95% and $XS=2.5$ ohm. Calculate: (i) mechanical power developed, (ii) armature current, (iii) back emf, (iv) power angle, and (v) maximum or pull-out torque of the motor.

Solution: $N_S = 120 \times 50/4 = 1500$ rpm = 25 rps.

(i) $P_{in} = P_m = P_{out} / \eta = 75 \times 103 / 0.95 = 78,950$ W

(ii) Since power input is known, we know that

$$\sqrt{3}V_L I_a \cos \phi = \sqrt{3} \times 440 \times I_a \times 0.8 = 78,950 \text{ W}; \quad I_a = \frac{78,950}{\sqrt{3} \times 440 \times 0.8} = 129 \text{ A}$$

(iii) Applied voltage/phase = $\sqrt{3} \times 440 = 254$ Let $V = 254 \angle 0^\circ$ as shown in Fig. 36.11. Now, $V = E_b + jIX_S$ and $\phi = \cos^{-1}(0.8) = 36.9^\circ$

or, $E_b = V - jIX_S = 254 \angle 0^\circ - 129 \angle 36.9^\circ \times 2.5 \angle 90^\circ = 516 \angle -30^\circ$

(iv) $\therefore$ Power angle, $\alpha = -30^\circ$

(v) Maximum or pull-out torque occurs when $\alpha = 90^\circ$.

$$P_{m(max)} = \frac{3E_bV}{X_S} \sin \alpha = \frac{3 \times 254 \times 516}{2.5} \sin 90^\circ = 157,276.8 \text{ W}$$

$\therefore$ Pull-out torque = $9.55 \times 157,276.8 / 1500 = 1001.328 \text{ N-m}$
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. 36.12**.

If DC 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. 36.13(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. 36.13(b)**.
The value of $\alpha$ and back emf $E_b$ can be found with the help of vector diagrams for various power factors.

**(i) Lagging Power Factor:** As seen from Fig. 36.14(a)

\[
AC^2 = AB^2 + BC^2 = [V - E_R \cos(\theta - \phi)]^2 + [E_R \sin(\theta - \phi)]^2
\]

\[
\theta = \tan^{-1} \left( \frac{X_S}{R_a} \right)
\]

\[
E_b = AC = \sqrt{[V - I_a Z_S \cos(\theta - \phi)]^2 + [I_a Z_S \sin(\theta - \phi)]^2}
\]

\[
\alpha = \tan^{-1}\left( \frac{BC}{AB} \right) = \tan^{-1}\left( \frac{I_a Z_S \sin(\theta - \phi)}{V - I_a Z_S \cos(\theta - \phi)} \right)
\]

\[
E_R = V + E_b
\]

\[
E_b = \sqrt{V^2 + E_R^2 - 2VE_R \cos(\theta + \phi)}
\]

\[
E_R = V(\cos0^0 + j\sin0^0) + E_b[\cos(180^0 - \alpha) + j\sin(180^0 - \alpha)]
\]

\[
E_R = [V - E_b \cos\alpha] + jE_b \sin\alpha
\]

Angle between $E_R$ and $V$ is:

\[
\theta - \phi = \tan^{-1} \left( \frac{E_b \sin\alpha}{V - E_b \cos\alpha} \right)
\]
(ii) **Leading Power Factor:** As seen from Fig. 36.14(b)

\[
E_b = \sqrt{[V + I_a Z_S \cos \{180^\circ - (\theta + \phi)\}]^2 + [I_a Z_S \sin \{180^\circ - (\theta + \phi)\}]^2}
\]

\[
\alpha = \tan^{-1}\left( \frac{I_a Z_S \sin \{180^\circ - (\theta - \phi)\}}{V - I_a Z_S \cos \{180^\circ - (\theta - \phi)\}} \right)
\]

\[
E_b = \sqrt{[V - I_a Z_S \cos (\theta + \phi)]^2 + [I_a Z_S \sin (\theta + \phi)]^2}
\]

\[
\alpha = \tan^{-1}\left( \frac{I_a Z_S \sin (\theta + \phi)}{V - I_a Z_S \cos (\theta + \phi)} \right)
\]

\[
E_b = \sqrt{V^2 + E_R^2 - 2 V E_R \cos (\theta - \phi)}
\]

\[
E_R = V + E_b
\]

\[
E_R = V (\cos 0^\circ + j \sin 0^\circ) + E_b [\cos (180^\circ - \alpha) + j \sin (180^\circ - \alpha)]
\]

\[
E_R = [V - E_b \cos \alpha] + j E_b \sin \alpha
\]

**Power factor angle:**

\[
\theta = \tan^{-1} \frac{X_S}{R_a}
\]
(iii) **Unity Power Factor**: As seen from Fig. 36.14(c)

Power factor angle:

\[
\theta = \tan^{-1} \frac{X_s}{R_a}
\]

Here, \(OB = I_a R_a\) and \(BC = I_a X_S\);

\[
E_b = \sqrt{[V + I_a R_a]^2 + [I_a X_S]^2}; \quad \alpha = \tan^{-1} \left( \frac{I_a X_S}{V - I_a R_a} \right)
\]
Example 20.1 A 25-hp 220V 60Hz four pole Y-connected synchronous motor is rotating with a light load. The angle between the rotor and stator fields is 3°. The excitation is adjusted for a generated armature voltage per phase of 110V. (a) what is the resultant armature voltage per phase? (b) what is the angle between resultant voltage \( E_R \) and terminal voltage \( V \).

Solution: Terminal voltage per phase, \( V = \frac{220}{\sqrt{3}} = 127V \)
\(
\alpha = 3^\circ. \ Cos\alpha = 0.9986 \ and \ sin\alpha = 0.0523 \\
\)

We know that, \( E_R = [V - E_b \cos \alpha] + jE_b \sin \alpha \)

Thus, \( E_R = \sqrt{[V - E_b \cos \alpha]^2 + [E_b \sin \alpha]^2} \)

\[
E_R = \sqrt{[127 - 110 \times 0.9986]^2 + [110 \times 0.0523]^2} = 17.95 \ V
\]

\( b \) \( \theta - \phi = \tan^{-1} \frac{E_b \sin \alpha}{V - E_b \cos \alpha} = \tan^{-1} \frac{110 \times 0.0523}{127 - 110 \times 0.9986} = 18.7^\circ \)
Effect of Increased Load with Constant Excitation

The effect of increased load on a synchronous motor will be studied under conditions of normal, under and over-excitation (ignoring the effects of armature reaction).

With normal-excitation, \( E_b = V \), with under-excitation, \( E_b < V \) and with over-excitation, \( E_b > V \). The value of excitation would be kept constant.

\( R_a \) is considered negligible as compared to \( X_s \) so that phase angle between \( E_R \) and \( I_a \) i.e. \( \theta = 90^\circ \).

Normal Excitation, \( (E_b = V) \)

Fig. 36.15(a) shows the condition when motor is running with light load so that (a) torque angle \( \alpha_1 \) is small, (b) so \( E_{R1} \) is small, (c) hence \( I_{a1} \) is small and (d) \( \phi_1 \) is small so that \( \cos \phi_1 \) is large.

Now, suppose that load on the motor is increased as shown in Fig. 36.15(b).

For meeting this extra load, motor must develop more torque by drawing more armature current.
What actually happens is as under:

1. Rotor falls back *in phase* i.e. load angle increases to $\alpha_2$ as shown in Fig. 36.15(b)

2. The resultant voltage in armature is increased *considerably* to new value $E_{R2}$.

3. As a result, $I_{a1}$ increases to $I_{a2}$, thereby increasing the torque developed by the motor.

$\phi_1$ increase to $\phi_2$, so that power factor *decreases* from $\cos\phi_1$ to the new value $\cos\phi_2$. 

![Diagram](image)
Since increase in $I_a$ is much greater than the *slight* decrease in power factor, the torque developed by the motor is *increased* (on the whole) to a new value sufficient to meet the extra load put on the motor.

It will be seen that essentially it is by increasing its $I_a$ that the motor is able to carry the extra load put on it.

The effect of increased load on a synchronous motor at *normal excitation* is shown in **Fig. 36.16**.

It is seen that there is comparatively much greater *increase* in $I_a$ than in $\phi$. 
Under-excitation ($E_b < V$)

As shown in Fig. 36.17, with a small load and hence, small torque angle $\alpha_1$, $I_{a1}$ lags behind $V$ by a *large* phase angle $\phi_1$ which means poor power factor.

A much larger armature current must flow for developing the same power because of poor power factor.

As load increases, $E_{R1}$ increases to $E_{R2}$, consequently $I_{a1}$ increases to $I_{a2}$ and power factor angle *decreases* from $\phi_1$ to $\phi_2$.

Due to increase both in $I_a$ and power factor, power generated by the armature increases to meet the increased load.

As seen, in this case, *change in power factor is more than the change in $I_a$.*
**Over-excitation \((E_b > V)\)**

When running on light load, \(\alpha_1\) is small, but \(I_{a1}\) is comparatively larger and *leads* \(V\) by a larger angle \(\phi_1\).

Like the under excited motor, as motor load is applied, the power factor improves and *approaches unity*.

The armature current also increases thereby producing the necessary armature power to meet the increased load (Fig. 36.18).

In this case, power factor angle \(\phi\) decreases (or power factor increases) at a faster rate than the armature current thereby producing the necessary increased power to meet the increased load applied to the motor.

Fig. 36.18
The main points regarding the above three cases can be summarized as under:

1. As load on the motor increases, $I_a$ increases regardless of excitation.

2. For under- and over-excited motors, power factor tends to approach unity with increase in load.

3. Both with under- and over-excitation, change in power factor is greater than $I_a$ with increase in load.

4. With normal excitation, when load is increased change in $I_a$ is greater than in power factor which tends to become increasingly lagging.
Different Torques of a Synchronous Motor

Various torques associated with a synchronous motor are as follows:

1. Starting torque,
2. Running torque,
3. Pull-in torque, and
4. Pull-out torque.

(a) **Starting Torque**: It is the torque developed by the motor when full voltage is applied to its stator (armature) winding.

It is also sometimes called *breakaway* torque.
(b) **Running Torque**: As its name indicates, it is the torque developed by the motor under running conditions.

It is determined by the horse-power and speed of the *driven* machine.

The peak horse power determines the maximum torque that would be required by the driven machine.

The motor must have a breakdown or a maximum running torque greater than this value in order to avoid stalling.

(c) **Pull-in Torque**: A synchronous motor is started as induction motor till it runs 2 to 5% below the synchronous speed.

Afterwards, excitation is switched on and the rotor pulls into step with the synchronously rotating stator field.

The amount of torque at which the motor will pull into step is called the pull-in torque.
(d) **Pull-out Torque**: The maximum torque which the motor can develop without pulling out of step or synchronism is called the pull-out torque.

Normally, when load on the motor is increased, its rotor progressively tends to fall back *in phase* by some angle (called load angle) behind the synchronously-revolving stator magnetic field though it keeps running synchronously.

Motor develops maximum torque when its rotor is retarded by an angle of 90°.

Any further increase in load will cause the motor to pull out of step (or synchronism) and stop.
Effect of Excitation on Armature Current and Power Factor

Consider a synchronous motor in which the mechanical load is constant.

The value of excitation for which back emf $E_b$ is equal (in magnitude) to applied voltage $V$ is known as 100% excitation which is shown in Fig. 36.47(a).

The armature current $I$ lags behind $V$ by a small angle $\phi$.

Its angle $\theta$ with $E_R$ is fixed by stator constants i.e. $\tan \theta = X_S/R$. 
In Fig. 36.47(b) excitation is less than 100% i.e. \( E_b < V \).

Here, \( E_R \) is advanced clockwise and so is armature current (because it lags behind \( E_R \) by fixed angle \( \theta \)).

The magnitude of \( I \) is increased but its power factor is decreased (\( \phi \) has increased).

Because input as well as \( V \) are constant, hence the power component of \( I \) i.e. \( I \cos \phi = OA \) will remain constant.

When field current is reduced, the motor pull-out torque is also reduced in proportion.
**Fig. 36.47(c)** represent the condition for over-excited motor i.e. $E_b > V$. Here, the resultant voltage vector $E_R$ is pulled anti-clockwise and so is $I$.

Now motor is drawing a leading current.

It may also happen for some value of excitation, that $I$ may be in with $V$ i.e. power factor is unity as shown in **Fig. 36.47(d)**.

At that time, the current drawn by the motor would be minimum.
Two important points stand out clearly from the above discussion:

1. The magnitude of armature current varies with excitation.

The current has large value both for low and high values of excitation. In between, it has minimum value corresponding to a certain excitation.

The variations of $I$ with excitation are shown in Fig. 36.48(a) which are known as ‘V’ curves because of their shape.
2. For the same input, armature current varies over a wide range and so causes the power factor also to vary accordingly.

When over-excited, motor runs with leading power factor and with lagging power factor when under-excited.

In between, the power factor is unity.

The variations of power factor with excitation are shown in Fig. 36.48(b).

The curve for power factor looks like **inverted ‘V’ curve**.

It would be noted that minimum armature current corresponds to unity power factor.
Fig. 36.48
It is seen that an over-excited motor can be run with leading power factor.

This property of the motor renders it extremely useful for phase advancing (and so power factor correcting) purposes in the case of industrial loads driven by induction motors (Fig. 36.49) and lighting and heating loads supplied through transformer.

Both transformers and induction motor draw lagging currents from the line.

![Diagram of Induction Motors and Synch Motor](image)
The power drawn by them has a large reactive component and the power factor has a very low value.

This reactive component, though essential for operating the electrical machinery, entails appreciable loss in many ways.

The lagging reactive power of induction motor and transformers required is supplied by synchronous motors.

The synchronous motors supply only the active component of the load current.

When used in this ways, a synchronous motor is called a **synchronous capacitor (synchronous condenser)**, because it draws, like a capacitor, leading current from the line.
Advantages of SM over IM

Synchronous motors have the following advantages over induction motor:

1. SM can be used for power factor correction in addition to supplying torque to drive loads

2. SMs are more efficient (at unity power factor) than IM of corresponding horsepower and voltage rating.

3. The field pole rotor of SM can permit the use of wider airgap than the squirrel cage IM.
4. SM can operate lagging, leading and unity power factor but IM can operate only lagging power factor.

5. SM may less costly for the same horsepower, speed and voltage ratings.

6. They give constant speed from no-load to full-load.
Disadvantages of SM over IM

1. They require dc excitation which must be supplied from external source.
2. They have tendency to hunt.
3. They cannot be used for variable speed jobs as speed adjustment cannot be done.
4. They cannot be started under load. Their staring torque is zero.
5. They may fall out of synchronism and stop when overloaded.
Compare a Synchronous Motor with an Induction Motor

1. For a given frequency, the synchronous motor runs at constant average speed whatever the load, while the speed of an induction motor falls somewhat with increase in load.

2. The synchronous motor can be operated over a wide range of power factors, both lagging and leading, but induction motor always runs with a lagging power factor which may become very low at light loads.

3. A synchronous motors is inherently not self-starting but induction motor is self-starting.

4. The changes in applied voltage do not affect synchronous motor torque as much as they affect the induction motor torque.
5. The breakdown torque of a synchronous motor varies approximately as the first power of applied voltage whereas that of an induction motor depends on the square of this voltage.

6. A DC excitation is required be synchronous motor but not by induction motor.

7. Synchronous motor are usually more costly and complicated than induction motors, but they are particularly attractive for low speed drives (below 300 rpm) because their power factor can always be adjusted to 1.0 and their efficiency is high. However, induction motors are excellent for speeds over 600 rpm.

8. Synchronous motor can be run at ultra-low speeds by using high power electronics converters which generated very low frequencies. Such motors of 10 MW range are used fro driving crusher, rotary kilns and variable speed ball mills etc.
Synchronous motors find extensive application for the following classes of service:

1. Power factor correction;
2. Constant speed, constant load drives; and
3. Voltage regulation.
The synchronous motors have the following fields of applications:

**Power houses and sub-station:** Used in power houses and sub-station in parallel to the bus-bar to improve the power factor.

**Factories:** Used in factories having large of induction motors or other power apparatus, operating at lagging power factor, to improve the power factor.

**Mills-industries etc.:** Used in textile mills, rubber mills, and other big industries, cement factories for power applications.

**Constant speed equipments:** Used to drive continuously operated and constant speed equipment such as: Fans, blowers, centrifugal pumps, motor-generator sets, and air compressors etc.
Power Factor Correction

It has been seen that a synchronous motor can be operate in both lagging and leading power factor by varying the field flux of excitation circuit.

An over-excited (back emf, \( E_b > \) supply voltage, \( V \)) motor can be run with leading power factor.

When a synchronous motor operates at leading power factor, the behavior of its as like a capacitor or condenser. That’s why a synchronous motor operated at leading power factor is referred to a synchronous capacitor (synchronous condenser).

Thus, over-excited synchronous motors leading power factor are widely used for improving power factor (by supplying leading reactive power) of those power systems which employ a large number of induction motor and other devices having lagging power factor.
Because of their high efficiency and high speed, synchronous motors (above 600 rpm) 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 300 rpm) are used for drives such as centrifugal and screw type pumps, ball and tube mills, vacuum pumps, chippers and metal rolling mills.
Voltage regulation

The voltage at the end of a transmission line varies greatly especially when large inductive loads are present. When an inductive load is disconnected suddenly, voltage tends to rise considerably above its normal value because of the line capacitance. By installing a synchronous motor with a field regulator (for varying its excitation), this voltage rise can be controlled.

When line voltage decreases due to inductive load, motor excitation is increased thereby raising its power factor which compensates for the line drop. If, on the other hand, line voltage rise due to line capacitive effect, motor excitation is decreased, thereby making its power factor lagging which helps to maintain the line voltage at its normal value.
Example 38.31 A synchronous motor absorbing 60 kW is connected in parallel with a factory load of 240 kW having a lagging power factor of 0.8. If the combined load has a power factor of 0.9, what is the value of the leading kVAR supplied by the motor and what power factor is it working?

Solution: Load connections and phase relationships are shown in Fig. 36.53.

Total load = 240 + 60 = 300 kW; combined power factor = 0.9 (lag);

ϕ = 25.8°; tan ϕ = 0.4834; combined kVAR = 300 × 0.4834 = 145 (lag)
Factory Load: \( \cos \phi_L = 0.8; \phi_L = 36.9^\circ; \tan \phi_L = 0.75; \)

Load \( kVAR = 240 \times 0.75 = 180 \) (lag)

[or load \( kVA = 240/0.8 = 300, \) \( kVVAR = 300 \times \sin \phi_L = 300 \times 0.6 = 180 \)]

\[ \therefore \text{leading \, kVAR \, supplied \, by \, synchronous \, motor} = 180 - 145 = 35 \]

For Synchronous Motor: \( kW = 60; \) leading \( kVAR = 35; \) \( \tan \phi_m = 35/60; \phi_m = 30.3^\circ; \cos 30.3^\circ = 0.863; \)

\[ \therefore \text{Motor power factor} = 0.863 \, (\text{leading}). \]

Incidentally, \( \text{motor \, kVA} = \sqrt{60^2 + 35^2} = 69.5 \)