Synchronous Machines

Salient pole machine has the following special features:

1. It has large diameter and small axial length.
2. The pole shoes cover about $2/3^{rd}$ of pole pitch.
3. This is in general low speed machine.
4. It is used in hydraulic turbine or diesel engines.

Non-salient pole machine has the following special features:

1. It has small diameter and large axial length.
2. Robust construction and noise less operation.
3. Less windage loss.
4. Better in dynamic balance.
5. High operating speed.
6. It is used in stream turbine.

Advantages of rotating field:

1. The size of the machines is reduced.
2. A stationary armature is more easily insulated.
3. The armature winding can be braced better mechanically against high electromagnetic force.
4. The armature current can be taken directly from the fixed terminals on the stationary armature.
5. The rotating field is comparatively light and can be constructed for high speed rotation.
6. The stationary armature may be cooled more easily.

Advantages of short-pitch winding:

1. The waveform of the induced emf is improved and the distorting harmonic can be reduced.
2. Copper is saved in the coil ends due to less span.
3. The inductance of the winding is reduced due to lesser length of coil ends.
4. It reduces the tooth ripples.
5. Mechanical strength of the coil is increased.

Advantages of distributed winding:

1. The harmonics emfs are reduced and so the waveform is improved.
2. Certain distorting harmonics can be altogether eliminated.
3. The distributed winding reduces armature reaction.
4. The core is better utilised.

SPEED AND FREQUENCY

The frequency of the generated voltage depends upon the number of field poles and on the speed at which the field poles are rotated. One complete cycle of voltage is generated in an armature coil when a pair of field poles (one north and one south pole) passes over the coil.

Let P = total number of field poles

p = pair of field poles

N = speed of the field poles in r.p.m.

n = speed of the field poles in r.p.s.

f = frequency of the generated voltage in Hz

Obviously, $\frac{N}{60} = n$

and $\frac{P}{2} = p$

In one revolution of the rotor, an armature coil is cut by $\frac{P}{2}$ north poles and $\frac{P}{2}$ south poles. Since one cycle is generated in an armature coil when a pair of field poles passes over the coil, the number of cycles generated in one revolution of the rotor will be equal to the number of pairs of poles. That is,

number of cycles per revolution $= p$

Also, number of revolutions per second $= n$

Now frequency = number of cycles per second

$$= \frac{\text{number of cycles}}{\text{revolutions}} \times \frac{\text{revolutions}}{\text{seconds}}$$

$$f = p \times n$$

Since $n = N/60$ and $p = P/2$

$$f = \frac{PN}{120}$$

Equations give the relationship between the number of poles, speed and frequency.

E.M.F. EQUATION OF AN ALTERNATOR

Let

$\Phi =$ useful flux per pole in webers (Wb)

$P =$ total number of poles

$Z_p =$ total number of conductors or coil sides in series per phase

$T_p =$ total number of coils or turns per phase

$n =$ speed of rotation of rotor in revolutions per second (r.p.s.)

$f =$ frequency of generated voltage (Hz)

Since the flux per pole is Φ, each stator conductor cuts a flux $P\Phi$.

The average value of generated voltage per conductor

$$= \frac{\text{flux cut per revolution in Wb}}{\text{time taken for one revolution in seconds}}$$

Since n revolutions are made in one second, one revolution will be made in $1/n$ second. Therefore the time for one revolution of the armature is $1/n$ second. The average voltage generated per conductor

$$E_{av}/\text{conductor} = \frac{P\Phi}{1/n} = nP\,\Phi \quad \text{volts} \tag{1}$$

We know that $$f = \frac{PN}{120} = \frac{Pn}{2} \tag{2}$$

$$Pn = 2f$$

Substituting the value of Pn in Eq. (1), we get

$$E_{av}/\text{conductor} = 2f\Phi \tag{3}$$

Since there are Z_p conductors in series per phase, the average voltage generated per phase is given by

$$E_{av}/\text{phase} = 2f\Phi Z_p \tag{4}$$

Since one turn or coil has two sides, $Z_p = 2T_p$, and the expression for the average generated voltage per phase can be written as

$$E_{av}/\text{phase} = 4f\Phi T_p \tag{5}$$

For the voltage wave, the form factor is given by

$$k_f = \frac{\text{r.m.s. value}}{\text{average value}}$$

For a sinusoidal voltage, $k_f = 1.11$. Therefore, the r.m.s. value of the generated voltage per phase can be written as

$$E_{r.m.s.}/\text{phase} = k_f \times E_{av}/\text{phase} = 1.11 \times 4 f\Phi T_p$$
$$= 4.44 f\Phi T_p$$

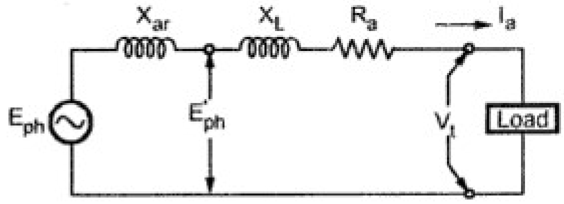
The suffix r.m.s. is usually deleted. The r.m.s. value of the generated voltage per phase is given by

$$E_p = 4.44 f\Phi T_p \tag{6}$$

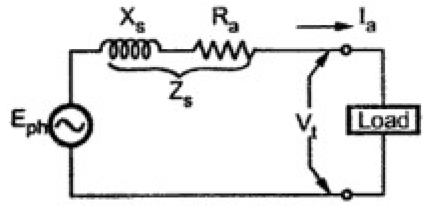
Concept of synchronous reactance and impedance: The sum of fictitious armature reaction reactance and the leakage reactance of armature is called synchronous reactance. So $X_s = X_{ar} + X_l$, where X_{ar} = fictitious armature reaction reactance and X_l = leakage reactance of armature.

Again, The synchronous impedance, $Z_s = R_a + jX_s$, where R_a = armature resistance per phase.

Equivalent circuit of an alternator: If E_{ph} induced voltage per phase on no-load condition then on load it changes to $\mathbf{E'_{ph}}$ due to armature reaction as shown below in the equivalent circuit. As current I_a flows through the armature, then there are two voltage drop due to R_a and X_l



In practice, the leakage reactance X_l and armature reaction reactance are combined to get synchronous reactance, X_s. Hence the equivalent circuit of the alternator is shown below



Thus in the equivalent circuit shown,

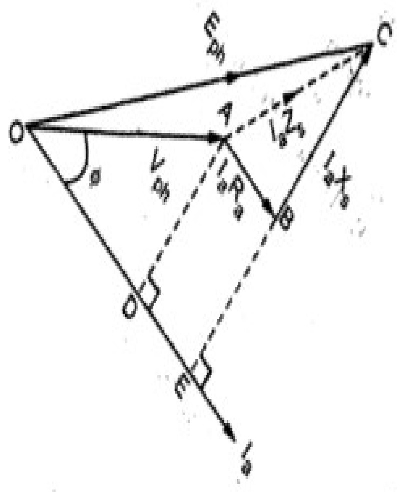
E_{ph} = Induced e.m.f. per phase on no load

$V_{t\,ph}$ = Terminal voltage per phase on load

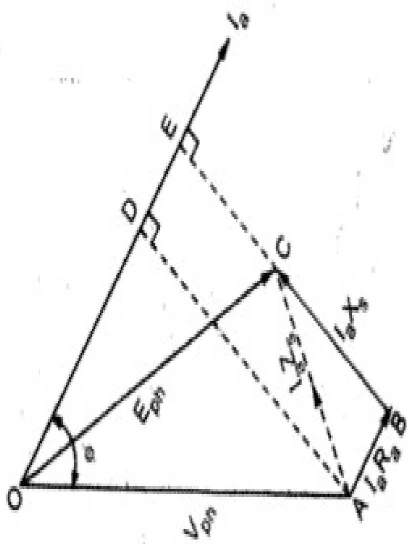
I_{aph} = Armature resistance per phase

Z_s = Synchronous impedance per phase

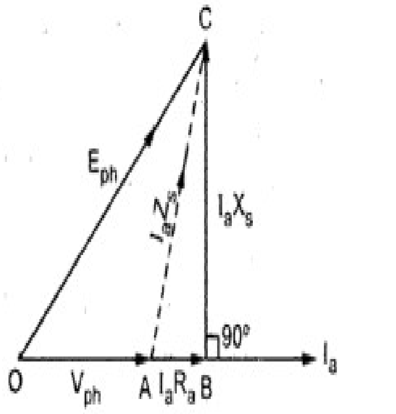
Phasor diagram of a loaded alternator:



Phasor diagram for lagging p.f. load



Phasor diagram for leading p.f. load



Phasor diagram for unity p.f. load

Expression of induced e.m.f:

For lagging power factor of load:

To derive the relationship between E_{ph} and V_{ph}, the perpendiculars are drawn on the current phasor from points A and B. These intersect current phasor at points D and E respectively.

Now,

$$OD = V_{ph} \cos \phi$$

$$AD = BE = V_{ph} \sin \phi$$

$$DE = I_a R_a$$

Consider Δ OCE, for which we can write,

$$(OC)^2 = (OE)^2 + (EC)^2$$

$$\therefore \quad (E_{ph})^2 = (OD + DE)^2 + (EB + BC)^2$$

$$\therefore \quad (E_{ph})^2 = (V_{ph} \cos\phi + I_a R_a)^2 + (V_{ph} \sin\phi + I_a X_s)^2$$

$$\therefore \quad \boxed{E_{ph} = \sqrt{(V_{ph} \cos\phi + I_a R_a)^2 + (V_{ph} \sin\phi + I_a X_s)^2}}$$

From this equation, the value of induced e.m.f. can be calculated.

For leading power factor of load:

To derive the relation between E_{ph} and V_{ph}, the perpendiculars are drawn on current phasor from points A and B. These intersect current phasor at points D and E respectively.

From Δ OAD,

$$OD = V_{ph} \cos \phi$$

$$AD = BE = V_{ph} \sin \phi$$

$$DE = I_a R_a$$

Consider Δ OCE, for which we can write,

$$(OC)^2 = (OE)^2 + (EC)^2$$

$$\therefore \quad (E_{ph})^2 = (OD + DE)^2 + (BE - BC)^2$$

$$\therefore \quad (E_{ph})^2 = (V_{ph} \cos\phi + I_a R_a)^2 + (V_{ph} \sin\phi - I_a X_s)^2$$

$$\therefore \quad \boxed{E_{ph} = \sqrt{(V_{ph} \cos\phi + I_a R_a)^2 + (V_{ph} \sin\phi - I_a X_s)^2}}$$

It can be observed that the sign of the $I_a X_s$ is negative as against its positive sign for lagging p.f. load. This is because X_s consists of X_{ar} i.e. armature reaction reactance. Armature reaction is demagnetising for lagging while magnetising for leading power factor loads. So sign of $I_a X_s$ is opposite for lagging and leading p.f conditions.

For unity power factor of load:

Consider ΔOBC, for which we can write,

$$(OC)^2 = (OB)^2 + (BC)^2$$

$$\therefore \quad (E_{ph})^2 = (OA + AB)^2 + (BC)^2$$

$$\therefore \quad (E_{ph})^2 = (V_{ph} + I_a R_a)^2 + (I_a X_s)^2$$

$$\therefore \quad \boxed{E_{ph} = \sqrt{(V_{ph} + I_a R_a)^2 + (I_a X_s)^2}}$$

As $\cos\phi = 1$, so $\sin\phi = 0$ hence does not appear in the equation.

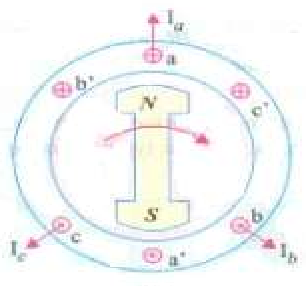
Note : The phasor diagrams can be drawn by considering voltage V_{ph} as a reference phasor. But to derive the relationship, current phasor selected as a reference makes the derivation much more simplified. Hence current is selected as a reference phasor.

It is clear from the phasor diagram that V_{ph} is less than E_{ph} for lagging and unity p.f. conditions due to demagnetising and cross magnetising effects of armature

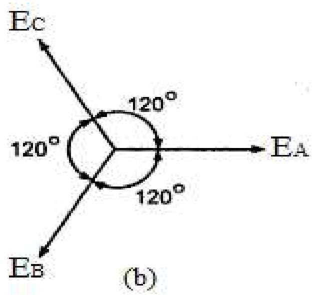
Armature reaction: As in a dc machine, the armature reaction is the effect of armature flux on main flux. But the armature reaction in synchronous machines affects the main field flux very differently for different power factor. So we will consider three cases- (i) when the load power factor is unity, (ii) when the load power factor is zero lagging and (iii) when the load power factor is zero leading.

It also be noted that in a three-phase machines the combined ampere-turn wave is sinusoidal and which is rotating synchronously. This ampere-turn is fixed relative to the poles and its amplitude is proportional to the load current but its position depends on the power factor of the load.

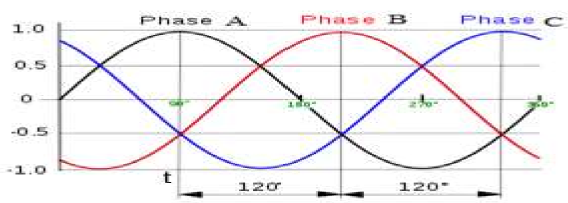
Let us consider 2 poles, three-phase alternator having a single layer winding which is shown in figure (a). The direction of the main field is vertically upward and the vector diagram of three-phase induced emf is shown in figure (b), since the induced emf is lagging the main field by 90 degree. The wave form of three-phase current is shown in figure (c).



(a)

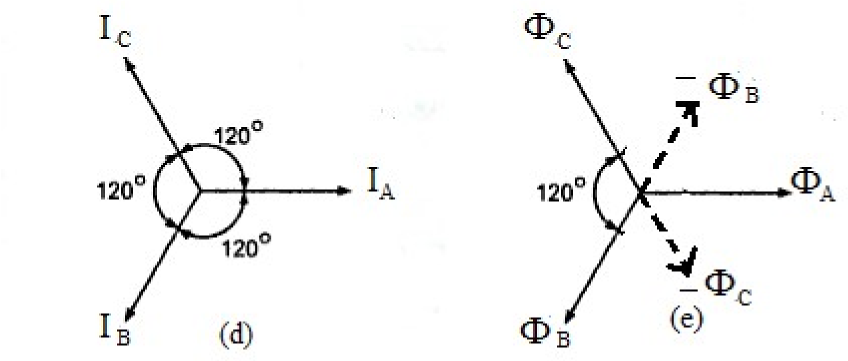


(b)



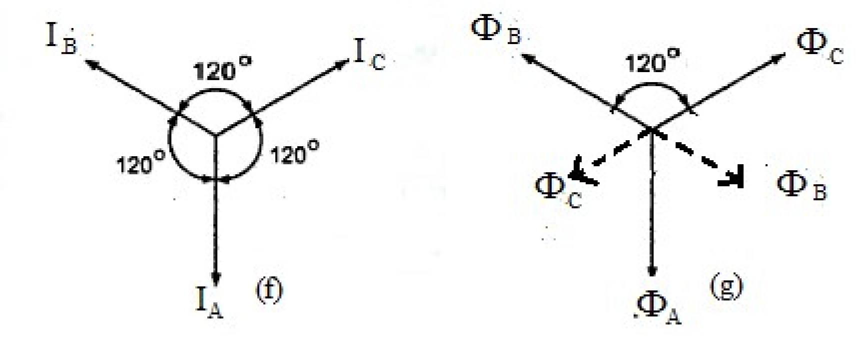
(c)

Case-I: Unity power factor of load: The phase current I_A, I_B and I_C are in phase with E_A, E_B and E_C respectively which is shown in figure (d). The armature mmf = (armature current)X (armature no of turn) = N I_A or NI_B or NI_B. So the direction of armature flux, i.e. Φ_A, Φ_B and Φ_C are the same as I_A, I_B and I_C respectively and it is shown in figure (e).



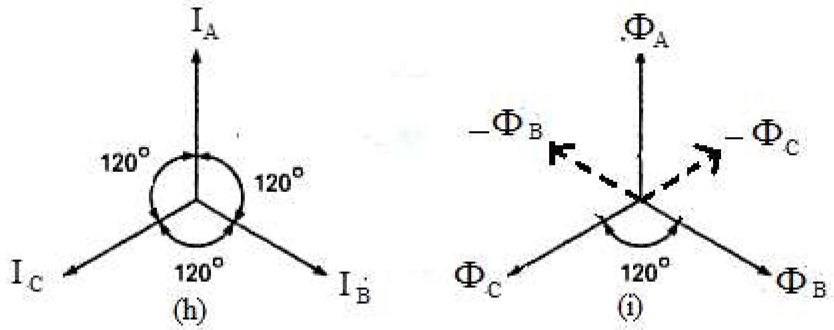
Let us investigate the armature mmf at instant t in figure (c). At this instant Φ_A maximum and both Φ_B and Φ_C are negative which is shown in figure (e). So the resultant direction of armature flux is along Φ_A. Therefore both the magnetic fields are quadrature to each other, i.e. 90^0 apart and the main magnetic field wave form distorts. So the armature reaction for unity power factor of load is distortional.

Case-II: Zero Lagging power factor of load: The armature current for this load is 90^0 lag the induced e.m.f. The phasor diagram of armature current and armature mmf are shown in figure (f) and (g) respectively.



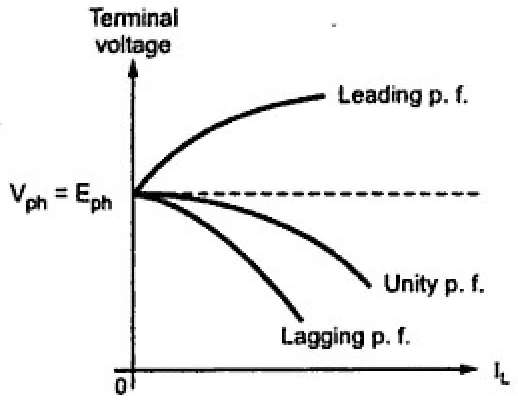
Let us investigate the armature mmf at instant t in figure (c). At this instant Φ_A maximum and both Φ_B and Φ_C are negative which is shown in figure (g). So the resultant direction of armature flux is along Φ_A. Therefore both the magnetic fields are 180^0 apart, i.e. they are opposition in nature. So the armature reaction for zero power factor lagging is de-magnetisation.

Case-III: Zero leading power factor of load: The armature current for this load is 90^0 lead to the induced e.m.f. The phasor diagram of armature current and armature mmf are shown in figure (h) and (i) respectively.



Let us investigate the armature mmf at instant t in figure (c). At this instant Φ_A maximum and both Φ_B and Φ_C are negative which is shown in figure (i). So the resultant direction of armature flux is along Φ_A. Therefore both the magnetic fields belong to the same direction. So the armature reaction for zero power factor leading is re-magnetisation.

Load characteristics of an alternator:



Need of parallel operation:

1. More alternators can supply a bigger load than a single alternator.
2. During periods of light load, one or more alternators may be shut down to run rest of the alternators at maximum efficiency.
3. If there is break down of generator, there is no interruption of the power supply.
4. When one machine is taken out for servicing, the remaining machines maintain the continuity of supply.
5. For increasing the future demand of load more machines can be added without disturbing the original installation.
6. The operating cost and cost of energy generated are reduced for parallel operation.

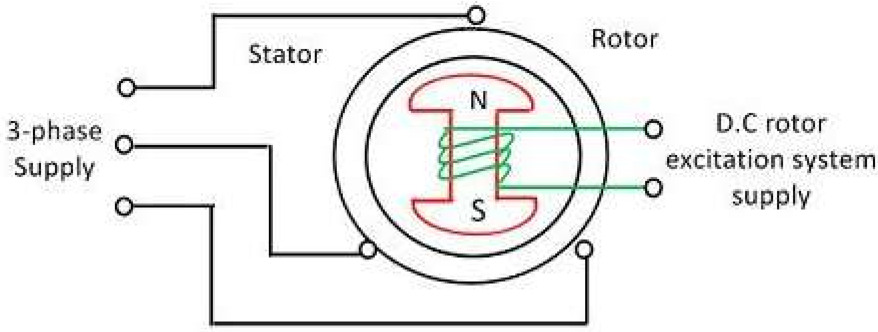
Condition of parallel operation:

1. The phase sequence of the busbar voltages and the incoming machines voltage must be the same.
2. The busbar voltage and the incoming machine terminal voltage must be the same.
3. The frequency of generated voltage of the incoming machine must be equal to the frequency of busbar line voltage.
4. The frequency of generated voltage of incoming machine must be equal to the frequency of the voltage of the busbar.

Synchronous motor

Working principle:

Consider a 2-poles synchronous motor as shown in figure-(1). When a three-phase ac supply is given to the stator, a rotating magnetic field of constant magnitude is produced. This rotates ar synchronous speed.

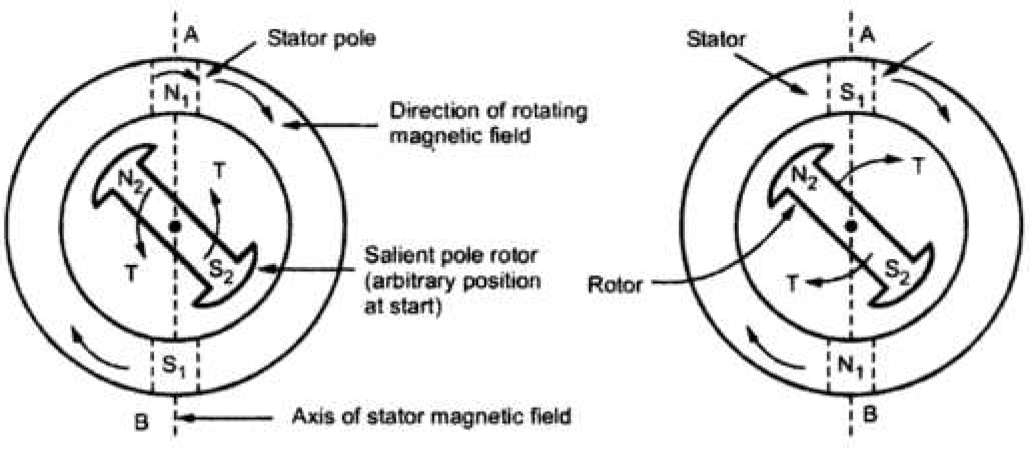


Synchronous Motor (1)

The rotor winding is excited by dc supply which produces another field which is stationary and not rotating. Thus, there are two fields in the air gap-one stationary and other rotating at synchronous speed. The rotor tries to align with the stator field just like two magnetic bars try to align to each other. So also the rotor tries to rotate with the rotating field at synchronous speed. It is well known that when the two magnetic fields are stationary to each other, continuous rotation is obtained. This happens when the rotor also rotates at synchronous speed. So, if we rotate the rotor of the synchronous motor by some external device, the magnetic lock between the stator poles and rotor poles will run at a synchronous speed.

Why the synchronous motor is not self-starting:

Now, suppose that a three-phase ac supply is given to the stator of the synchronous motor having 2-poles. A rotating magnetic field is produced whose speed is given by N_s=(120 f)/P= 3000 rpm = 50 rps. So the stator poles-N_1 and-S_1 rotates at the speed of 50 revolutions per second in the clockwise direction as shown in figure (2) at a particular instant.



(a) Action of synchronous motor (b) Action of synchronous motor

(2)

When the rotor is excited, the position acquired by the rotor poles is also shown in figure (2). According to the figure (2) (a), due to the force of repulsion between like poles, S_1-S_2 and N_1-N_2, the stationary rotor tries to rotate in the anti clockwise direction. But before the rotor can move in the anti clockwise direction, the stator poles change their position quickly as shown in figure (2) (b). At this instant, due to the force of attraction between unlike poles N_1-S_2 and S_1-N_2, the rotor experience a torque in the clockwise direction. So, the stationary rotor experiences a torque continuously changing in direction. Due to inertia, the rotor is not able to response quickly and hence remains stationary. This is why the synchronous motor is not self-starting.

Synchronous condenser: In normal excitation, the motor power factor is unity. If the motor is overexcited, the motor operates at leading power factor and if the motor is under-excited, it operates at lagging power factor. Therefore, when the motor is operated at no0load with over-excitation, it takes current that leads the voltage by nearly 90^0 which means that the motor works like a capacitor. So when the motor operates under this condition, the synchronous motor is called synchronous condenser or synchronous capacitor.

Application of synchronous motor:

The synchronous motors have the following applications:

1. Power factor correction:
   Over-excited synchronous motor operate at leading power factor and hence they are widely used for improving power factor of those power system which are connected with various induction motor and other lagging load like welder and fluorescent lamps, etc.
2. Constant speed and constant load drives:
   A synchronous motor runs at synchronous speed. Therefore, this motor is perfect choice where constant speed is necessary like in centrifugal pumps, belt-driven compressors, rubber and paper mills, etc.
3. Voltage regulation:
   When the line voltage decrease due to inductive load, by increasing the motor excitation the power factor is increased compensating the line drop. Similarly, line voltage increase due to capacitive effect, by decreasing the motor excitation the power factor is made lagging, thus maintaining the line voltage at its normal value.

Hunting in Synchronous Motor

We come across the term **HUNTING** when we study about three phase synchronous motor operations. The word hunting is used because after sudden application of load the rotor has to search or hunt for its new equilibrium position. That phenomenon is referred to as **hunting in synchronous motor**. Now let us know what the condition of equilibrium is in the 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 constant value of torque angle (δ). If there is sudden change in load torque, the equilibrium is disturbed and there is resulting torque which changes speed of the motor.

What is Hunting?

Unloaded synchronous machine has zero degree load angle. On increasing the shaft load gradually load angle will increase. Let us consider that load P_1 is applied suddenly to unloaded machine shaft so machine will slow down momentarily. Also load angle (δ) increases from zero degree and becomes δ_1. During the first swing electrical power developed is equal to mechanical load P_1. Equilibrium is not established so rotor swings further. Load angle exceeds δ_1 and becomes δ_2. Now electrical power generated is greater than the previous one. Rotor attains synchronous speed. But it does not stay in synchronous speed and it will continue to increase beyond synchronous speed. As a result of rotor acceleration above synchronous speed the load angle decreases. So once again no equilibrium is attained. Thus rotor swings or oscillates about new equilibrium position. This phenomenon is known as hunting or phase swinging. Hunting occurs not only in synchronous motors but also in synchronous generators upon abrupt change in load.

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:

The following technique given below is used to reduce the phenomenon of hunting.

- Use of damper windings
- Uses of flywheels
- By designing synchronous machines with suitable synchronising power coefficients.