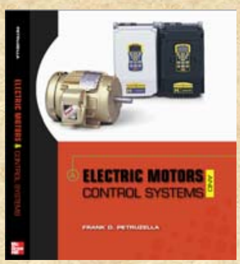


Chapter 5

Electric Motors

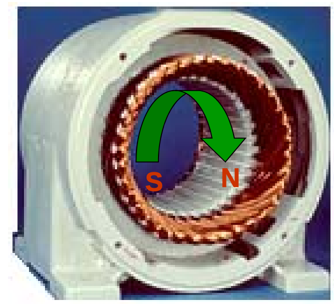
PART 3 Three-Phase Alternating Current Motors

ROTATING MAGNETIC FIELD

A *rotating magnetic field* is the key to the operation of AC motors. The magnetic field of the *stator* is made to rotate electrically around and around in a circle.

Stator Lamination

Stator Windings

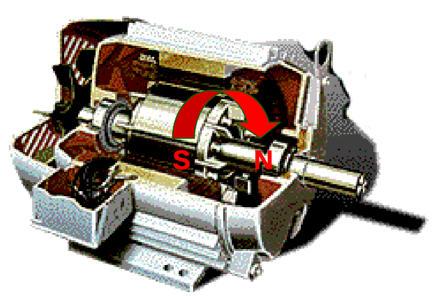


Stator Rotating Magnetic Field

A second magnetic field, that of the *rotor*, is made to follow the rotating field of the stator by being attracted and repelled by it.

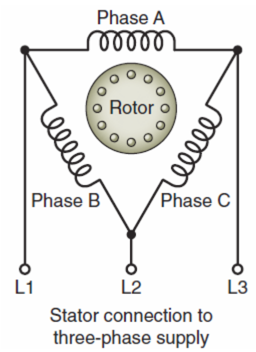
Rotor Laminations

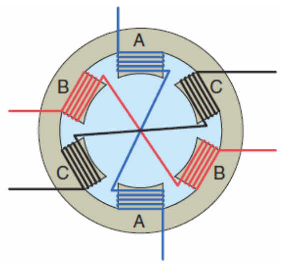
Rotor Windings



Rotor Magnetic Field Follows That Of The Stator

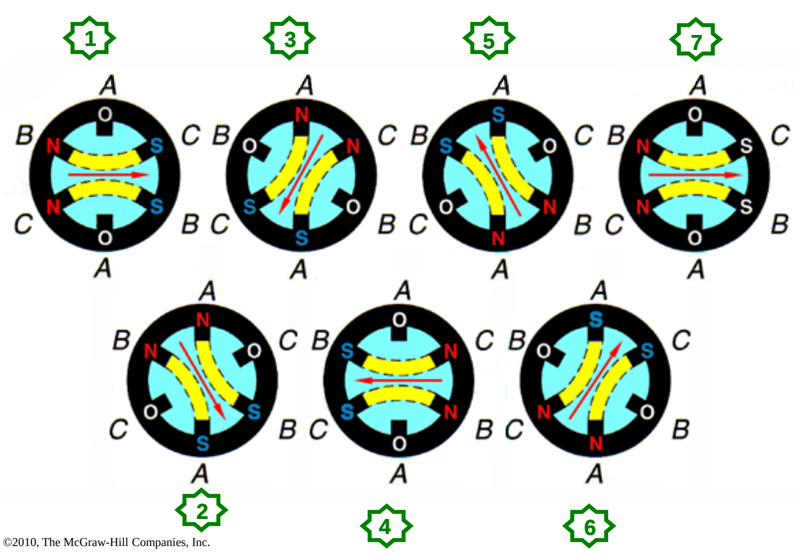
Three sets of stator windings are placed *120 electrical degrees* apart with each set connected to one phase of the 3-phase power supply



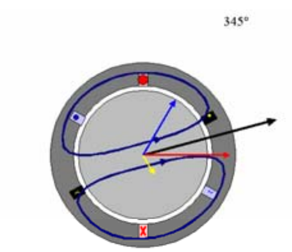


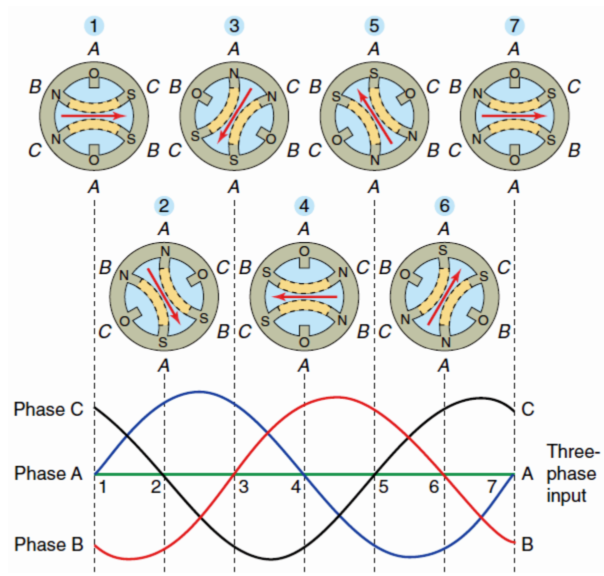
When 3-phase current passes through the stator windings, a rotating magnetic field effect is produced that travels around the inside of the stator core.

When 3-phase current passes through the stator windings, a rotating magnetic field effect that travels around the inside of the stator core is set up.

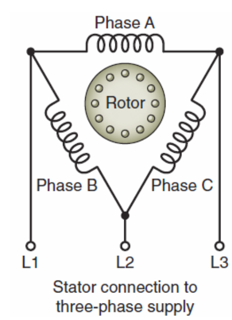


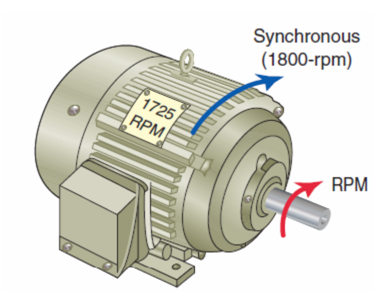
Polarity of the rotating magnetic field is shown at six selected positions marked off at 60° intervals on the sine waves representing the current flowing in the three phases, A, B, and C.





Simply ***interchanging any two*** of the three-phase power input leads to the stator windings reverses direction of rotation of the magnetic field.





- The motor ***synchronous speed*** is the speed of the stator's magnetic field rotation.
- In order to develop torque the rotor always turn at a slightly slower rate than the synchronous speed.
- The ***motor actual*** speed is that listed on the nameplate.

The synchronous speed of an AC motor can be calculated by the formula:

$$S = \frac{120f}{P}$$

where

S = synchronous speed in rpm
f = frequency, Hz, of the power supply
P = number of poles wound in each of the single-phase windings

EXAMPLE 5-3

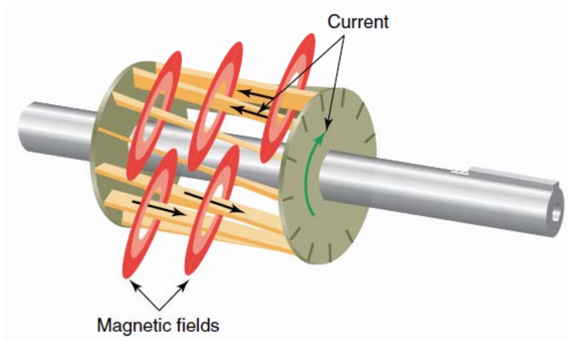
Problem: Determine the synchronous speed of a four-pole AC motor connected to a 60-Hz electrical supply.

Solution:

$$S = \frac{120f}{P} = \frac{120 \times 60}{4} = 1{,}800 \text{ rpm}$$

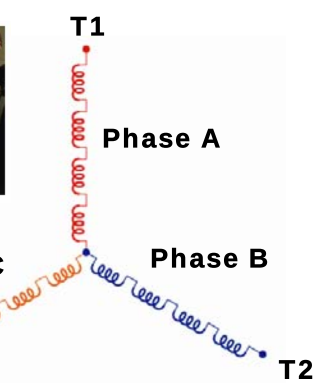
INDUCTION MOTOR

The *induction motor* is so named because no external voltage is applied to its rotor.



- There are no slip rings or any DC excitation supplied to the rotor.
- The AC current in the stator induces a voltage into the rotor winding to produce rotor current and associated magnetic field
- The stator and rotor magnetic fields then interact and cause the rotor to turn.

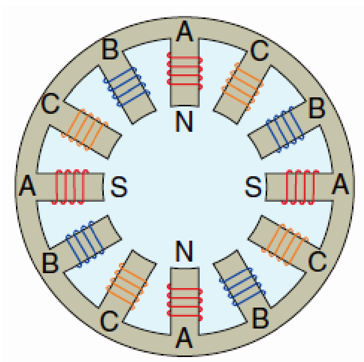
A 3-phase motor stator winding consists of three separate groups of coils called *phases* and designated as *A, B, and C.*



Y Stator Coil Grouping

The phases are displaced from each other by 120 electrical degrees and contain the same number of coils, connected for the same number of poles.

Poles **refer to a coil or group of coils wound to produce a unit of magnetic polarity. The number of poles a stator is wound for will always be an even number and refers to the total number of north and south poles per phase.**

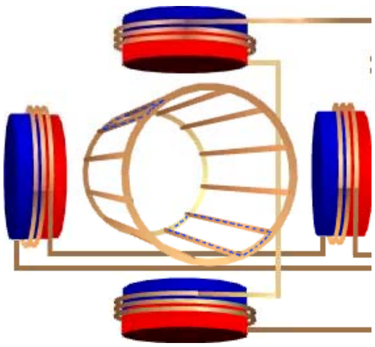


Y connected *4-pole* 3-phase induction motor.

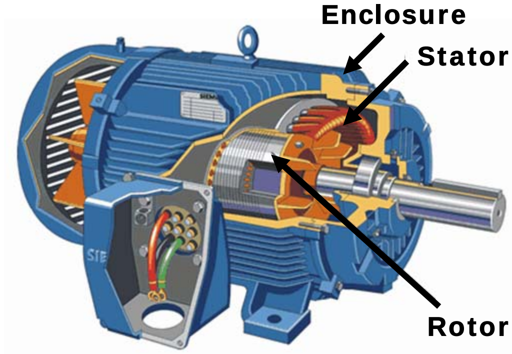
SQUIRREL CAGE INDUCTION MOTOR

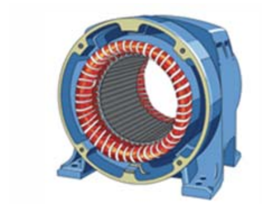
An induction motor rotor can either be a *wound* rotor or a *squirrel cage* rotor. The majority of induction motors are of the squirrel cage rotor type.

The rotor is constructed using a number of single bars short circuited by end rings and arranged in a hamster-wheel or squirrel-cage configuration.



- **When voltage is applied to the stator winding, a rotating magnetic field is established.**
- **This rotating magnetic field causes a voltage and resulting current to be induced in the rotor.**
- **These rotor currents establish their own magnetic field, which interacts with the stator magnetic field to produce a torque which spins the rotor.**



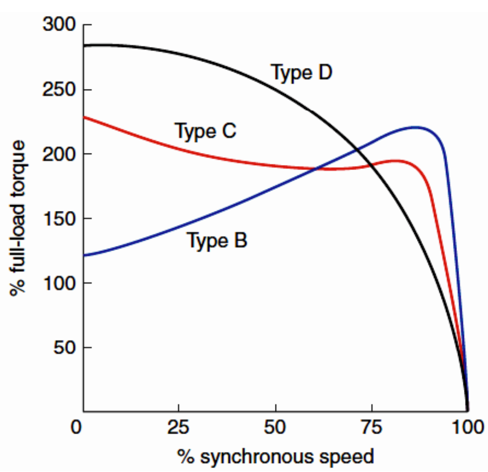


Three-Phase Stator Winding

Squirrel Cage Rotor

The resistance of the squirrel cage rotor has an important effect on the operation of the motor. A high resistance rotor develops a high starting torque at low starting current. A low resistance rotor develops low slip and high efficiency at full load.

Squirrel cage motor *speed/torque* characteristics.



NEMA DESIGN B - Considered a standard type with normal starting torque, low starting current, and low slip at full load.

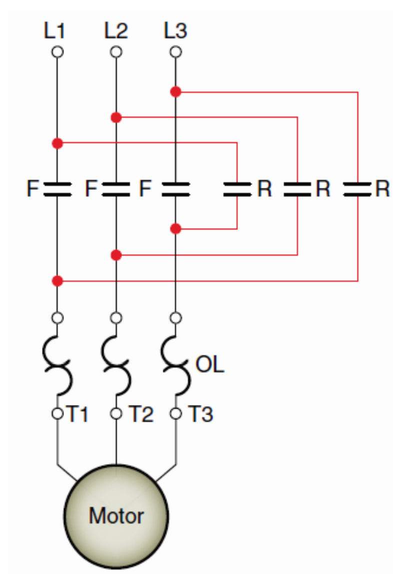
NEMA DESIGN C – This type has higher than standard rotor resistance, which improves the rotor power factor at start, providing more starting torque.

NEMA DESIGN D – The even higher high rotor resistance of this type produces a maximum amount of starting torque.

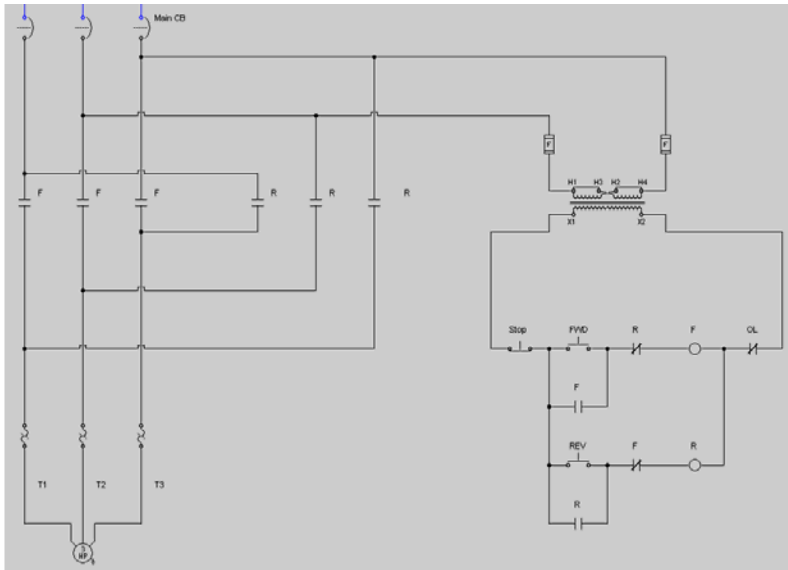
Squirrel cage motor *operating* characteristics.

- The motor normally operates at essentially a **constant speed** close to that of the synchronous speed.
- **Large starting currents** required by this motor can result in line voltage fluctuations.
- Once started, the motor will continue to run with a **phase loss** as a single-phase motor. The current drawn from the remaining two lines will almost double, and the motor will overheat. The motor will not start if it lost a phase.
- Interchanging any **two of the three** main power lines to the motor reverses the direction of rotation.

Forward and *Reverse* motor starter.

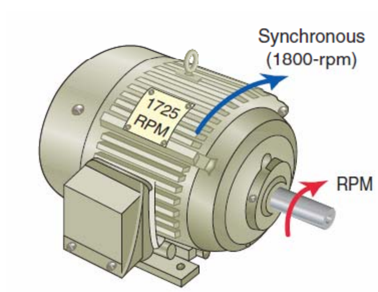


Simulated Forward and Reverse Motor Starter



The rotor does not revolve at synchronous speed, but tends to *slip* behind.

If the rotor turned at the same speed at which the field rotates, there would be no relative motion between the rotor and the field and no voltage induced.



$$\text{Percent slip} = \frac{\text{Synchronous speed} - \text{Actual speed}}{\text{Synchronous speed}} \times 100$$

EXAMPLE 5-4

Problem: Determine the percent slip of an induction motor having a synchronous speed of 1,800 rpm and a rated actual speed of 1,750 rpm.

Solution:

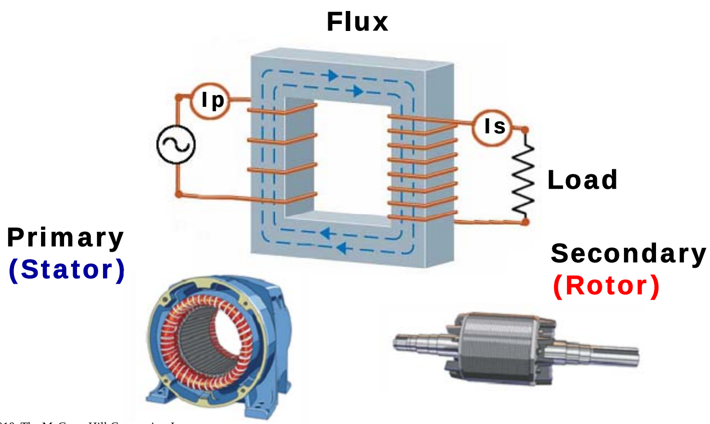
Percent slip

$$= \frac{\text{Synchronous speed} - \text{Actual speed}}{\text{Synchronous speed}} \times 100$$

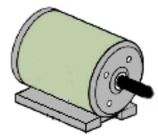
$$= \frac{1{,}800 - 1{,}750}{1{,}800} \times 100$$

$$= 2.78\%$$

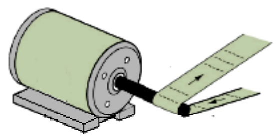
Loading of an induction motor is similar to that of a transformer. Both involve changing flux linkages with respect to a primary (stator) winding and secondary (rotor) winding.



➢The **no-load** current is low and similar to the exciting current in a transformer.



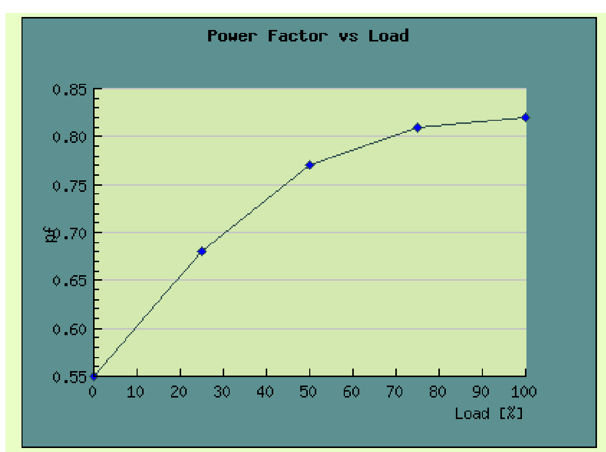
➢When the motor is **under-load**, the rotor current develops a flux that opposes and, therefore, weakens the stator flux.



➢This allows **more current to flow in the stator** windings, just as an increase in the current in the secondary of a transformer results in a corresponding increase in the primary current.

Whenever a motor is running on no-load, the *power factor (PF)* is very low and when they are operated at full load the power factor is much higher.

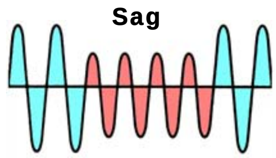
Power Factor



Load

The moment a motor is started it draws a high inrush current called the *locked-rotor current.*

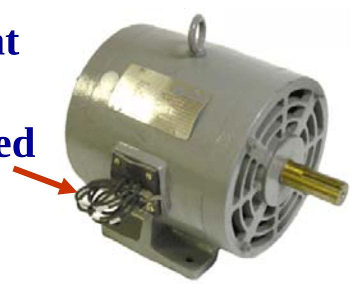
Induction motors started at rated voltage, have locked rotor starting currents of up to *six times* their nameplate full-load current



High locked-rotor motor current can create voltage dips or sags in the power lines, which may cause objectionable light flicker and problems with other operating equipment.

A motor that draws excessive current under locked rotor conditions is more likely to cause nuisance tripping of protection devices during motor start-ups.

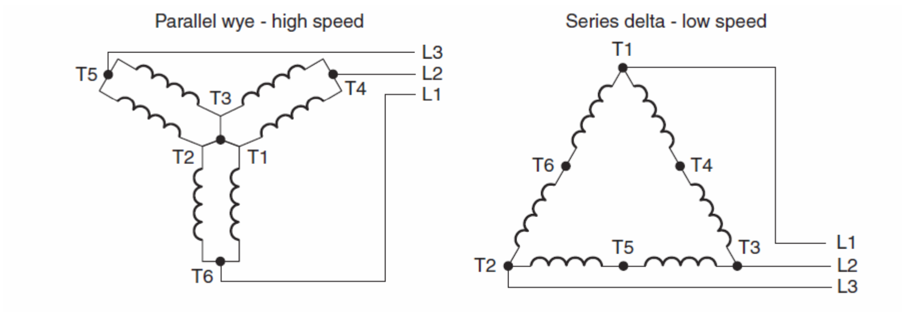
A *multi-speed* motor will run at different speeds depending on how the windings are connected to form a different number of magnetic poles.



Two-speed, single winding motors are called consequent pole motors. The low speed on a single winding consequent pole motor is always one-half of the higher speed.

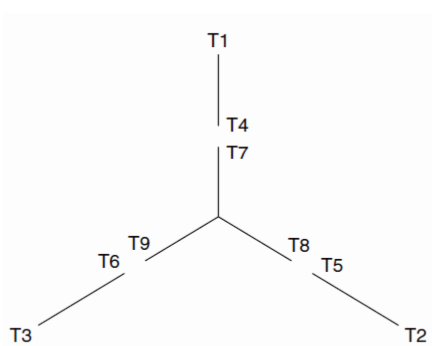
With separate winding motors a separate winding is installed in the motor for each desired speed.

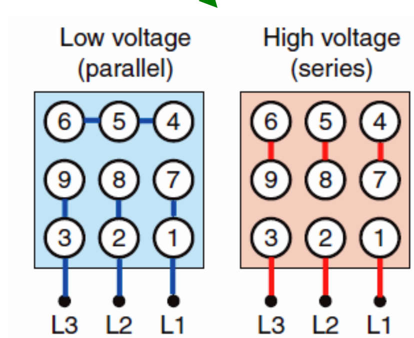
Dual-speed (1750 / 875 RPM) single winding motor.



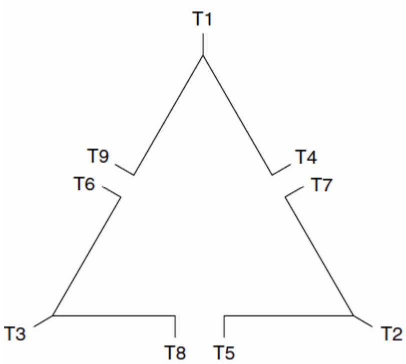
NEMA Nomenclature—6 Leads					
Speed	L1	L2	L3		Typical connection
High	6	4	5	1&2&3 join	2 wye
Low	1	2	3	4-5-6 open	1 delta

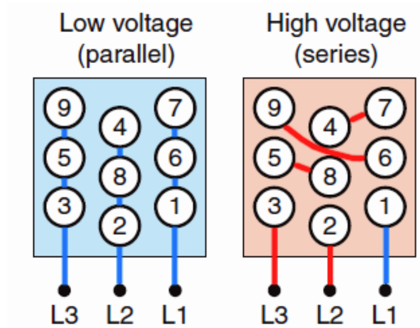
Single speed AC induction motors are frequently supplied with multiple external leads for *various voltage ratings* in fixed frequency applications.





9-lead dual-voltage wye-connected motor





9-lead dual-voltage delta-connected motor

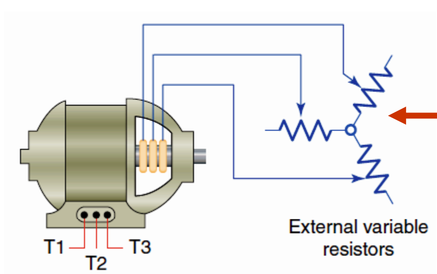
These types of reconnections should not be confused with the reconnection of multi-speed polyphase induction motors. In the case of multi-speed motors, the reconnection results in a motor with a different number of magnetic poles and therefore a different synchronous speed at a given frequency.

WOUND ROTOR INDUCTION MOTOR

The *wound rotor* induction motor is a variation on the standard cage induction motors that uses a three-phase winding wound on the rotor, which is terminated to slip rings.

Slip rings

Wound Rotor



The rotor slip rings connect to three phases of *start-up resistors* in order to provide current and speed control on start-up.

- The motor is normally started with full external resistance in the rotor circuit that is gradually reduced to zero, either manually or automatically
- This results in a very high starting torque from zero speed to full speed at a relatively low starting current.
- With zero external resistance, the motor a wound rotor motor characteristics approach that of the squirrel cage motor.
- Interchanging any two stator voltage supply leads reverses the direction of rotation.

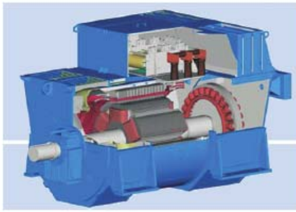
Wound rotor motors are also used for *varying-speed* service.

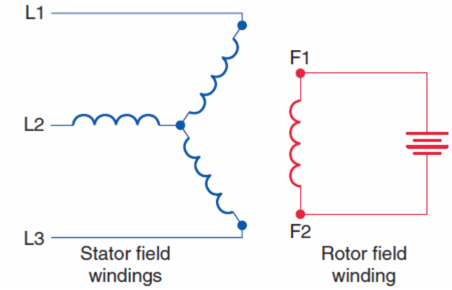
To use a wound rotor motor as an adjustable speed drive, the rotor control resistors must be rated for continuous current.

Speed varies with this load, so that they should not be used where constant speed at each control setting is required.

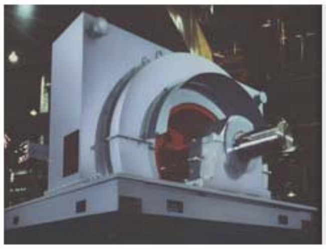
THREE-PHASE SYNCHRONOUS MOTOR

As its name suggests a *three-phase synchronous motor* runs at a *constant speed* from no-load to full-load.



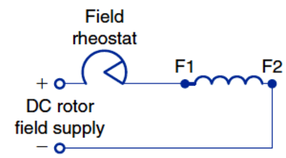


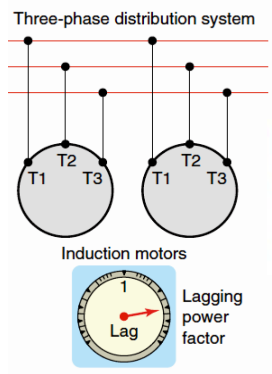
- Three phase AC voltage is applied to the stator windings and a rotating magnetic field is produced.
- DC voltage is applied to the rotor winding and a second magnetic field that acts like a magnet and is attracted by the rotating stator field is produced.



- The attraction between the stator and rotor magnetic fields exerts a torque on the rotor and causes it to rotate at the synchronous speed of the rotating stator field
- The rotor does not require the magnetic induction from the stator field for its excitation. As a result the motor has zero slip compared to the induction motor which requires slip in order to produce torque.
- Synchronous motors are not self-starting requiring a method of bringing the rotor up to near synchronous speed before the rotor DC power is applied. One method is to use a rotor that has two windings one of which is a squirrel-cage-type type for starting.

An electrical systems lagging power factor can be corrected by overexciting the rotor of a synchronous motor operating within the same system.





Power Factor Correction

- **An underexcited DC field will produce a lagging PF and for this reason is seldom used.**
- **When the field is normally excited, the motor will run at a unity PF.**
- **When overexcited the motor will produce a leading PF.**