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AP-III/DEPT OF EEE

Construction of three phase synchronous motor

Similar to d.c machine where there is no construction difference between a generator and motor ,there is no difference between the construction of synchronous motor and alternator ,both being the synchronous machines.

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

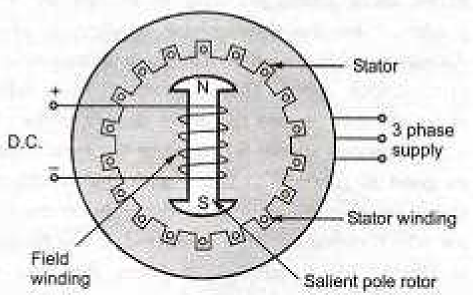


Fig. 4.3.1 Schematic representation of three phase synchronous motor

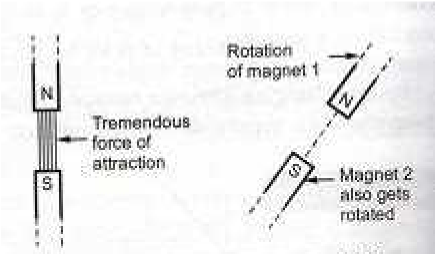
i) stator :consisting of a three phase star or delta connected winding . this is excited by a three phase a .c. supply.

ii) Rotor: rotor is afield winding , the construction of which can be salient (projected pole) or non salient (cylindrical) type . practically most of the synchronous motor use salient i.e projected pole type construction the field winding is excited by a separate d.c supply through slip rings**.**

Principle of working

Synchronous motor works on the principle of the magnetic locking when two unlike poles are brought near each other ,if the magnets are strong there exists a tremendous force of attraction between those two poles. In such condition the two magnets are said to be magnetically locked.

If now one of the two magnets is rotated, the other also rotates in the same direction, with the same speed due to the force of attraction i.e. due to magnetic locking condition. The principle is shown schematically in fig.



Principle of magnetic locking

So to have the magnetic locking condition, there must exist two unlike poles and magnetic axes of two must be brought very close to each other. Let us see the application of this principle in case of synchronous motor.

Consider a three phase synchronous motor, whose stator is wound for 2 poles. The two magnetic fields are produced in the synchronous motor by exciting both the windings, stator and rotor with three phase a.c. supply then the flux produced by the three phase winding is excited by a three phase a.c. supply then the flux produced by the three phase winding is always of rotating type, which is already discussed in the section 4.2. Such a magnetic flux rotates in space at a speed called synchronous speed. This magnetic field is called rotating magnetic field. The rotating magnetic field creates the effect similar to the physical rotation of magnets in space with a synchronous speed. So stator of the synchronous motor produces one magnet which is as good as rotating in space with the synchronous speed. The synchronous speed of a stator rotating in space with the synchronous speed. The synchronous speed of a stator rotating magnetic field depends on the supply frequency and the number of poles for which stator winding is wound. If the frequency of the a.c. supply is f Hz and stator is wound for P number of poles, then the speed of the rotating magnetic field is synchronous given by,

$N_s =$ r.p.m**.**

In this case, as stator is wound for say 2 poles, with 50 Hz supply, the speed of the rotating magnetic field will be 3000r.p.m. This effect is similar to the physical rotation of two poles with a speed of N_Sr.p.m. For simplicity of understanding let us assume that the stator poles are N_1 and S_1 which are rotating at a speed of N_S. The direction of rotation of rotating magnetic field is say clockwise.

When the field winding on rotor is excited by a d.c. supply, it also produces two poles, assuming rotor construction to be two pole, salient type. Let these poles be N_2 and S_2.

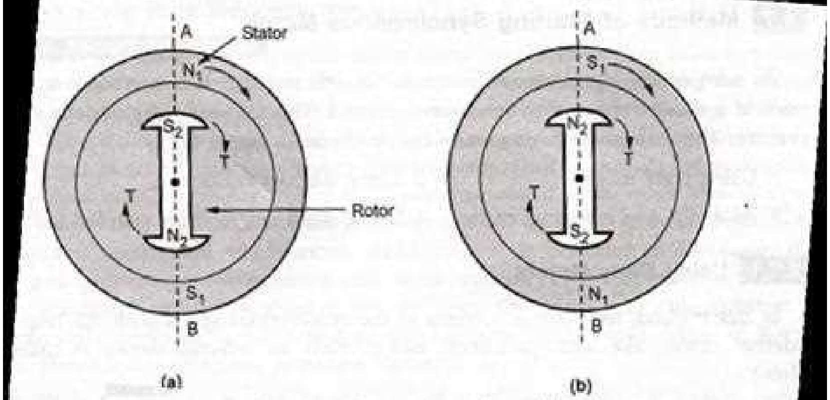
Now one magnet is rotating at N_s having poles N_1 and S_1 while at start rotor is stationary i.e. second magnet is stationary having poles N_2 and S_2. If somehow the unlike poles N_1 and S_1 or S_2 and N_2 are brought near each other, the magnetic locking may get established between stator and rotor poles. As stator poles are rotating, due to magnetic locking rotor will also rotate in the same direction as that of stator poles i.e. in the direction of rotating magnetic field, with the same speed i.e. Ns. hence synchronous motor rotates at one and only one speed i.e. synchronous speed. but this all depends on existence of magnetic locking between stator poles to pull the rotor poles from their stationary position into magnetic locking condition. Hence synchronous motors are not self starting. Let s use the reason behind this in detail.

Now suppose the rotor is rotated by some external means at a speed almost equal to synchronous speed. And then the rotor is excited to produce its poles. At a certain instant now, the stator and rotor unlike poles will face each other such that their magnetic axes are near each other. Then the force of attraction between the two, pulls both of them into the magnetic locking condition.

One magnetic locking is established, the rotor and stator poles continue to occupy the same relative positions. Due to this, rotor continuously experiences a unidirectional torque in the direction of the rotating magnetic field. Hence rotor rotates at synchronous speed and said to be in synchronism with rotating magnetic field. The external device used to rotate rotor near synchronous speed can be removed once synchronism is established. The rotor then continues its rotation at Ns due to magnetic locking. This is the reason why synchronous motor runs only at synchronous speed and does not rotate at any speed other than the synchronous. This operation is shown in the fig.

It is necessary to keep field winding i.e. rotor excited from d.c. supply to maintain the magnetic locking, as long as motor is operating.

So a general procedure to start a synchronous motor can be stated as:



Unidirectional torque experienced by rotor

1. Give a three phase a.c supply to a three phase winding. This will produce rotating magnetic field rotating at synchronous speed Ns r.p.m.

2. Then drive the rotor by some external means like diesel engine in the direction of rotating magnetic field, at a speed very near or equal to synchronous speed.

3. Switch on the d.c. supply given to the rotor which will produce rotor poles. Now there are two fields one is rotating magnetic field produced by stator while the other is produced by rotor which is physically rotated almost at the same speed as that of rotating magnetic field.

4. At a particular instant, both the fields get magnetically locked. The stator field pulls rotor field into synchronism. Then the external device used to rotate rotor can be removed. But rotor will continue to rotate at the same speed as that of rotating magnetic field i.e. Ns due to magnetic locking.

Key Point So the essence of the discussion is that to start the synchronous motor, it needs some device to rotate the rotor at a speed very near or equal to the synchronous speed.

Methods of Starting Synchronous Motor

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 methods 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.

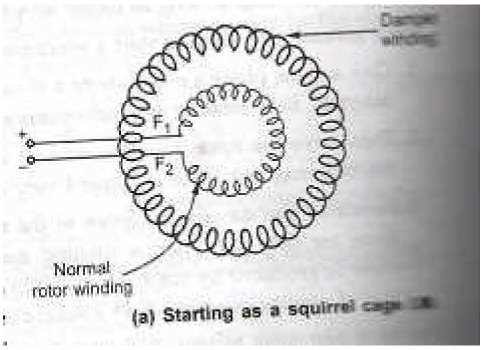
Using Pony Motors

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 synchronous is established pony motor is decoupled. The motor then continues to rotate as a synchronous motor.

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.



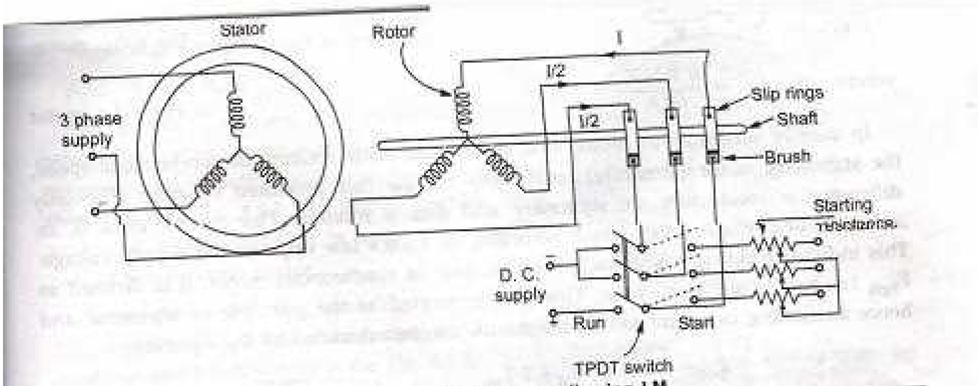
(a) Starting as a squirrel cage

Once the stator is excited by a three phase supply, the motor 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 cannot 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.

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 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 motor gets pulled into synchronism and starts rotating at synchronous speed. The damper winding is shorted by shorting the slip rings. The initial resistance added in the rotor not only provided high starting torque but also limits high inrush of starting current. Hence it acts as a rotor resistance starter.

The synchronous motor started by this method is called a slip ring induction motor is shown in the fig.



Starting as a slip ring I.M.

It can be observed from the fig. 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 I/2 through each, when switch is thrown on d.c. supply side.

Using Small D.C. Machine

Many a times, a large synchronous motors 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.

Operation of synchronous Motor at Constant Load Variable Excitation

In the last article we have seen that when load changes, for constant excitation, current drawn by the motor increases. But if excitation i.e. field current is changed keeping load constant, the synchronous motor reacts by changing its power factor of operation. This is most interesting feature of synchronous motor. Let us see the details of such operation.

Consider a synchronous motor operating at a certain load. The corresponding load angle is ɤ

At start, consider normal behaviour of the synchronous motor, where excitation is adjusted to get $E_b = V$ i.e. induced e.m.f. is equal to applied voltage. Such an excitation is called Normal Excitation of the motor. Motor is drawing certain current I_a from the supply and power input to the motor is say P_{in}. The power factor of the motor is lagging in nature as shown in the fig.

Now when excitation is changed E_b changes but there is hardly any change in the losses of the motor. So the power input also remains same for constant load demanding same power output.

Now $P_{in} = \sqrt{3}\, V_L\, I_L \cos\phi = 3(V_{ph}\, I_{aph} \cos\phi)$

Most of the times, the voltage applied to the motor is constant. Hence for constant power input as V_{ph} is constant, 'I_{aph} cosϕ' remains constant.

Key Point: So for this entire operation of variable excitation it is necessary to remember that the cosine component of armature current, 'I_a cosϕ' remains constant.

So motor adjusts its cosϕ i.e. p.f. nature and value so that I_a cosϕ remains constant when excitation of the motor is changed keeping load constant. This is the reason why synchronous motor reacts by changing its power factor to variable excitation conditions.

Under Excitation

When the excitation is adjusted in such a way that the magnitude of induced e.m.f is less than the applied voltage ($E_b < V$) the excitation is called Under Excitation.

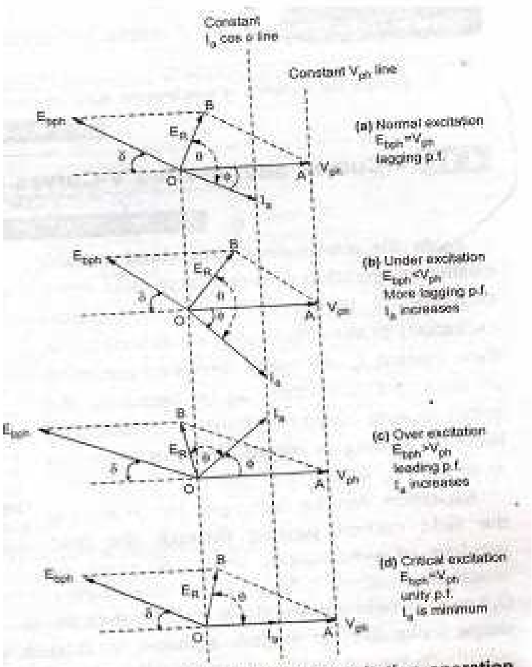
Due to this, E_R increases in magnitude. This means for constant Z_s, current drawn by the motor increases. But E_R phase shifts in such a way that, phasor I_a also shifts (as $E_R \wedge I_a = \theta$) to keep I_a cosϕ component constant. This is shown in the fig. So in under excited condition, current drawn by the motor increases. The p.f. cosϕ decreases and becomes more and more lagging in nature.

Over Excitation

The excitation to the field winding for which the induced e.m.f. becomes greater than applied voltage (Eb > V,) is called over excitation.

Due to increased magnitude of EB,ER also increases in magnitude. But the phase of ER also changes. Now $E_R \wedge I_a = \theta$ is constant, hence I_a also changes its phase. So Ø changes. The I_a increases to keep I_a cosϕ constant as shown in fig.

The phase of ER changes so that I_a becomes leading with respect to V_{ph} in over excited condition. So power factor of the motor becomes leading in nature



Constant load variable excitation operation

So over excited synchronous motor works on leading power factor. So power factor decreases as over excitation increases but it becomes more and more leading in nature.

Critical Excitation

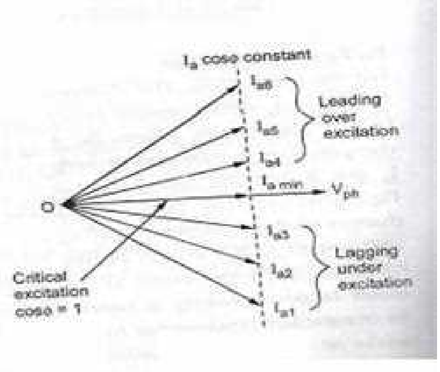
When the excitation is changed, the power factor changes. The excitation for which the power factor of the is unity (cosϕ =1) is called critical excitation. Then I_{aph} is in phase with V_{ph}. Now I_a cosϕ must be constant, cosϕ =1 is at its maximum hence motor has to draw minimum current from supply for unity power factor condition.

So for critical excitation, cosϕ =1 and current drawn by the motor is minimum compared to current drawn by the motor for various excitation conditions. This is shown in the fig.

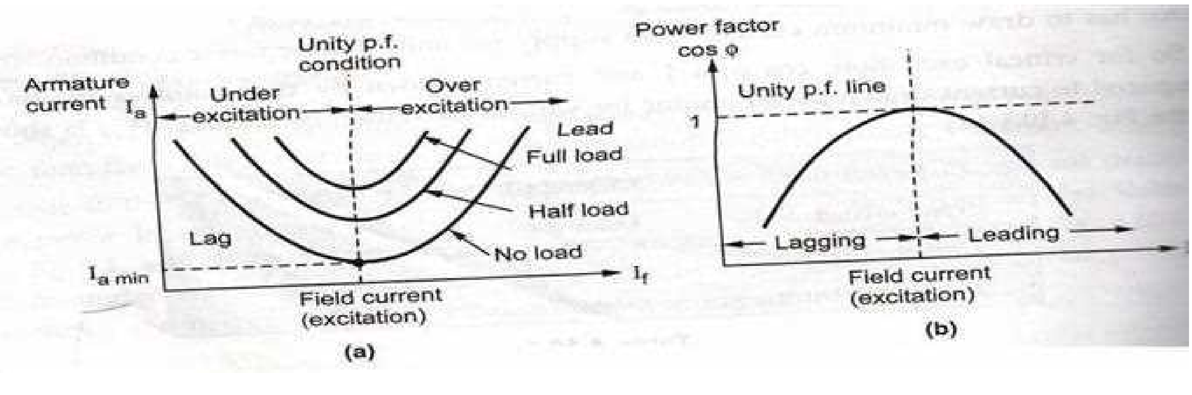
Under excitation	Lagging p.f.	$E_b < V$
Over excitation	Leading p.f.	$E_b > V$
Critical excitation	Unity p.f	$E_b \cong V$
Normal excitation	Lagging	$E_b = V$

V- Curves and Inverted V- Curves

From the above discussion about variable excitation operation of motor, it is clear that if excitation is varied from very low (under excitation) to very high (over excitation) value, then current I_a decreases, becomes minimum at unity p.f. and then again increases. But initial lagging current becomes unity and then becomes leading in nature. This can be shown as in fig.



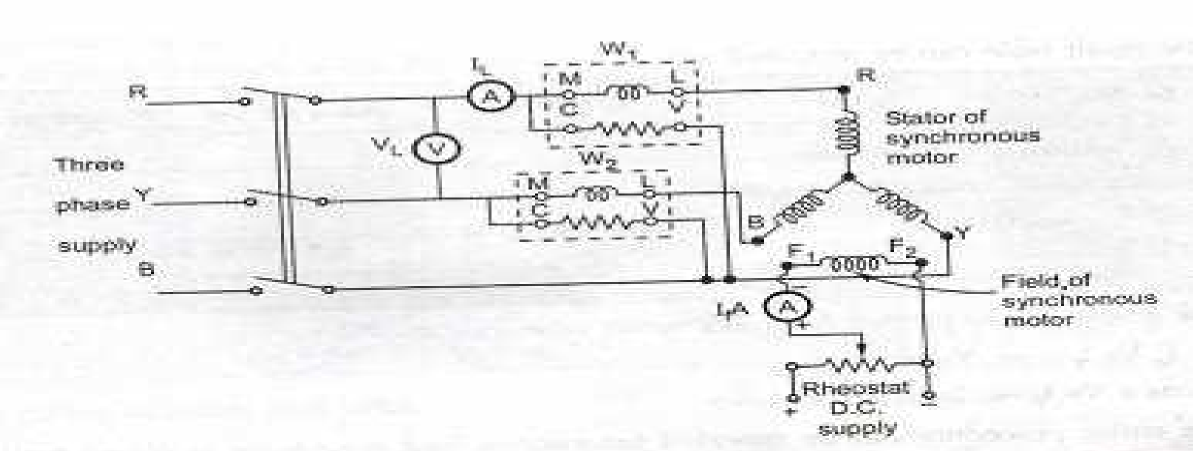
Excitation can be increased by increasing the field current passing through the field winding of synchronous motor. If graph of armature current drawn by the motor (I_a) against field current (I_f) is plotted, then its shape looks like an English alphabet V. If such graphs are obtained at various load conditions we get family of curves, all looking like V. Such curves are called V- curves of synchronous motor. These are shown in the fig.



As against this, if the power factor (cosϕ) is plotted against field current(If), then the shape of the graph looks like an inverted V. Such curves obtained by plotting p.f. against If, at various load conditions are called Inverted V-curves of synchronous motor. These curves are shown in the fig.

Experimental Setup to Obtain V- Curves

Fig shows an experimental setup to obtain V- curves and Inverted V-curves of synchronous motor.



Experimental setup for V-curves

Stator is connected to three phase supply through wattmeters and ammeter. The two wattmeter method is used to measure input power of motor. The ammeter is reading line current which is same as armature (stator) current. Voltmeter is reading line voltage.

A rheostat in a potential divider arrangement is used in the field circuit. By controlling the voltage by rheostat, the field current can be changed. Hence motor can be subjected to variable excitation condition to note down the readings.

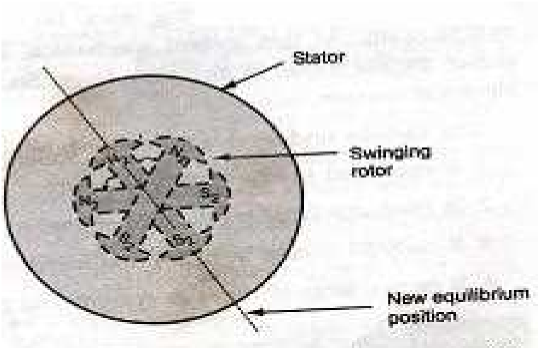
Hunting in synchronous motor

It is seen that, when synchronous motor is on no load, the stator and rotor pole axes almost coincide with each other.

When motor is loaded, the rotor pole axis falls back with respect to stator. The angle by which rotor retards is called load angle or angle of retardation .

If the load connected to the motor is suddenly changed by a large amount, then rotor tries to retard to take its new equilibrium position.

But due to inertia of the rotor, it cannot achieve its final position instantaneously. While achieving its new position due to inertia it passes beyond its final position corresponding to new load. This will produce more torque than what is demanded. This will try to reduce the load angle and rotor swings in other direction. So there is periodic swinging of the rotor on both sides of the new equilibrium position, corresponding to the load. Such a swing is shown in the fig.



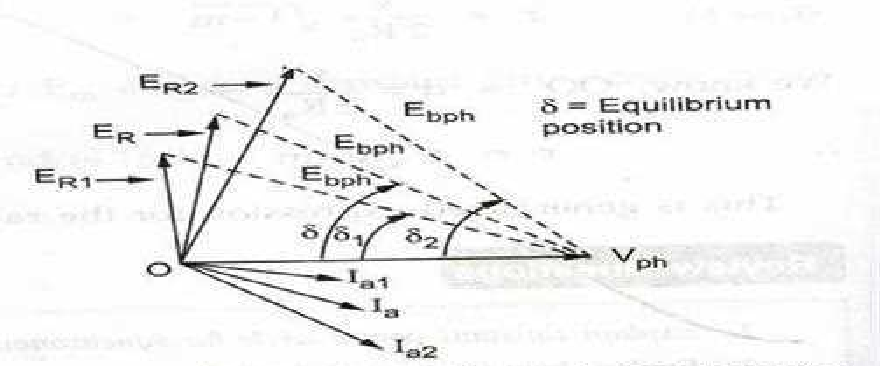
Hunting in synchronous motor

Such oscillations of the rotor about its new equilibrium position, due to sudden application or removal of load is called swinging or hunting in synchronous motor.

The main causes of hunting are,

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

Due to such hunting, the load angle changes its value about its final value. As changes, for same excitation i.e. E_{bph} the current drawn by the



Current variations during hunting

motor also changes. Hence during hunting there are changed in the current drawn by the motor which may cause problem to the other appliances connected to the same line. The changes in armature current due to hunting is shown in the fig.

If such oscillations continue for longer period, there are large fluctuations in the current. If such variations synchronise with the period of oscillation of the rotor, the amplitude of the swing may become so great that motor may come out of synchronism. At this instant mechanical stresses on the rotor are severe and current drawn by the motor is also very large. So motor gets subjected to large mechanical and electrical stresses.

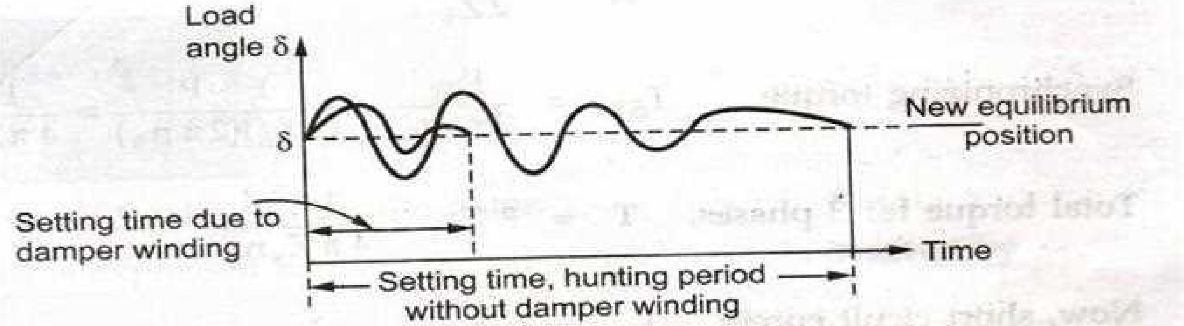
The various undesirable effects of hunting are,

1. It may lead to loss of synchronism.
2. It produces large mechanical stress.
3. It causes increase in losses and increases temperature rise.
4. It causes large changes in current and power flow.

Key point: Hence hunting is not desirable phenomenon from motor point of view and must be prevented.

Use of Damper Winding to Prevent Hunting

It is mentioned earlier that in the slots provided in the pole faces, a short circuited winding is placed. This is called damper winding.



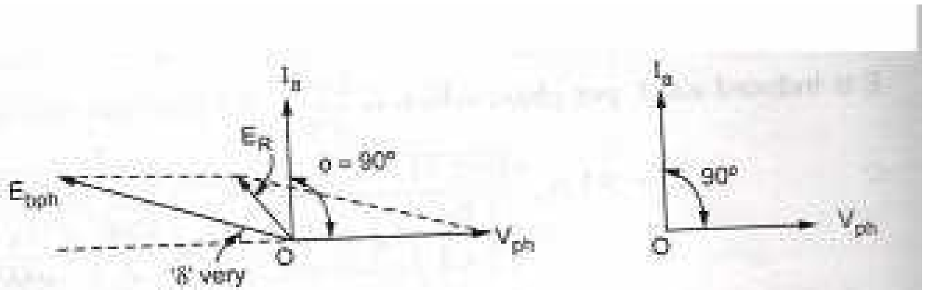
Effect of damper winding on hunting

When rotor starts oscillating i.e. when hunting starts a relative motion between damper winding and the rotating magnetic field is created. Due to this relative motion, e.m.f. gets induced in the damper winding. According to Lez’s law, the direction of induced e.m.f. is always so as to oppose the cause producing it. The cause is the hunting. So such induced e.m.f oppose the hunting. The induced e.m.f tries to damp the oscillations as quickly as possible. Thus hunting is minimised due to damper winding.

The time required by the rotor to take its final equilibrium position after hunting is called as setting time of the rotor. If the load angle is plotted against time, the schematic representation of hunting can be obtained as shown in the fig. It is shown in the diagram that due to damper winding the setting time of the rotor reduces considerably.

Synchronous Condensers

When synchronous motor is over excited it takes leading p.f. current. If synchronous motor is on no load, where load angle is very small and it is over excited(E_b>V) then power factor angle increases almost up to 90°. And motor runs with almost zero leading power factor condition. This is shown in the phasor diagram fig.



Synchronous condenser

This characteristics is similar to a normal capacitor which always takes leading power factor current. Hence over excited synchronous motor operating on no load condition is called as synchronous condenser or synchronous capacitor. This is the property due to which synchronous motor is used as a phase advancer or as power improvement device.

Disadvantages of Low Power Factor

In various industries, many machines are of induction motor type. The lighting and heating loads are supplied through transformers. The induction motors and transformers draw lagging current from the supply. Hence the overall power factor is very and lagging in nature.

The power is given by,

$P = V I \cos\phi$ i.e. $I =$ .... Single phase

The supply voltage is constant and hence for supplying a fixed power P, the current is inversely proportional to the p.f. $\cos\phi$. Let P = 5 kW is to be supplied with a voltage of 230 V then,

Case i) $\cos \phi = 0.8$, $I = 27.17$A

Case ii) $\cos \phi = 0.6$, $I = 36.23$ A

Thus as p.f. decreases, becomes low, the current drawn from the supply increases to supply same power to the load. But if p.f. maintained high, the current drawn from supply is less.

The high current due to low p.f. has following disadvantages:

1. For higher current, conductor size required is more which increases the cost.

2. The p.f. is given by

Cos ϕ = =

Thus for fixed active power P, low p.f. demands large kVA rating alternators and transformers. This increases the cost.

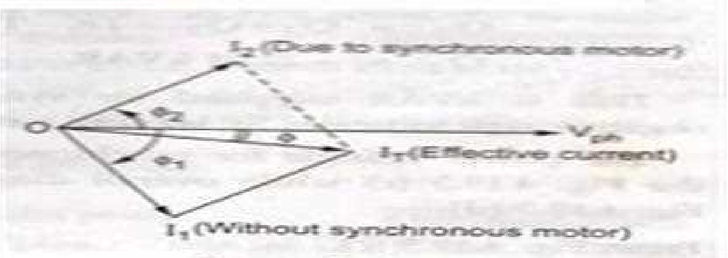
3. Large current means more copper losses and poor efficiency.

4. Large current causes large voltage drops in transmission lines, alternators and other equipments. This results into poor regulation. To compensate such drop extra equipment is necessary which further increases the cost.

Key point Hence power factor improvement is must in practice. Hence the supply authorities encourage consumers to improve the p.f.

Use of Synchronous Condensers in Power Factor Improvement

The low power factor increases the cost of generation, distribution and transmission of the electrical energy. Hence such low power factor needs to be corrected. Such power factor correction is possible by connecting Synchronous motor across the supply and operating it on no load with over excitation.



Power factor correction by synchronous condenser

Now let V_{ph} is the voltage applied and I_{1ph} is the current lagging V_{ph} by angle $\phi1$. This power factor ϕ 1 is very low, lagging.

The Synchronous motor acting as a Synchronous condenser is now connected across the same supply. This draws a leading current of I_{2ph}.

The total current drawn from the supply is now phasor of I_{ph} and I_{2ph}. This total current I_T now lags V_{ph} by smaller angle ϕ due to which effective power factor gets improved. This is shown in the fig.

This is how the Synchronous motor as a Synchronous condenser is used to improve power factor of the combined load.