NSCET
E-LEARNING PRESENTATION
LISTEN ... LEARN... LEAD...
UNIT 02
Synchronous Motor
“Intellectuals solve problems, geniuses prevent them.”

—ALBERT EINSTEIN
CONSTRUCTION OF THREE PHASE SYNCHRONOUS MOTOR

The synchronous motor construction is basically similar to rotating field type alternator. It consists of two parts:

i) **Stator**: Consisting of a three phase star or delta connected winding. This is excited by a three phase a.c. supply.

ii) **Rotor**: Rotor is a field winding, the construction of which can be salient (projected pole) or non-salient (cylindrical) type. Practically most of the synchronous motors use salient i.e. projected pole type construction. The field winding is excited by a separate d.c supply through slip rings.
PRINCIPLE OF OPERATION

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. 1, 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.
Note:

1. The average torque exerted on the rotor of synchronous motor is zero. Hence the synchronous motor is not self starting.

2. To obtain a continuous torque, the rotor should rotate at synchronous speed given by expression $120 S f N P$

3. Different power stages in a synchronous motor are as under
OPERATION ON INFINITE BUS BARS

The infinite bus represents a bus bar of constant voltage and frequency, which can deliver or absorb active and reactive power without any limitations. The fig. shows a synchronous machine which is to be connected to the bus bars with the help of switch K. If the synchronous machine is running as a generator then its phase sequence should be same as that of bus bars. The machine speed and field current is adjusted in such a way so as to have the machine voltage same as that of bus bar voltage. The machine frequency should be nearly equal to bus bar frequency so that the machine speed is nearer to synchronous speed.
Application of Synchronous Motor

1. Power Factor Correction
2. Constant speed, constant load drives
3. Voltage Regulation
EFFECT OF EXCITATION ON ARMATURE CURRENT AND POWER FACTOR
(V AND INVERTED V CURVES)

• V-curve is plotted between armature current and field current.
• Change of armature current takes place by varying the field current is noted here..
• The middle line is considered as the unity pf line and at the right side of the unity pf line is considered as lagging pf line in case of synchronous motor reducing the external DC supply or by reducing the DC source voltage or by making the rotor under excited by means of controlled rectifier, which causes more lagging current draw from the source to make the airgap flux or reactive VAR constant in nature and during this field current is kept lower (so that under excited state occurs).
• Reactive VAR or the lagging power or magnetising current is consumed by the motor from the source and thus synchronous motor operates at lagging pf condition.
To make the pf of the synchronous motor leading in nature the rotor is made overexcited by varying the field current.

In case of the overexcited condition the field current is increased.

During overexcited state synchronous motor operates in leading pf. Because more airgap flux opposes the lagging component of current and reduce the lagging current thus the power factor is improved upto 0.9 lagging pf. The angle between the load current and voltage reduced. Thus it makes the pf leading in nature...

But alternator operates in lagging pf during overexcited condition and its operated in leading PF at under excited condition.

During over excited condition alternator delivers reactive vars which makes it synchronous condensor.

The synchronising power is given by \( (E_f * V_t) \cos (\text{load angle}) / X_s \).

By varying the excitation we can control the relevance \( E_f \) thus we can control the synchronization power. By varying the synchronization power and \( E_f \) the power factor of the machine can also be varied easily which is described above ...(significance of inverted v curve).
• **The inverted V curve** shows the variation of the armature current by varying the field excitation.

• Obviously armature current caused armature reaction which will oppose the field fluxes or the field they are inversely proportional to each other...

• In case of alternator during overexcited state armature current increases and thus it delivers reactive VAR. and for synchronous motor at overexcited state armature current gets reduced
Comparison between Synchronous Motor & Induction Motor

<table>
<thead>
<tr>
<th>No.</th>
<th>Synchronous motor</th>
<th>Induction motor</th>
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</thead>
<tbody>
<tr>
<td>1.</td>
<td>Construction is complicated</td>
<td>Construction is simpler, particularly in case of cage rotor.</td>
</tr>
<tr>
<td>3.</td>
<td>Separate d.c. source is required for rotor excitation.</td>
<td>Rotor gets excited by the induced e.m.f. So separate source is not necessary.</td>
</tr>
<tr>
<td>4.</td>
<td>The speed is always synchronous irrespective of load.</td>
<td>The speed is always less than synchronous but never synchronous.</td>
</tr>
<tr>
<td>5.</td>
<td>Speed control is not possible.</td>
<td>Speed control possible though difficult.</td>
</tr>
<tr>
<td>6.</td>
<td>As load increases, load angle increases, keeping speed constant as synchronous.</td>
<td>As load increases, the speed keeps on decreasing.</td>
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<tr>
<td>7.</td>
<td>By changing excitation, the motor p.f. can be changed from lagging and leading.</td>
<td>It always operates at lagging p.f. and p.f. control is not possible.</td>
</tr>
<tr>
<td>8.</td>
<td>It can be used as synchronous condenser for p.f. improvement.</td>
<td>It can not be used as a synchronous condenser.</td>
</tr>
<tr>
<td>9.</td>
<td>Motor is sensitive to sudden load changes and hunting results.</td>
<td>Phenomenon of hunting is absent.</td>
</tr>
<tr>
<td>10.</td>
<td>Motor is costly and requires frequent maintenance.</td>
<td>Motor is cheap specially cage motors are maintenance free.</td>
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HUNTING

✓ The word hunting is used because after the sudden application of load the rotor has to search or ‘hunt’ for its new equilibrium position.
✓ That phenomenon is referred to as hunting in a synchronous motor. Now let us know what is the condition of equilibrium in synchronous motor.
✓ A steady state operation of synchronous motor is a condition of equilibrium in which the electromagnetic torque is equal and opposite to load torque.
✓ In steady state, rotor runs at synchronous speed thereby maintaining a constant value of torque angle (δ).
✓ If there is a sudden change in load torque, the equilibrium is disturbed and there is resulting torque which changes the speed of the motor.
Causes of Hunting in Synchronous Motor

1. Sudden change in load.
2. Sudden change in field current.
3. A load containing harmonic torque.
4. Fault in supply system.

Effects of Hunting in Synchronous Motor

1. It may lead to loss of synchronism.
2. Produces mechanical stresses in the rotor shaft.
3. Increases machine losses and cause temperature rise.
4. Cause greater surges in current and power flow.
5. It increases possibility of resonance.
Reduction of Hunting in Synchronous Motor

Two techniques should be used to reduce hunting. These are –

• Use of Damper Winding: It consists of low electrical resistance copper / aluminum brush embedded in slots of pole faces in salient pole machine. Damper winding damps out hunting by producing torque opposite to slip of rotor. The magnitude of damping torque is proportional to the slip speed.

• Use of Flywheels: The prime mover is provided with a large and heavy flywheel. This increases the inertia of prime mover and helps in maintaining the rotor speed constant.

• Designing synchronous machine with suitable synchronizing power coefficients.
STARTING METHODS OF SYNCHRONOUS MOTOR

Synchronous motors run at synchronous speed. The synchronous speed of a motor depends on the supply frequency and the number of poles in the motor. Synchronous speed is given by \( N_s = \frac{120f}{P} \)

Where, \( f \) = supply frequency and \( p \) = number of poles.

We can change the synchronous speed of the motor by changing the supply frequency and the number of poles. But the motor would always run with this speed for a given supply frequency and the number of poles.

Synchronous motors have lots of advantages but being not self-starting unlike 3 phase induction motors, is a major disadvantage. In synchronous motors, the stator has 3 phase windings and is excited by 3 phase supply whereas the rotor is excited by DC supply. The 3 phase windings provide rotating flux whereas the DC supply provides constant flux.
The torque produced on the rotor is a pulsating one and not uni-directional. Considering the frequency to be 50 Hz, from the above relation we can see that the 3 phase rotating flux rotates about 3000 revolutions in 1 min or 50 revolutions in 1 sec. At a particular instant rotor and stator poles might be of the same polarity (N-N or S-S) causing a repulsive force on the rotor and the very next second it will be N-S causing attractive force. But due to the inertia of the rotor, it is unable to rotate in any direction due to attractive or repulsive force and remain in standstill condition. Due to this, the motor cannot start on its own. The rotor of the synchronous motor has to be brought to synchronous speed by using external means.
As seen earlier, synchronous motor is not self starting. It is necessary to rotate the rotor at a speed very near to synchronous speed. This is possible by various method in practice. The various methods to start the synchronous motor are,

1. Using pony motors
2. Using damper winding
3. As a slip ring induction motor
4. Using small d.c. machine coupled to it.

1. Using pony motors
In this method, the rotor is brought to the synchronous speed with the help of some external device like small induction motor. Such an external device is called ‘pony motor’. Once the rotor attains the synchronous speed, the d.c. excitation to the rotor is switched on. Once the synchronism is established pony motor is decoupled. The motor then continues to rotate as synchronous motor.
2. Using Damper Winding
In a synchronous motor, in addition to the normal field winding, the additional winding consisting of copper bars placed in the slots in the pole faces. The bars are short circuited with the help of end rings. Such an additional winding on the rotor is called damper winding. This winding as short circuited, acts as a squirrel cage rotor winding of an induction motor. The schematic representation of such damper winding is shown in the Fig.1.
Once the rotor is excited by a three phase supply, the motors starts rotating as an induction motor at sub synchronous speed.
Then d.c. supply is given to the field winding. At a particular instant motor gets pulled into synchronism and starts rotating at a synchronous speed.
As rotor rotates at synchronous speed, the relative motion between damper winding and the rotating magnetic field is zero.
Hence when motor is running as synchronous motor, there can not be any induced e.m.f. in the damper winding.
So damper winding is active only at start, to run the motor as an induction motor at start. Afterwards it is out of the circuit. As damper winding is short circuited and motor gets started as induction motor, it draws high current at start so induction motor starters like star-delta, autotransformer etc. used to start the synchronous motor as an induction motor.
3. As a Slip Ring Induction Motor

The above method of starting synchronous motor as a squirrel cage induction motor does not provide high starting torque. So to achieve this, instead of shorting the damper winding, it is designed to a form a three phase star or delta connected winding. The three ends of this winding are brought out through slip rings. An external rheostat then can be introduced in series with the rotor circuit. So when stator is excited, the motor starts as a slip ring induction motor and due to resistance added in the rotor provides high starting torque. The resistance is then gradually cut off, as motor gathers speed. When motor attains speed near synchronous. d.c. excitation is provided to the rotor, then motors gets pulled into synchronism ans starts rotating at synchronous speed. The damper winding is shorted by shorting the slip rings. The initial resistance added in the rotor not only provides high starting torque but also limits high inrush of starting current. Hence it acts as a motor resistance starter.

The synchronous motor started by this method is called a slip ring induction motor is shown in the Fig.1(b).

It can be observed from the Fig. 1(b) that the same three phase rotor winding acts as a normal rotor winding by shorting two of the phases. From the positive terminal, current ‘I’ flows in one of the phases, which divides into two other phases at start point as 1/2 through each, when switch is thrown on d.c. supply side.
4. Using Small D.C. Machine
Many a times, a large synchronous motor are provided with a coupled d.c. machine. This machine is used as a d.c. motor to rotate the synchronous motor at a synchronous speed. Then the excitation to the rotor is provided. Once motor starts running as a synchronous motor, the same d.c. machine acts as a d.c. generator called exciter. The field of the synchronous motor is then excited by this exciter itself.
Performance Characteristic

The effects of changes in mechanical or shaft load on armature current, power angle, and power factor can be seen from the phasor diagram shown in Fig: As the applied stator voltage, frequency, and field excitation are assumed, constant. The initial load conditions, are represented by the thick lines.

The effect of increasing the shaft load to twice its initial value are represented by the light lines indicating the new steady state conditions. When the shaft load is doubled both \( I_a \cos \theta \) and \( E_f \sin \theta \) are doubled.

While redrawing the phasor diagrams to show new steady-state conditions, the line of action of the new \( jI_aX_s \) phasor must be perpendicular to the new \( I_a \) phasor. Furthermore, as shown in Fig: if the excitation is not changed, increasing the shaft load causes the locus of the \( E_f \) phasor to follow a circular arc, thereby increasing its phase angle with increasing shaft load. Note also that an increase in power factor.
Effect of changes in field excitation on synchronous motor performance

As increasing the strength of the magnets will increase the magnetic attraction, and thereby cause the rotor magnets to have a closer alignment with the corresponding opposite poles of the rotating magnetic poles of the stator. This will obviously result in a smaller power angle. When the shaft load is assumed to be constant, the steady-state value of Ef sin must also be constant. An increase in Ef will cause a transient increase in Ef sin, and the rotor will accelerate. As the rotor changes its angular position, decreases until Ef sin has the same steady-state value as before, at which time the rotor is again operating at synchronous speed, as it should run only at the synchronous speed.

This change in angular position of the rotor magnets relative to the poles of rotating magnetic field of the stator occurs in a fraction of a second. The effect of changes in field excitation on armature current, power angle, and power factor of a synchronous motor operating with a constant shaft load, from a constant voltage, constant frequency supply, is illustrated in Fig: 2.32. For a constant shaft load,
Power Factor Characteristic of Synchronous Motors

In an induction motor, only one winding (i.e., stator winding) produces the necessary flux in the machine. The stator winding must draw reactive power from the supply to set up the flux. Consequently, induction motor must operate at lagging power factor. But in a synchronous motor, there are two possible sources of excitation; alternating current in the stator or direct current in the rotor. The required flux may be produced either by stator or rotor or both.

(i) If the rotor exciting current is of such magnitude that it produces all the required flux, then no magnetizing current or reactive power is needed in the stator. As a result, the motor will operate at unity power factor.
(ii) If the rotor exciting current is less (i.e., motor is under-excited), the deficit in flux is made up by the stator. Consequently, the motor draws reactive power to provide for the remaining flux. Hence motor will operate at a lagging power factor.

(iii) If the rotor exciting current is greater (i.e., motor is over-excited), the excess flux must be counterbalanced in the stator. Now the stator, instead of absorbing reactive power, actually delivers reactive power to the 3-phase line. The motor then behaves like a source of reactive power, as if it were a capacitor. In other words, the motor operates at a leading power factor. To sum up, a synchronous motor absorbs reactive power when it is under excited and delivers reactive power to source when it is over-excited.
A factory takes 600 kVA at a lagging power factor of 0.6. A synchronous motor is to be installed to raise the power factor to 0.9 lagging when the motor is taking 200 kW. Calculate the corresponding apparent power (in kVA) taken by the motor and the power factor at which it operates.

**Solution:**

Load power factor, $\cos \varphi = 0.6$

$\sin \varphi = 0.8$

Load kVA = 600.

P1, Load power = load kVA*\(\cos \varphi\) = 360 kW

Q1, Load reactive power = kVA*\(\sin \varphi\) = 480 kVar

P2, Motor power = 200 kW

Overall P.F., $\cos \alpha = 0.9$ lag

$\tan \alpha = 0.484$

Since, $\tan \alpha = (QQ1-QQ2)/(PP1+PP2)$,

$QQ2 = QQ1 - (PP1 + PP2) \tan \alpha = 208.78 \text{ Kvar}$

S2, Apparent power of the motor = $\sqrt{PP2^2 + QQ2^2} = 289.118 \text{ Kva}$

Motor P.F. = $P2/S2 = 0.692 \text{ lead}$
A 480-V, 60 Hz, 400-hp 0.8-PF-leading eight-pole Δ-connected synchronous motor has a synchronous reactance of 0.6 Ω and negligible armature resistance. Ignore its friction, windage, and core losses for the purposes of this problem. Assume that $|\mathbf{E}_A|$ is directly proportional to the field current $I_F$ (in other words, assume that the motor operates in the linear part of the magnetization curve), and that $|\mathbf{E}_A| = 480$ V when $I_F = 4$ A.

(a) What is the speed of this motor?

(b) If this motor is initially supplying 400 hp at 0.8 PF lagging, what are the magnitudes and angles of $\mathbf{E}_A$ and $\mathbf{I}_A$?

(c) How much torque is this motor producing? What is the torque angle $\delta$? How near is this value to the maximum possible induced torque of the motor for this field current setting?

(d) If $|\mathbf{E}_A|$ is increased by 30 percent, what is the new magnitude of the armature current? What is the motor's new power factor?

(e) Calculate and plot the motor's V-curve for this load condition.
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(e) Calculate and plot the motor’s V-curve for this load condition.
SOLUTION

(a) The speed of this motor is given by

\[
n_m = \frac{120 f_n}{P} = \frac{120(60 \text{ Hz})}{8} = 900 \text{ r/min}
\]

(b) If losses are being ignored, the output power is equal to the input power, so the input power will be

\[
P_in = (400 \text{ hp})(746 \text{ W/hp}) = 298.4 \text{ kW}
\]

This situation is shown in the phasor diagram below:

[Diagram]

The line current flow under these circumstances is

\[
I_L = \frac{P}{\sqrt{3} V_f PF} = \frac{298.4 \text{ kW}}{\sqrt{3}(480 \text{ V})(0.8)} = 449 \text{ A}
\]

Because the motor is \( \Delta \)-connected, the corresponding phase current is \( I_a = 449/\sqrt{3} = 259 \text{ A} \). The angle of the current is \( -\cos^{-1}(0.80) = -36.87^\circ \), so \( I_a = 259 \angle -36.87^\circ \text{ A} \). The internal generated voltage \( E_d \) is

\[
E_d = V_o - jX_s I_a
\]

\[
E_d = (480 \angle 0^\circ \text{ V}) - j(0.6 \Omega)(259 \angle -36.87^\circ \text{ A}) = 406 \angle -17.8^\circ \text{ V}
\]
(c) This motor has 6 poles and an electrical frequency of 60 Hz, so its rotation speed is \( n_m = 1200 \) r/min. The induced torque is

\[
\tau_{\text{ind}} = \frac{P_{\text{out}}}{\omega_m} = \frac{298.4 \text{ kW}}{(900 \text{ r/min})(1 \text{ min/60 s})(2\pi \text{ rad/1 r})} = 3166 \text{ N} \cdot \text{m}
\]

The maximum possible induced torque for the motor at this field setting is the maximum possible power divided by \( \omega_m \)

\[
\tau_{\text{ind,max}} = \frac{3V_sE_A}{\omega_mX_S} = \frac{3(480 \text{ V})(406 \text{ V})}{(900 \text{ r/min})(1 \text{ min/60 s})(2\pi \text{ rad/1 r})(0.6 \Omega)} = 10,340 \text{ N} \cdot \text{m}
\]

The current operating torque is about 1/3 of the maximum possible torque.

(d) If the magnitude of the internal generated voltage \( E_A \) is increased by 30%, the new torque angle can be found from the fact that \( E_A \sin \delta \propto P = \text{constant} \).

\[
E_{42} = 1.30 E_{41} = 1.30(406 \text{ V}) = 487.2 \text{ V}
\]

\[
\delta_2 = \sin^{-1} \left( \frac{E_{41}}{E_{42}} \sin \delta_1 \right) = \sin^{-1} \left( \frac{406 \text{ V}}{487.2 \text{ V}} \sin(-17.8^\circ) \right) = -14.8^\circ
\]

The new armature current is

\[
I_{42} = \frac{V_y - E_{42}}{jX_S} = \frac{480 - 0^\circ \text{ V} - 487.2 - 14.8^\circ \text{ V}}{j0.6 \Omega} = 208 - 4.1^\circ \text{ A}
\]

The magnitude of the armature current is 208 A, and the power factor is \( \cos(-24.1^\circ) = 0.913 \) lagging.
5-3. A 230-V, 50 Hz, two-pole synchronous motor draws 40 A from the line at unity power factor and full load. Assuming that the motor is lossless, answer the following questions:

(a) What is the output torque of this motor? Express the answer both in newton-meters and in pound-feet.

(b) What must be done to change the power factor to 0.85 leading? Explain your answer, using phasor diagrams.

(c) What will the magnitude of the line current be if the power factor is adjusted to 0.85 leading?

SOLUTION

(a) If this motor is assumed lossless, then the input power is equal to the output power. The input power to this motor is

\[ P_{in} = \sqrt{3} V_{L} I_{L} \cos \theta = \sqrt{3} (230 \text{ V})(40 \text{ A})(1.0) = 15.93 \text{ kW} \]

The rotational speed of the motor is

\[ n_m = \frac{120 f_{se}}{P} = \frac{120(50 \text{ Hz})}{4} = 1500 \text{ r/min} \]

The output torque would be

\[ \tau_{load} = \frac{P_{out}}{n_m} = \frac{15.93 \text{ kW}}{(1500 \text{ r/min})(\frac{1 \text{ min}}{60 \text{ s}})(\frac{2\pi \text{ rad}}{1 \text{ r}})} = 101.4 \text{ N} \cdot \text{m} \]

In English units,

\[ \tau_{load} = \frac{7.04 P_{out}}{n_m} = \frac{(7.04)(15.93 \text{ kW})}{(1500 \text{ r/min})} = 74.8 \text{ lb} \cdot \text{ft} \]

(b) To change the motor's power factor to 0.8 leading, its field current must be increased. Since the power supplied to the load is independent of the field current level, an increase in field current increases \(|E_A|\) while keeping the distance \(E_A \sin \delta\) constant. This increase in \(E_A\) changes the angle of the current \(I_A\), eventually causing it to reach a power factor of 0.8 leading.
(c) The magnitude of the line current will be

\[ I_L = \frac{P}{\sqrt{3} V_T \text{ PF}} = \frac{15.93 \text{ kW}}{\sqrt{3}(230 \text{ V})(0.8)} = 50.0 \text{ A} \]