

Disadvantages of Synchronous Motor:

- It requires both D.C. and A.C. supplies.
- Do not have any starting torque.
- The starting, synchronizing and control devices are expensive.
- The motor is more sensitive to system disturbances.

Advantages:

- Power factor of synchronous motor can be easily controlled by varying the field excitation. Over excited synchronous motor running at leading power factor improves system power factor.
- Synchronous motors have high efficiency and constant speed.
- For operating speed less than 500 r.p.m. and for high power rating, synchronous motors are cheaper than induction motors. At this speed range we will have salient pole type motors.

Methods of starting:

A synchronous motor is not self starting. The synchronous torque is developed only at synchronous speed. So, the average synchronous is zero at starting. In order that a synchronous motor can develop steady electro-magnetic torque, the relative speed between stator and rotor fields must be zero, i.e. the rotor must be brought up to a speed equal to the armature reaction field rotating at synchronous speed. This can be accomplished by mainly following methods:

- Auxiliary motor starting.
- Clutch and Brake Gear
- Induction motor starting.

Auxiliary Motor Starting:

Some of the early motors are equipped with auxiliary motors which were designed to be used only for starting and which develops sufficient torque to bring the synchronous motors up to synchronous speed.

When direct connected induction motor is used, the motor is either

- A machine with a very low rotor resistance and the same number of poles or
- A motor with a pole-pair fewer and a rotor rheostat, or
- A machine with solid unwound rotor .

The method involves running the machine up a speed close to the synchronous speed (induction speed), and synchronizing. Automatic synchronization is effected by connecting the stator of the synchronous motor first to a low voltage auto-transformer tapplings, then through reactors on to full voltage, and lastly short circuiting the reactor.

When D.C. motors are for this purpose, they can be properly designed to be used as a generator for field excitation after the synchronous speed is reached. The unit can be started by using the D.C. machine as a D.C. shunt motor.

Disadvantages of starting by auxiliary motor are:

- The starting torque is small. The unit cannot start with load, because that require auxiliary motor of large size.
- Some sort of synchronizing device is necessary to synchronize the motor to the line from which it is to be operated.

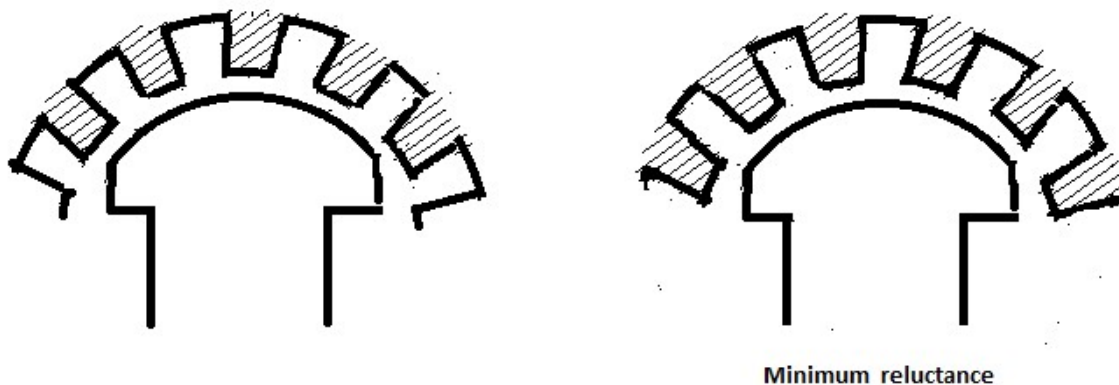
Clutch and Brake Gear Arrangement

When starting torque required is very high (greater than the full load torque) then this method is used. Both stator and rotor are free to rotate. The rotor is coupled to the load . Supply is given to the stator winding. As the inertia of the rotor and the load is high, the stator starts rotating and runs up to full speed. After synchronizing a brake is applied to the stator so as to slow it down. As the stator slows down simultaneously the rotor starts accelerating. When the stator is brought to rest, the rotor and the load reaches synchronous speed. Large starting torque is developed by this method. So, some times these motors are referred to as super-synchronous motor .

Induction Motor Starting of a Synchronous Motor

As most of these machines are of salient pole type, poly phase synchronous motors are started almost universally as induction motor by making use of their damper bars as squirrel cage winding of induction motor.

Damper bars are copper bars placed in the slots present in the pole face of salient pole synchronous machine and are short circuited. The eddy current and hysteresis losses in the pole faces, produced by the revolving field of armature reaction, produce a starting torque.



If the synchronous motor is to be started as an induction motor, care should be taken to design it in such a way that the reluctance of the air gap under the pole is the same for all positions. Otherwise the rotor has a tendency to lock in the position of minimum reluctance and a large torque is required to move it from the locked position.

The machine may be also designed as a synchronous –induction motor, with a three phase rotor winding on a non-salient pole core resembling a normal induction motor. The two methods are considered in more details below'

Damper Bar Starting of a Synchronous Motor

Starting a synchronous motor as an induction motor requires the rotor to have either solid pole-shoes, or laminated pole shoes carrying damper bars. When three phase supply (full or reduced) is given to the stator, a rotating field is created. The armature reaction field thus created is rotating at synchronous speed and is constant and fixed in space with respect to the field poles when the machine is rotating at synchronous speed. When the rotor is at rest or rotating at a speed other than the synchronous speed, there is relative motion between the armature reaction field and the rotor, which induces currents in the solid pole shoe or in the damper bars. A torque is produced by the interaction of the rotating field and the induced currents. Normally this torque is sufficient to start the motor and bring the rotor near to the synchronous speed. A synchronous motor can only attain induction speed by this torque. If properly designed slip will be low and rotor is pulled into step even before the field is applied, as the machine is salient pole. Space harmonics in the armature reaction field may produce cusps in the starting torque curve, which tend to make the motor lock at some sub-synchronous speed, but this difficulty can be avoided by proper design.

When such a motor has attained synchronous speed, excitation is entirely due to armature reaction. If now the field is closed and it so happens that that the polarity opposes the polarity produced by the armature reaction, the motor slips back 180° and is pulled into step only at the expense of large inrush current. To avoid this field is excited through high resistance when the speed is near to the synchronous speed. Synchronizing torque develops and the rotor is pulled into step.

DAMPER BAR RESISTANCE: the starting torque of an induction motor depends upon the resistances and leakage reactance. We know that for maximum torque

$$s_{mT}r_2' = \sqrt{(r_1^2 + (x_1 + x_2')^2)} \quad \text{or} \quad s_{mT} = \frac{\sqrt{(r_1^2 + (x_1 + x_2')^2)}}{r_2'}$$

Where r_1 = stator resistance ; r_2' = rotor resistance ;

x_1 = stator inductance and x_2' = rotor inductance

Now the difference between the actual speed of the induction motor and its synchronous speed i.e. the slip speed depends on the secondary resistance. If the rotor resistance is low the slip will be small, which is advantageous from the point of view of the pulling in process. So, for fast pull in, a low damper

resistance is necessary. On the other hand for high starting torque we require a high rotor resistance. The conditions are contradictory so a compromise has to be made.

Now, frequency of the damper bar current is very low near the synchronous speed, so the effective resistance is almost equal to the D.C. resistance and the skin effect is small. However at the instant of starting the frequency is the line frequency, so the effective resistance is large as the skin effect is high. This phenomenon is utilized to design the damper bars.

The chief disadvantage of the method :

- High current required during starting. This current is mainly magnetizing current at low power factor, disturbing regulation.
- High voltage is induced in the open field winding.

The high voltage induced in the field winding during starting is caused by the armature reaction field sweeping past the pole faces. This voltage is maximum at the time of starting and zero when the synchronous speed is reached. To keep this voltage low:

- i) The voltage for the field excitation should be low, corresponding to a small number of field turns.
- ii) A switch can be provided to sectionalize the field winding during starting and the voltage strain on the field insulation is then limited to that in the single section instead of that generated in the entire field winding. It is seldom used because of constructional difficulties.
- iii) Normally extra insulation is provided, so the field can withstand the high voltage induced. However the presence of the damper winding reduces the voltage considerably, which would otherwise be induced in the field.

It might seem that shorting the field winding might help. But the short circuited field winding acts like a single phase winding and tend to hold the motor at half speed. The phenomenon is discussed in details below:

GEORGE'S PHENOMENON:

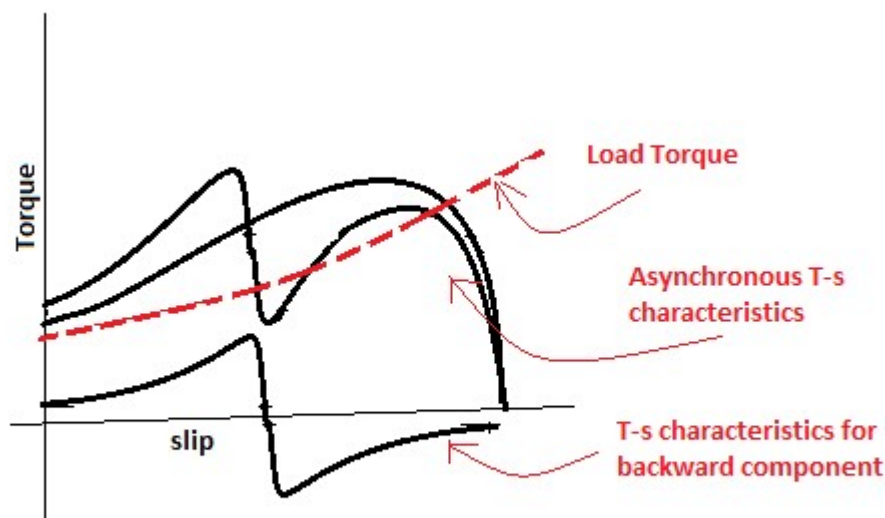
- The number of field winding turns is larger than the armature turns ,
- The starting slip is unity.

Thus with full supply voltage impressed across the armature, the voltage induced in the open field winding is large. For large synchronous motors with large inertia, when starting time is high, this induced voltage may cause brake down of insulation between field winding and the field core; and between the slip rings, if the field is kept open. A discharge path must be provided.

On the other hand if the winding is shorted on itself a large current will flow. At any slip's' this current will develop a pulsating field at an angular frequency of $s\omega_s$. This pulsating field can be resolved into backward and forward field.

- The forward component rotates in the direction of the rotating field (say in clockwise direction) at an angular speed, ω_2 , radians per second, with respect to the field winding. With respect to the rotor conductor this component has a speed of $\omega_2 + \omega_r = \omega_s$ rad/sec in the same direction as the r.m.f. and develops asynchronous torque.
- The backward component rotates at a speed ω_2 of in the opposite direction w.r.t. the stationary field. With respect to the rotor conductor, this component has a speed of $\omega_r - \omega_2 = (1 - 2s)\omega_s$ rad/sec in the counter clock wise direction.

At $s=0.5$ backward component is zero, so torque is zero. At $s=0.45$ the backward component has a speed of $0.1\omega_s$ in the counter clock wise direction, producing a generator torque. At $s=0.55$ backward component speed is $0.1\omega_s$ in the clock wise direction, producing a motoring torque.



The magnitude of the backward component of torque depends on the value of the field mmf and may be sufficient to run the motor at a speed nearly fifty percent of the synchronous speed. This phenomenon is known as '**GEORGE'S PHENOMENON**'. This backward torque may be decreased by having high resistance in the field circuit. A resistance 7 to 10 times the field resistance is usually sufficient to keep the backward component torque to a harmless value. It also provide an effective discharge path to the induced high voltage.

APPLIED VOLTAGE:

STARTING ON FULL VOLTAGE : If the full voltage is applied to the stator at starting, the switchgear required is simple and cheap. Only a main switch and a field control gear is required. The starting current however is large, 3 to 7 times the full load current. Such high current may not be permissible, in that case a three phase damper winding connected to slip rings may be utilized along with resistor. Machines several hundreds of kW may be started without undue reduction of the line voltage.

Starting with reduced voltage : if the lower torque available is sufficient , reduced voltage may be applied initially, to reduce the starting current. Methods are :

1. Series reactor
2. Auto-transformer
3. Star-delta switching
4. Transformer tapings

1. **Series Reactor :** inductive reactors are connected between the stator and the supply to reduce the voltage. The reactors are short circuited after the machine has been synchronized.
2. **Auto-transformer:** The method is similar to auto-transformer starting of an Induction motor. But the interruption of the circuit during the starting sequence may produce several switching transients in the supply and the possibility of loss of synchronism when passing from start to normal running connection. This disadvantage is overcome in Korndorfer method, in which the motor is given half normal voltage at starting, from a star connected auto transformer. When induction speed is reached the star point is removed, leaving the auto transformer operating as reactor. The motor voltage rises to a value near to normal. At the last step the auto transformers are bypassed.
3. **Star Delta switching:** Similar to the starting of induction motor by star delta starter. Disadvantage is the momentary interruption of the supply.
4. **Transformer Tapings:** This method is used for very large motors , where the size justifies the cost of starting gear.

Usual practice during starting:

1. Its field is kept open and about half normal full voltage is applied to the armature terminals. The motor starts slowly and if the damper bars are properly designed it should speed up with increasing acceleration. The time required to attain full speed depend on applied voltage and size of the motor. For motor of moderate size it is around one minute or one and a half minute.
2. Near to the synchronous speed the field circuit is closed through a resistor and full voltage is applied to the armature. The field is then adjusted to run at the desired p.f.
3. Slightly overexcited motors are preferred, because:
 - Over excited motors runs at leading p.f. there by compensating the reactive power drawn by other loads.
 - Over excited motors are more stable.
 - If the motor is to be operated at fixed excitation, the field should be adjusted initially to made the motor operate at u.p.f. at its average load unless the conditions under which it operates make some other p.f. more desirable.

LENGTH OF AIR GAP:

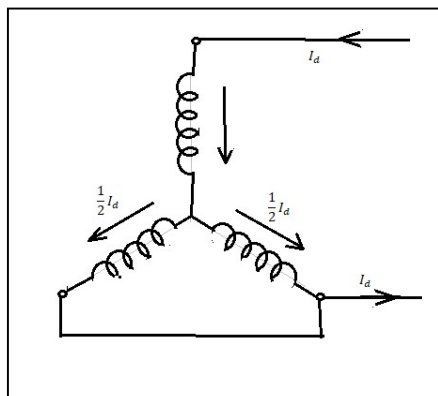
When the synchronous motor is to be started as an induction motor, the air gap should be small. But a short air gap gives rise to soft coupling which is undesirable. The selection of the best length of air gap for any motor is a compromise and depends on the particular service demanded.

Although the regular short circuited damper gives sufficient starting torque for most practical purposes, it is unsuitable when high starting torque is required as in certain industrial processes. To get high starting torque coil wound dampers are used and are connected in star with the free terminals brought out to slip rings. The slip rings are shorted through adjustable resistances. As the motor speeds up, the resistances are cut out in steps by centrifugally controlled contactors until the slip rings are short circuited. By use of the proper resistances, the maximum induction motor torque can be developed at the instant of starting without excessive current.

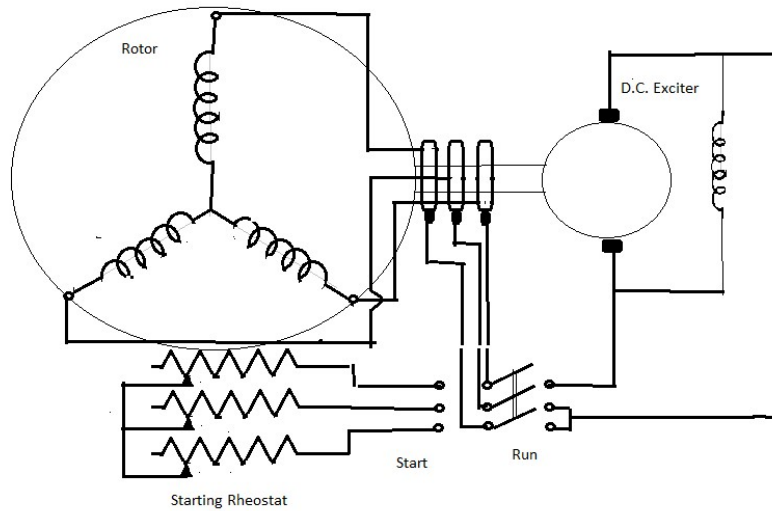
Synchronous Induction Motor:

A synchronous motor started with the help of damper winding suffers from the disadvantage of low starting torque. With the synchronous induction motor, which starts as a wound rotor induction motor and runs as a synchronous motor, large starting torque and low starting current can be obtained. The motor has stator and rotor winding similar to the wound rotor induction motor. At starting the slip rings are closed through rotor resistance starter so that with proper choice of resistance, large starting can be obtained. As the rotor reaches the speed near to synchronous, the rotor winding is thrown over the dc exciter and under certain condition, the rotor pulls into synchronism.

Consider a normal slip ring induction motor with a three phase rotor. Let the winding be connected to a D.C. exciter as shown in the figure which furnishes a current I_d . The current distribution is shown in the figure. One phase carries I_d and the other two in parallel carries $\frac{1}{2}I_d$ each. Current distribution creates N and S poles on the rotor just as do the three phase alternating currents carried by the rotor



when the machine works as an induction motor. The essential difference is that the direct current excitation is fixed, so the pole axis are also fixed. Thus it is possible to use normal slip-ring motor windings to produce fixed poles. In this method the motor is started as a slip ring induction motor with rheostat connected to the slip rings. When the rheostat is fully cut out and the motor is running with a small slip, the connection is changed and the rotor winding is connected to the D.C. supply.

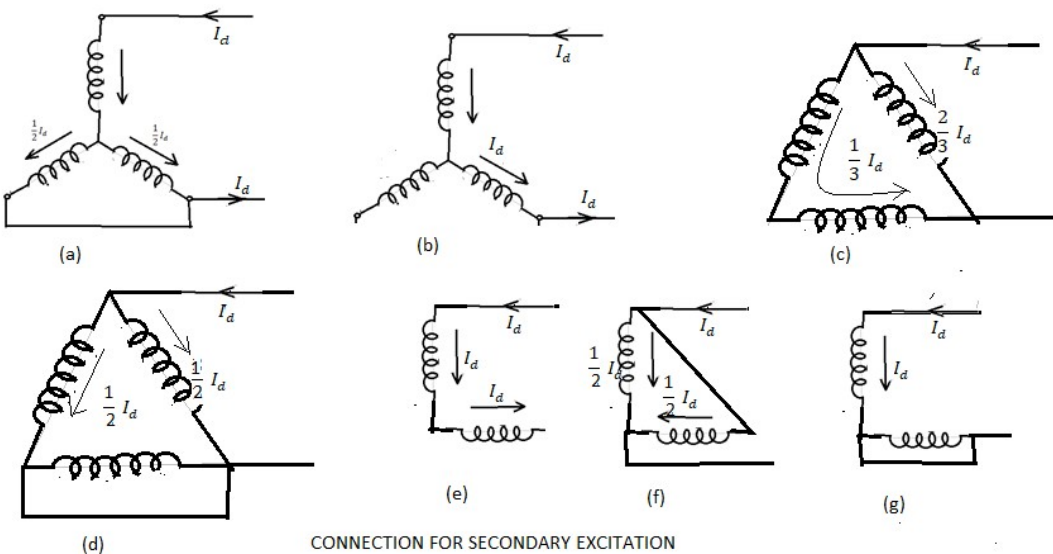


CONNECTION FOR SYNCHRONOUS INDUCTION MOTOR

The connection of the machine at starting as a slip ring motor renders possible the development of high starting torque. So, synchronous induction motors are used for constant speed motor with large starting torque, low starting current and power factor correction.

EQUIVALENT SECONDARY CURRENT:

In the previous connection the secondary phases carry current in the ratio $1 : \frac{1}{2} : \frac{1}{2}$, corresponding to the instants in the cycle of a a.c. excited winding when current is maximum in one phase and one-half negative in other two phases. Consequently the D.C. excitation I_d gives a magnetizing current corresponding to an A.C. peak of I_d or r.m.s. $I_a = I_d/\sqrt{2}$. Thus for an appropriate to an a.c. current of I_a , the D.C. excitation supplied to the secondary must be $I_d = \sqrt{2}I_a = 1.41I_a$.



CONNECTION FOR SECONDARY EXCITATION

Generally the rotor is star connected and connection (a) is used since the short circuited phase behaves as the damper winding and helps to reduce oscillation.

However a well designed induction motor if used as a synchronous induction motor, suffers from several disadvantages;

1. An induction motor has a very small air gap, so that its magnetizing current is minimum. This means large magnetizing reactance X_m and under synchronous operation, the synchronous reactance $X_s = X_m + x_l$ is also large.
2. No load current of the synchronous machine is very large.

Advantages;

1. Smaller excitation current and smaller excitation loss.

Disadvantages;

1. Large no load current is nearly equal to the full load current.
2. Wide variation of power factor with load.
3. Smaller exciting current and lower overload capacity.
4. Poor power factor except near the limit of stability.
5. Low synchronizing torque since X_s is large.

If synchronous reactance is reduced by increasing the gap, the disadvantages are removed. Both exciting current and excitation losses will be higher. Normally the gap length is twice that of induction motor.

Salient Pole Synchronous Induction Motor:

A salient pole synchronous induction motor has armature and field windings similar to a salient pole synchronous motor, but the damper bars are replaced by three phase wound rotor winding. During starting, the three phase wound winding is closed through an external resistance, 7-10 times its own resistance to avoid George's phenomena. During synchronous operation, the starting resistance is put to zero so that the winding is shorted on itself and behaves as damper winding to reduce hunting. Separate field and starting winding ensure low excitation loss and higher starting torque.

It is advantageous to have salient poles on the stator and the three phase armature winding on the rotor as this will need lesser number of slip rings and reduce control gear problem.

Comparison between synchronous induction motor (SIM) and the salient pole synchronous motor (SSM) are given below:

1. SIM has higher starting torque (2 times), lower starting current (60%) in comparison with SSM when the latter is started by an auto transformer with 60% tap. A SIM can be easily started with full load.

2. Air gap in SIM is little larger than a wound rotor induction motor but smaller than the effective gap length of a SSM. The field volt-ampere require under a particular load condition is less and thus the exciter capacity requires is small.
3. Since the effective rotor resistance of SIM is smaller than the field resistance of a SSM, exciter should have lower voltage and higher current. This leads to lower excitation loss.
4. Rotor resistance starting is cheap and simple.
5. In SSM, additional pole phase winding, provides damping. In a SIM short circuited phases in rotor provides damping.
6. SIM is less stable against fluctuating load since a salient pole field system is much stronger than a wound field system. The pull out torque of the former is less.
7. If load on the motor is larger than the synchronous pull out torque, a SIM doesn't stop; it loses synchronism and continues to run as an induction motor. However there will be fluctuation in torque and slip since there is rotor dc excitation. When the load is reduced below pull out value, the motor automatically pulls into synchronism.
8. Non uniform heating in exciting winding in a SIM is often a problem. This can be avoided by using: a) separate winding for starting and excitation, B) two-phase winding instead of three phases on the rotor. But it results in higher harmonics.

COMPARISON OF INDUCTION AND SYNCHRONOUS MOTORS

	INDUCTION		SALIENT POLE SYNCHRONOUS
	CAGE-ROTOR	SLIP-RING	
Stator Winding	Form wound insulated coils placed in slots	Same	Same, except that for equal rating there are usually fewer coils, thus providing air space between ends of coils, and improved insulation
Rotor Winding	Cage winding carries starting and running current	Form wound insulated coils placed in slots, carry starting current at high voltage and running current at low voltage	Cage winding carries starting current only Definite pole, low voltage, direct current exciting winding, easy to insulate, carries relatively small constant running current, regardless of load
Slip-Ring	none	Three that carry starting current at high voltage and running current at low voltage.	Two, that carry direct current excitation at low voltage.
Air-Gap	small	small	Three to five times greater than induction motor
Automatic Control	Three switches: starting; magnetizing and running; an auto-transformer; three control relays and two over load relays.	Three or more switches: one primary and two or more to cut out secondary resistance; four or more operating relays and two overload relays; resistance grids	One or more switches for starting and running duty; a field contactor; two operating relays and two over load relays. But direct-on-line starting is becoming usual