Three Phase Squirrel Cage Induction Motor Lab

Theory

Electrical Machine:

An Electrical machine is a common name given to devices which perform conversion of energy from one form to another.

Depending on the type of current used for operation, Electrical machines can be classified as AC machine and DC machine.

DC machine is actually an alternating current machine, but furnished with a special device called the Commutator, which under certain conditions converts AC into DC and vice-versa.

Inspite of the fact that the Commutator has made the operating condition of a DC machine is complicated it is a highly versatile energy converting device. By means of various combinations of shunt, series and separately excited field winding they can be designed to give a wide variety of voltage, current or speed-torque characteristic for both the dynamic and steady-state operation. Because of the ease with which they can be controlled, DC motor are often used in applications requiring a wide range of motor speeds or precise control of motor output- rolling mills, overhead cranes and traction; drives for process industry, battery driven vehicles, machine tools requiring precise speed control, in miniature range in tape recorders, cameras etc. Small DC motor is widely employed in control applications. Small DC generators are used for power supply in ships, air-crafts automobiles and other vehicles isolated from inland AC network system.

AC Machine

DC Machine

Both induced EMFs and mechanical force are developed in a machine, whether it is a Generator or a Motor. As such a DC Generator and Motor have an identical construction.

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Constructional features:

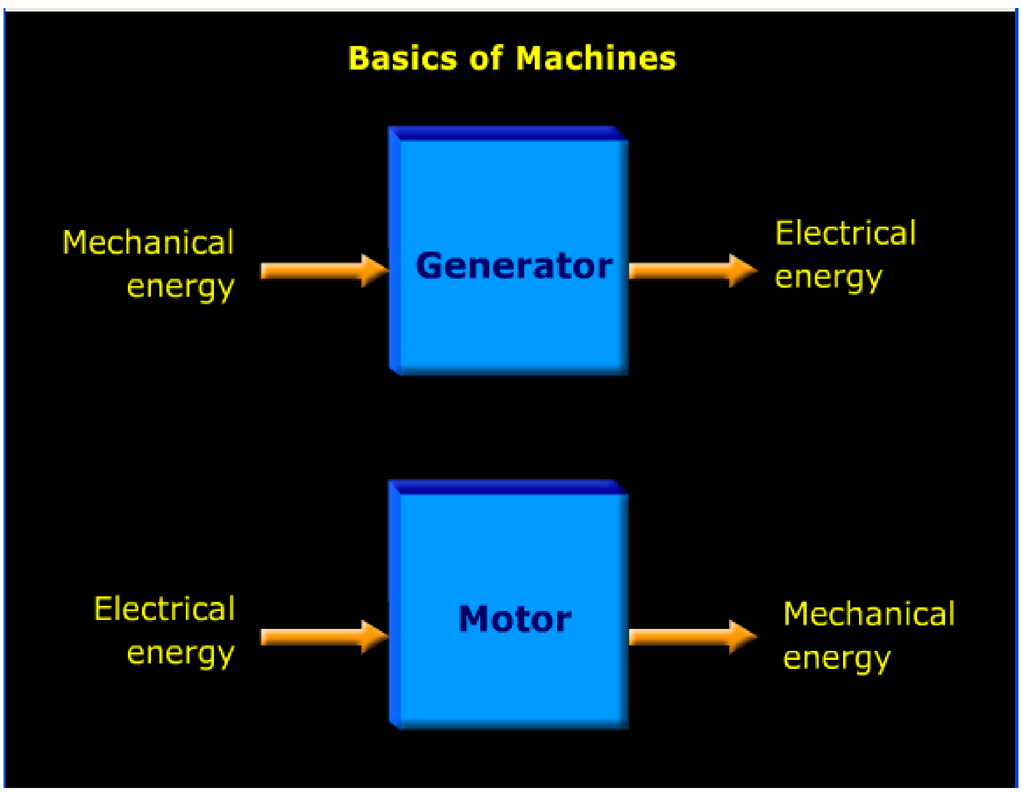
Electrical machines as per their power outputs may be classified as:

- Small size electrical machine with an output up to 0.6 KW.
- Medium size electrical machines with power outputs ranging from 0.6 KW to 250KW.
- Large size electrical machines with outputs exceeding 250 KW but not beyond about 5000 KW.

Electrical machines as per their operating speeds:

- Low speed machines- speed range, 250 to 400 rpm.
- Medium speed machines- speed range, 400 to 1500 rpm.
- High speed machines-speed more than 1500 rpm.

According to the operation performed, An Electrical machine can be called as a motor or a generator.



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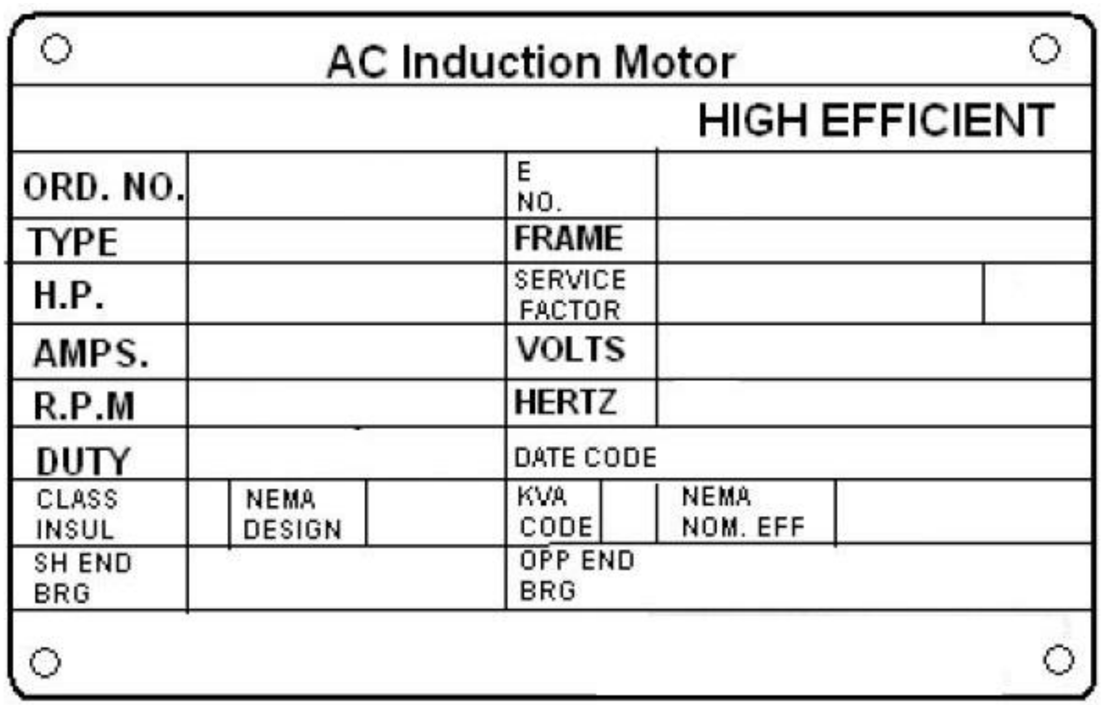
Induction Motor Basics:

Name Plate Parameters

A typical nameplate of an induction motor lists the following parameters:

- Rated terminal supply voltage in Volts.
- Rated frequency of the supply in Hz. (Hertz)
- Rated current in Amps. (Amperes)
- Speed in RPM. (Rotation Per Minute)
- Power rating in Watts or Horsepower (HP).
- Rated torque in Newton meters or Pound-inches.
- Winding insulation type - Class A, B, F or H.
- Type of stator connection (for 3-phase only), star (Y) or delta (Δ).

When the rated voltage and frequency are applied to the terminals of an induction motor, it draws the rated current (or corresponding power) and runs at base speed and can deliver the rated torque.



AC Induction Motor Nameplate

Motor Enclosures:

Motors are usually designed with covers over the moving parts. These covers, called **enclosures**, are classified by NEMA (National Electrical Manufacturers Association) according to the degree of environmental protection provided and the method of cooling. If the cover has openings, the motor is classified as an **open** motor; if the enclosure is complete, the motor is classified as an **enclosed** motor. Each of these types of motors has many modifications. **Table 1** lists the various types possible for both open and totally enclosed motors.

OPEN	TOTALLY ENCLOSED
Drip proof	Totally enclosed, non ventilated
Splash proof	Totally enclosed, fan cooled
Guarded	Dust ignition proof
Semi-guarded	Water proof
Drip proof guarded	Totally enclosed, pipe ventilated
Externally ventilated	Totally enclosed, water cooled
Pipe ventilated	Water air cooled
Weather protected	Air to air cooled
Type I	Fan cooled, guarded
Weather protected	Air over
Type II	Explosion proof

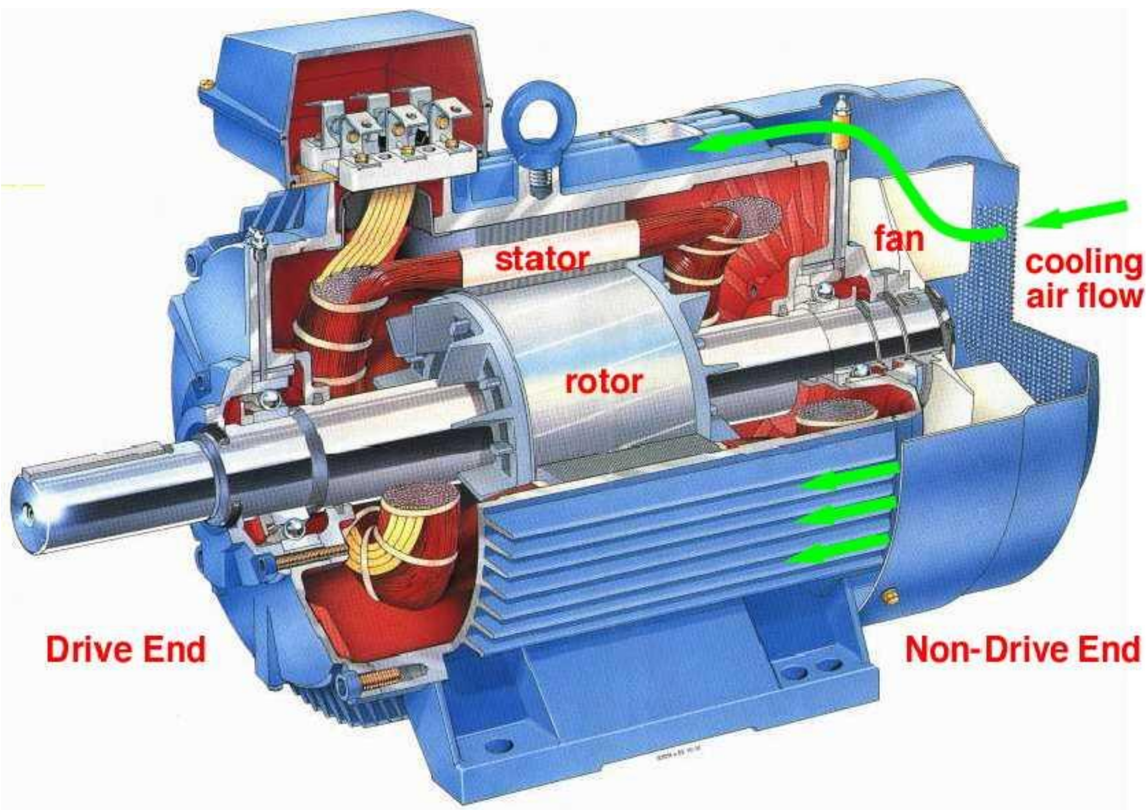
Construction of AC Machine:

The poly phase induction motor is widely used AC motor. Almost more than 90% of the mechanical power used in industry is provided by three phase induction motor. The reasons are its low cost, simple and rugged construction, absence of commutator, good operating characteristics. It's efficiency as high as 90% and a power factor of 0.89. The distinguishing feature of such a motor is that it is singly excited motor.

The induction motor essentially consists of two parts:

The three phase induction motor is very simple in construction compared to other motors. The essential components of poly phase induction motor are

- Stator
- Rotor



Stator

A laminated stator core carrying a poly phase winding. The main parts of a stator are as:

- **Stator frame:** It is the outer body of the motor. Its functions are to supports the stator core and winding, to protect the inner parts of the machine and serve as a ventilating housing. The frame may be die-cast of fabricated.
- **Stator core:** The stator of an induction motor is quite similar in construction to that of a three phase synchronous motor. The stator core is to carry the alternating flux which produces hysteresis and eddy current losses. In order to reduce hysteresis and eddy current losses in the stator core it is assembled of high grade, low electrical losses, silicon steel punching. The thickness of punching varies from 0.35mm to0.65mm.
- **Field winding:** In a poly phase induction motor the stator winding is usually three phase winding which is usually supplied from a three phase supply mains. The three phase of the winding can be connected either star or delta.

a) Stator frame

b) Stator core

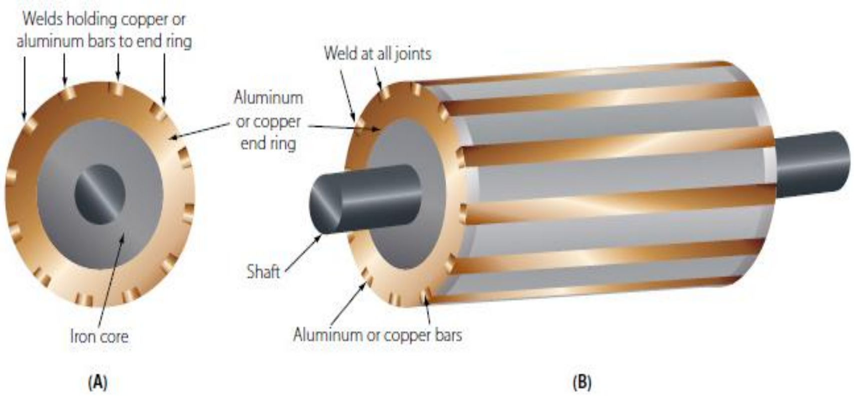
c) Field winding

Rotor

The rotor comprises a cylindrical laminated iron core, with slots around the core carrying a rotor conductor. In general the same sheet steel laminated is employed for the rotor core as for the stator. A laminated rotor core carries either a cage or poly phase winding. The rotor employed in three phase induction motors, according to the type of winding used, are of two types:

- **Squirrel cage rotor:** It is consisting of a laminated cylindrical core having semi closed circular slots at the outer periphery. Copper or aluminum placed in these slots and short circuited at each end by copper or aluminum rings called short circuiting rings.

  Thus, the rotor winding is permanently short circuited and it is not possible to add any external resistance in the rotor circuit. Figure (a) shows squirrel cage rotor.



Most common AC motors use the Squirrel Cage Rotor, which will be found in virtually all domestic and light industrial alternating current motors. The squirrel cage takes its name from its shape - a ring at either end of the rotor, with bars connecting the rings running the length of the rotor.

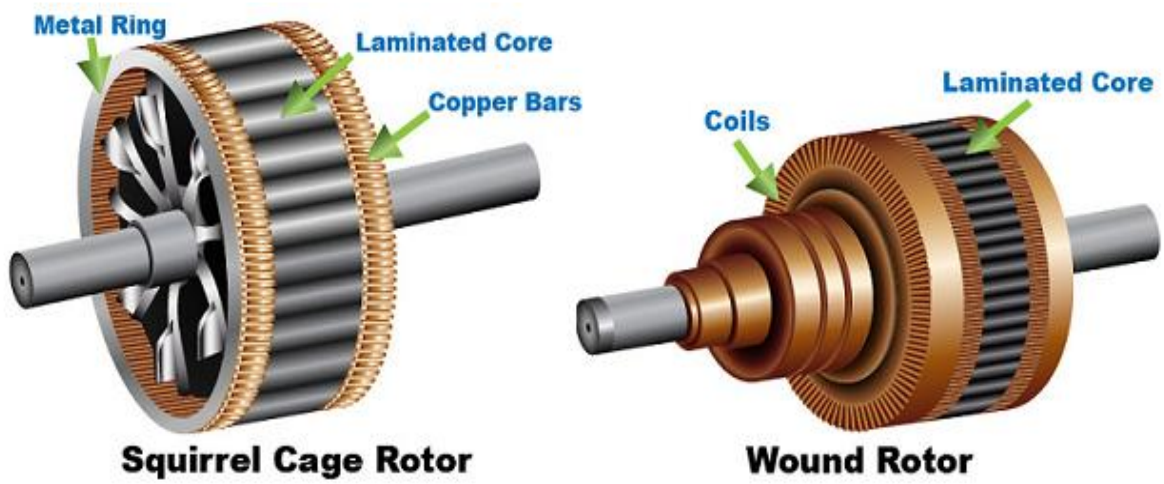
It is typically cast aluminum or copper poured between the iron laminates of the rotor, and usually only the end rings will be visible. The vast majority of the rotor currents will flow through the bars rather than the higher-resistance and usually varnished laminates. Very low voltages at very high currents are typical in the bars and end rings; high efficiency motors will often use cast copper in order to reduce the resistance in the rotor.

In operation, the squirrel cage motor may be viewed as a transformer with a rotating secondary - when the rotor is not rotating in sync with the magnetic field, large rotor currents are induced; the large rotor currents magnetize the rotor and interacts with the stator's magnetic fields to bring the rotor into synchronization with the stator's field. An unloaded squirrel cage motor at synchronous speed will consume electrical power only to maintain rotor speed against friction and resistance losses; as the mechanical load increases, so will the electrical load - the electrical load is inherently related to the mechanical load. This is similar to a transformer, where the primary's electrical load is related to the secondary electrical load.

This is why, as an example, a squirrel cage blower motor may cause the lights in a home to dim as it starts, but doesn't dim the lights when its fan belt (and therefore mechanical load) is removed. Furthermore, a stalled squirrel cage motor (overloaded or with a jammed shaft) will consume current limited only by circuit resistance as it attempts to start. Unless something else limits the current (or cuts it off completely) overheating and destruction of the winding insulation is the likely outcome.

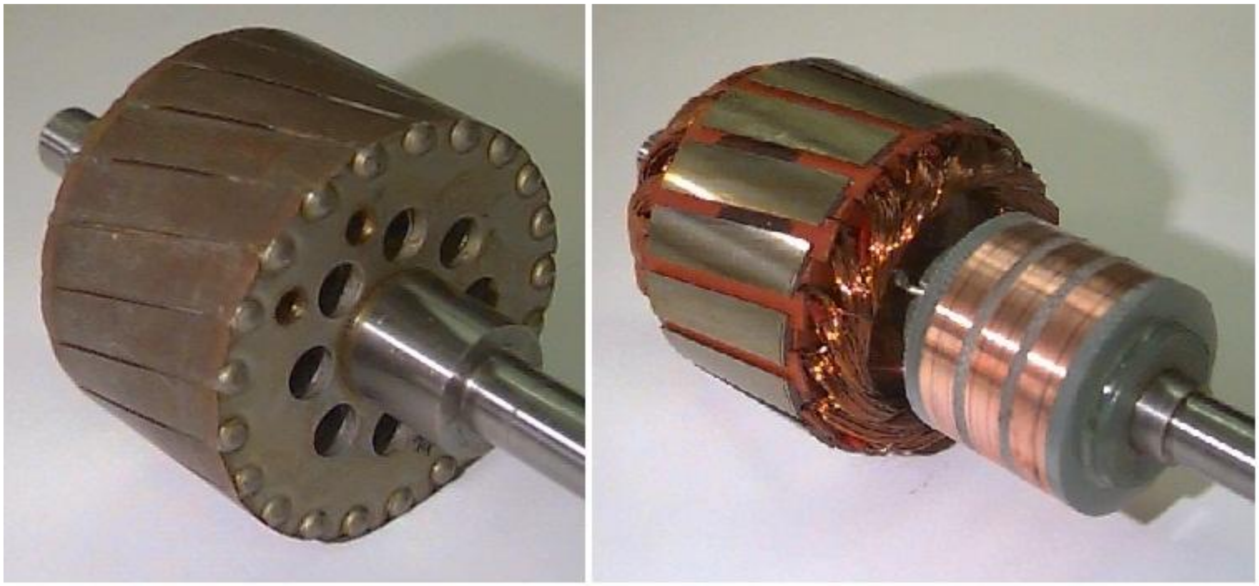
In order to prevent the currents induced in the squirrel cage from superimposing itself back onto the supply, the squirrel cage is generally constructed with a prime number of bars, or at least a small multiple of a prime number (rarely more than 2). There are an optimum number of bars in any design, and increasing the number of bars beyond that point merely serves to increase the losses of the motor particularly when starting.

Virtually every washing machine, dishwasher, standalone fan, record player, etc. uses some variant of a squirrel cage motor. In squirrel cage motors, the motor speed is determined by the load it drives and by the number of poles generating a magnetic field in the stator. If some poles are switched in or out, the motor speed can be controlled by incremental amounts.



- **Phase wound rotor:** It is also called slip ring rotor and the motors employing this type of rotor are known as phase wound or slip ring induction motor. Slip ring rotor consists of a laminated cylindrical core having semi-closed slots at the outer periphery and carries a three phase insulated winding.

  The rotor is wound for the same numbers of poles as that of stator. The three finish terminals are connected together forming star point and the three star terminals are connected to three copper slip rings fixed on the shaft. In this case, depending upon the requirement any external resistance can be added Figure (b) shows phase wound rotor.



a) Squirrel cage rotor b) Phase wound

An alternate design, called the wound rotor, is used when variable speed is required. In this case, the rotor has the same number of poles as the stator and the windings are made of wire, connected to slip rings on the shaft. Carbon brushes connect the slip rings to an external controller such as a variable resistor that allows changing the motor's slip rate. In certain high-power variable speed wound-rotor drives, the slip-frequency energy is captured, rectified and returned to the power supply through an inverter.

Compared to squirrel cage rotors, wound rotor motors are expensive and require maintenance of the slip rings and brushes, but they were the standard form for variable speed control before the advent of compact power electronic devices. Transistorized inverters with variable-frequency drive can now be used for speed control, and wound rotor motors are becoming less common. (Transistorized inverter drives also allow the more-efficient three-phase motors to be used when only single-phase mains current is available, but this is never used in household appliances, because it can cause electrical interference and because of high power requirements).

Several methods of starting a poly-phase motor are used. Where the large in rush current and high starting torque can be permitted, the motor can be started across the line, by applying full line voltage to the terminals (Direct-on-line, DOL). Where it is necessary to limit the starting inrush current (where the motor is large compared with the short-circuit capacity of the supply), reduced voltage starting using series inductors, an autotransformer, thyristors or other devices are used.

A technique sometimes used is (Star-Delta, YΔ) starting, where the motor coils are initially connected in Y for acceleration of the load, then switched to delta when the load is up to speed. This technique is more common in Europe than in North America. Transistorized drives can directly vary the applied voltage as required by the starting characteristics of the motor and load.

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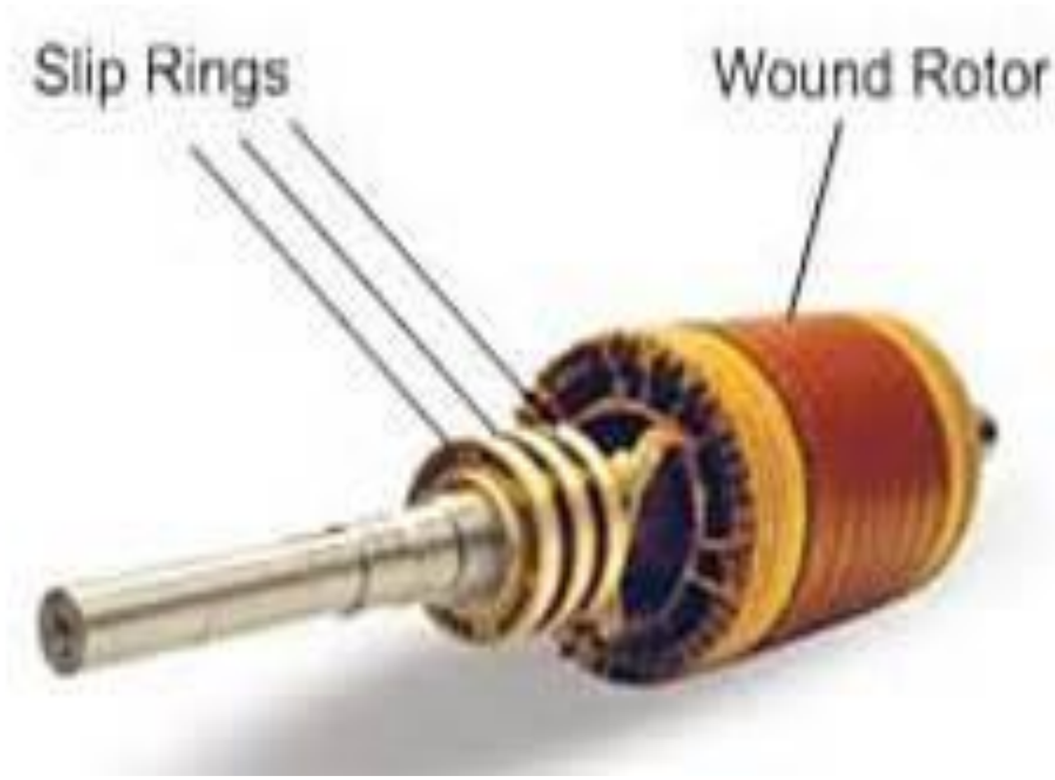
This type of motor is becoming more common in traction applications such as locomotives, where it is known as the asynchronous traction motor. In wound-rotor motors, the impedance of the rotor windings can be altered externally, which changes the current in the windings and thus affords continuous speed control.

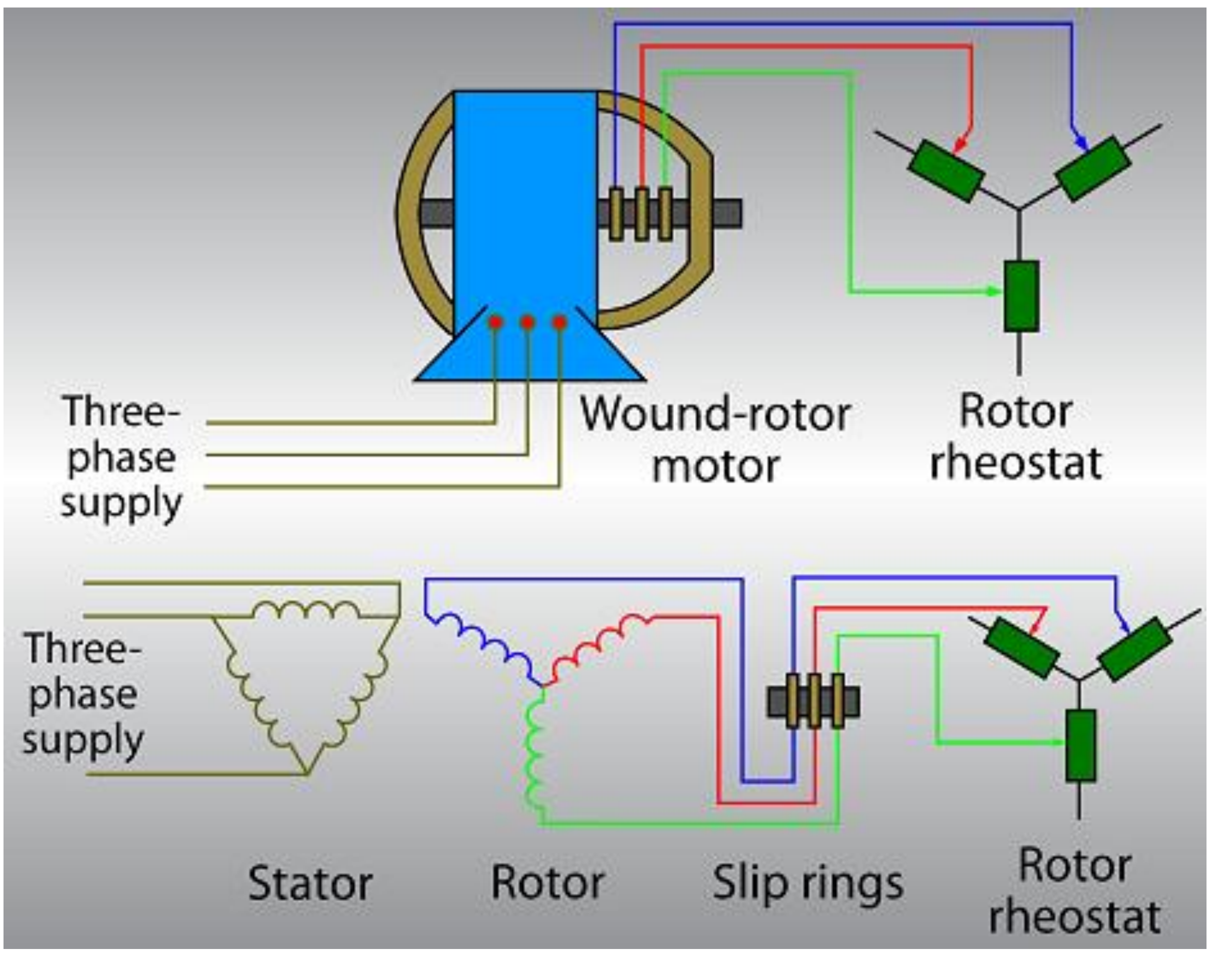


Advantage of Wound Rotor Motor:

- High starting torque with low starting current by inserting an external resistance in each phase of the rotor circuit.
- Speed can be controlled easily.
- No abnormal heating during starting.
- Smooth acceleration during heavy load.

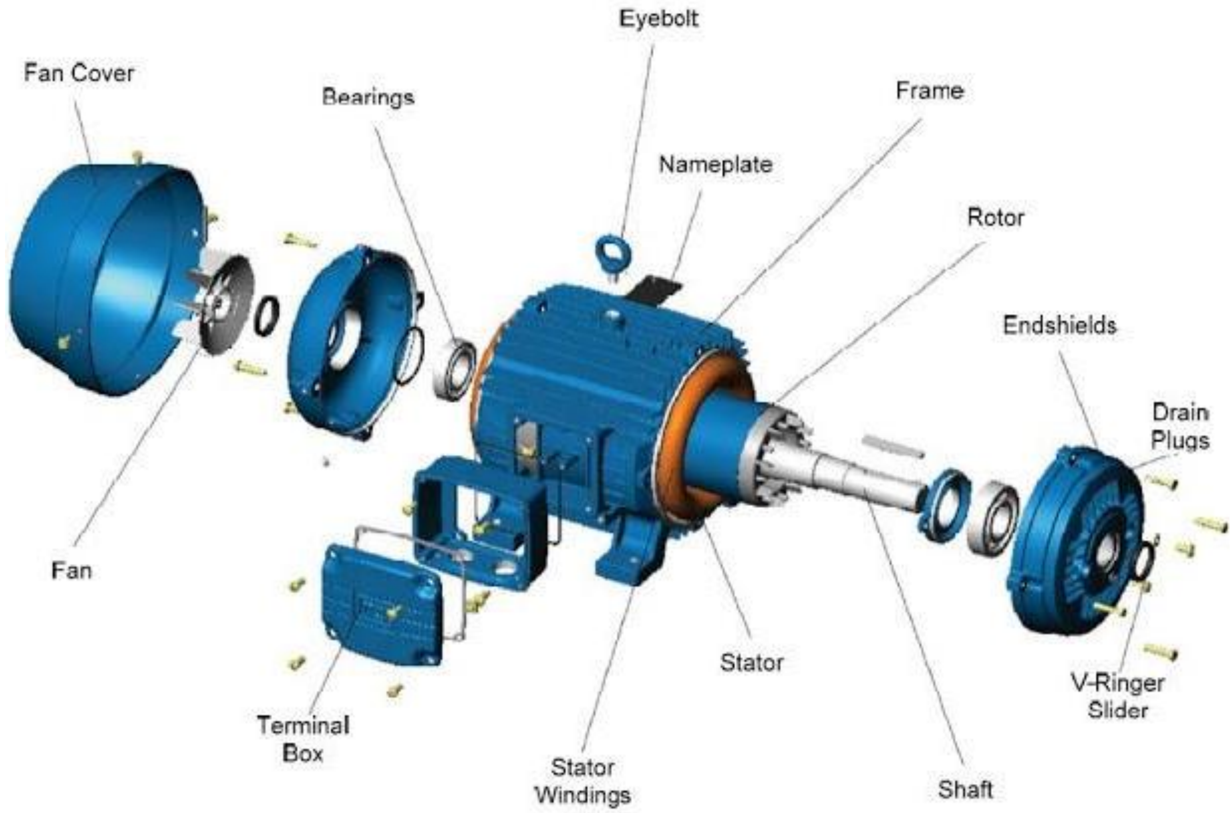
Disadvantage of Wound Rotor Motor:

- Lower efficiency and low power factor.
- Speed regulation is poor.
- Initial and maintenance cost are more due to slip ring brushes etc.



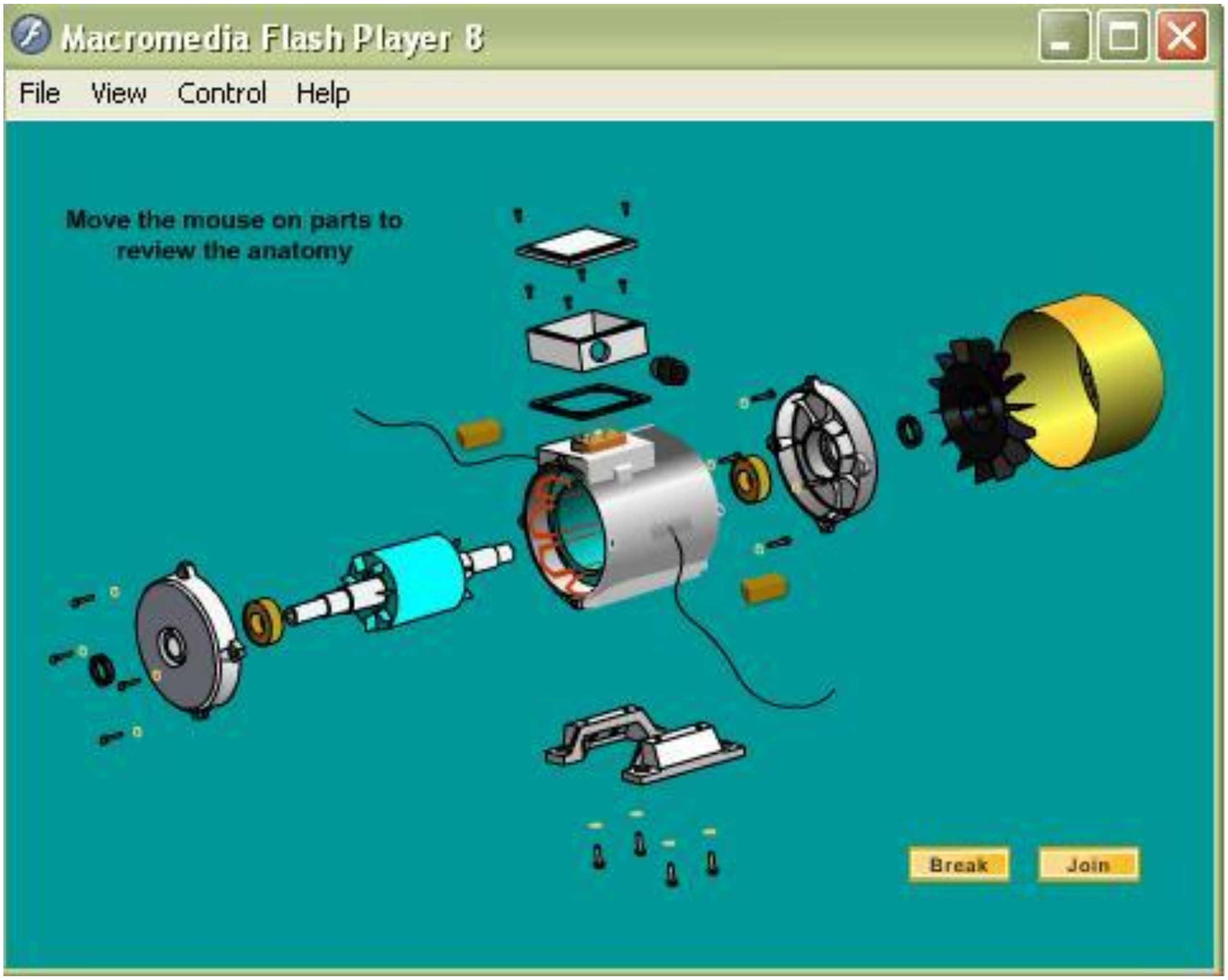
Schematic of Three Phase Wound Type Induction Motor

Three Phase Squirrel Cage Induction Motor Lab



A typical 3-phase induction motor

Three Phase Squirrel Cage Induction Motor Lab



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Operating Principle of Three Phase Induction Motor:

A [3 phase induction motor] derives its name from the fact that the rotor current is induced by the magnetic field, instead of electrical connections.

The operating principle of a 3 phase induction motor is based on the production of rmf.

Production of a rotating magnetic field:

The [stator] of an induction motor consists of a number of overlapping windings offset by an electrical angle of 120°. When the primary winding or stator is connected to a three phase alternating current supply, it establishes a rotating magnetic field which rotates at a synchronous speed.

The direction of rotation of the motor depends on the phase sequence of supply lines, and the order in which these lines are connected to the stator. Thus interchanging the connection of any two primary terminals to the supply will reverse the direction of rotation.

The number of poles and the frequency of the applied voltage determine the synchronous speed of rotation in the motor's stator. Motors are commonly configured to have 2, 4, 6 or 8 poles. The synchronous speed, a term given to the speed at which the field produced by primary currents will rotate, is determined by the following expression.

Synchronous speed of rotation

= (120* supply frequency) / Number of poles on the stator

Rotating Fields

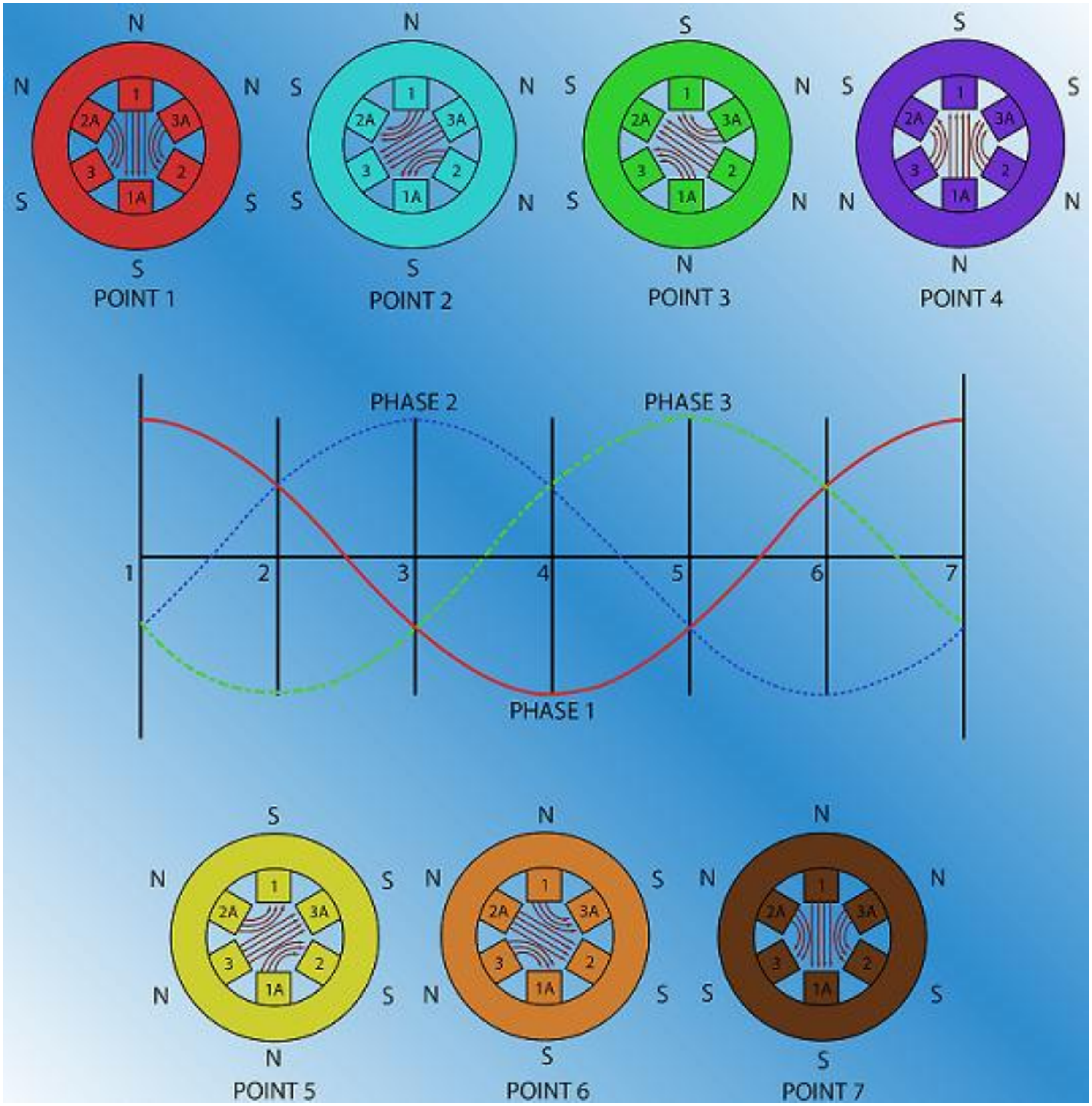
This section shows how the stator windings can be connected to a three-phase AC input to create a magnetic field that rotates. Another magnetic field in the rotor can be made to chase it by being attracted and repelled by the stator field. Because the rotor is free to turn, it follows the rotating magnetic field in the stator.

Poly-phase AC is brought into the stator and connected to windings that are physically displaced 120 degrees apart. These windings are connected to form north and south magnetic poles, as shown in below **Figure**. An analysis of the electromagnetic polarity of the poles at points 1 through 7 in below **Figure** shows how the three phase AC creates magnetic fields that rotate.

At point 1, the magnetic field in phase 1 is at maximum. Negative voltages are shown in phases 2 and 3. The negative voltages in these windings create smaller magnetic fields, which will tend to aid the field set-up in coil 1-1A.

At point 2, phase 3 creates a maximum negative flux in coil 3-3A. This strong negative field is aided by the weaker magnetic fields developed by phases 1 and 2.

The three-phase AC input rises and falls with each cycle. Analyzing each point on the voltage graph shows that the resultant magnetic field rotates clockwise. When the three-phase input completes a full cycle at point 7, the magnetic field has completed an entire revolution of 360 degrees.



AC Generation in Induction Machine

Rotor Behavior in a Rotating Field

An oversimplification of rotor behavior shows how the magnetic field of the stator influences the rotor. First, assume that a simple bar magnet were placed in the center of the stator diagrams shown in above **Figure**. Also, assume that the bar magnet is free to rotate. It has been aligned so that at point 1, its south pole is opposite the large North of the stator field.

Unlike poles attract and like poles repel. As the AC completes a cycle, going from point 1 to point 7, the stator field rotates and pulls the bar magnet with it because of the attraction of unlike poles and the repulsion of like poles. The bar magnet would be rotating at the same speed of the revolving flux of the stator. This speed is known as synchronous speed. Synchronous speed of a motor is given by the equation:

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

Where: N = speed in RPM

f = frequency in cycles per second

P = number of magnetic poles

Production of magnetic flux:

A rotating magnetic field in the stator is the first part of operation. To produce a torque and thus rotate, the rotors must be carrying some current. In induction motors, this current comes from the rotor conductors. The revolving magnetic field produced in the stator cuts across the conductive bars of the rotor and induces an e.m.f.

The rotor windings in an induction motor are either closed through an external resistance or directly shorted. Therefore, the e.m.f induced in the rotor causes current to flow in a direction opposite to that of the revolving magnetic field in the stator, and leads to a twisting motion or torque in the rotor.

As a consequence, the rotor speed will not reach the synchronous speed of the r.m.f in the stator. If the speeds match, there would be no e.m.f. induced in the rotor, no current would be flowing, and therefore no torque would be generated. The difference between the stator (synchronous speed) and rotor speeds is called the slip.

The rotation of the magnetic field in an induction motor has the advantage that no electrical connections need to be made to the rotor.

Slip of Induction Motor:

When the rotor of an induction motor is subjected to the revolving magnetic field produced by the stator windings, a voltage is induced in the longitudinal bars. The induced voltage causes a current to flow through the bars. This current, in turn, produces its own magnetic field, which combines with the revolving field so that the rotor assumes a position in which the induced voltage is minimized.

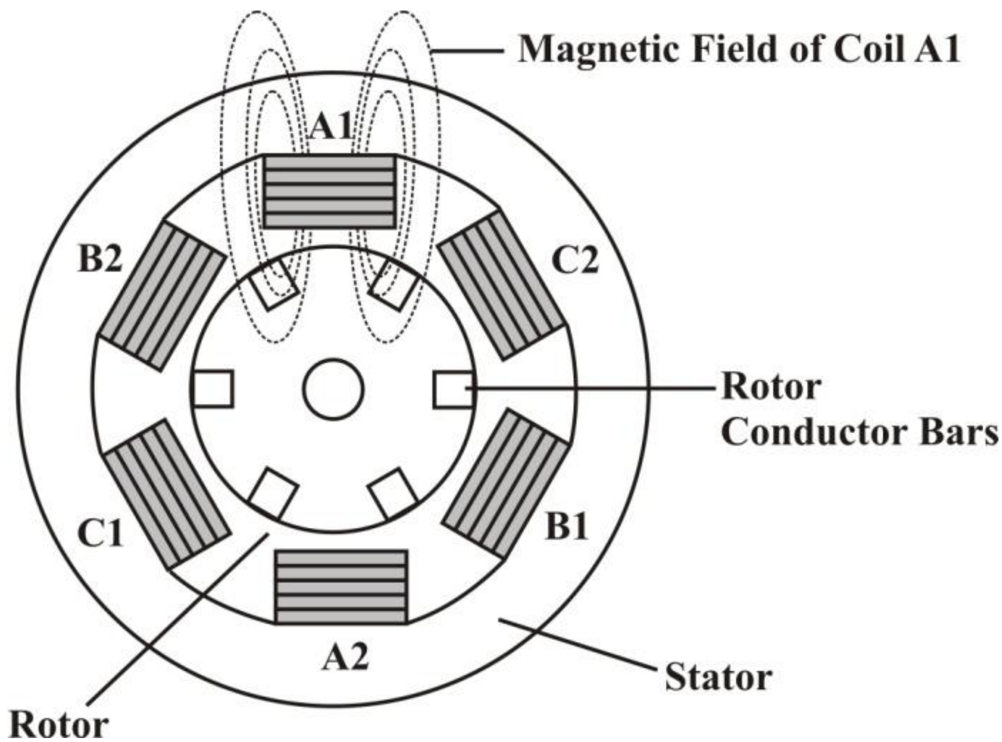
As a result, the rotor revolves at very nearly the synchronous speed of the stator field, the difference in speed being just sufficient enough to induce the proper amount of current in the rotor to overcome the mechanical and electrical losses in the rotor. If the rotor were to turn at the same speed as the rotating field, the rotor conductors would not be cut by any magnetic lines of force, no emf would be induced in them, no current could flow, and there would be no torque. The rotor would then slow down. For this reason, there must always be a difference in speed between the rotor and the rotating field. This difference in speed is called slip and is expressed as a percentage of the synchronous speed. For example, if the rotor turns at 1,750 rpm and the synchronous speed is 1,800 rpm, the difference in speed is 50 rpm. The slip is then equal to 50/1,800 or 2.78 percent.

Operating Principle of Induction Motor:

Where a polyphase electrical supply is available, the three-phase (or polyphase) AC induction motor is commonly used, especially for higher-powered motors. The phase differences between the three phases of the polyphase electrical supply, create a rotating electromagnetic field in the motor. Through electromagnetic induction, the time changing and reversing (alternating in direction polyphase currents) rotating magnetic field induces a time changing and reversing (alternating in direction) current in the conductors in the rotor; this sets up a time changing and counter balancing moving electromagnetic field that causes the rotor to turn in the direction of the rotating field. The rotor always moves (rotates) slightly behind the phase peak of the primary magnetic field of the stator and is thus always moving slower than the rotating magnetic field produced by the polyphase electrical supply.

The principle of the revolving magnetic field is the key to the operation of the AC motor. Induction motors rely on revolving magnetic fields in their stators (stationary windings) to cause their rotors to turn. Stators themselves do not turn. Stators are permanently attached to the inside of the motor housing in the same manner that the stationary windings in the generator are connected to the main frame. The revolving magnetic fields created in the stator windings provide the necessary torque to move the rotor. The idea behind it is that a magnetic field in a stator can be made to appear to rotated electrically, around the inner periphery of the motor housing. This is done by overlapping several different stator windings. A magnetic field is developed in each different stator winding at a different time. Just before the magnetic field of one winding decays, the winding overlapping it develops the same magnetic polarity. As this second magnetic field decays in the second winding, another overlapping winding develops a magnetic field of the same polarity, and the sequence repeats itself. Successive stator windings develop magnetic fields in an orderly procession and appear to progressively move around the inside of the motor housing. These individual magnetic fields are the property of current flow in the motor stator. This current flow comes from the three individual phase currents of the three-phase generator output.

The figure 11 shows the three single-phase voltages/currents that develop in the generator main armature completing individual circuits. Circuit A-B in the generator armature has a like A-B winding in the motor's stator. Each of the three circuit combinations (A-B, B-C, and C-A) are developed independently in the generator over a short period of time. The generator circuits are then completed through the motor's stator windings in a similar manner. As long as the current and magnetic field develops and decays in an orderly, progressive manner around the periphery of the motor frame, a revolving magnetic field exists. A revolving magnetic field in the stator is only part of the operation. Another magnetic field needs to be created in the rotor so that the torque and rotation can develop using the principles of magnetic attraction and repulsion. The magnetic field developed in the rotor is a product of induction. As soon as the stator and the rotor windings develop their magnetic affiliation, torque will develop, and the rotor will turn.

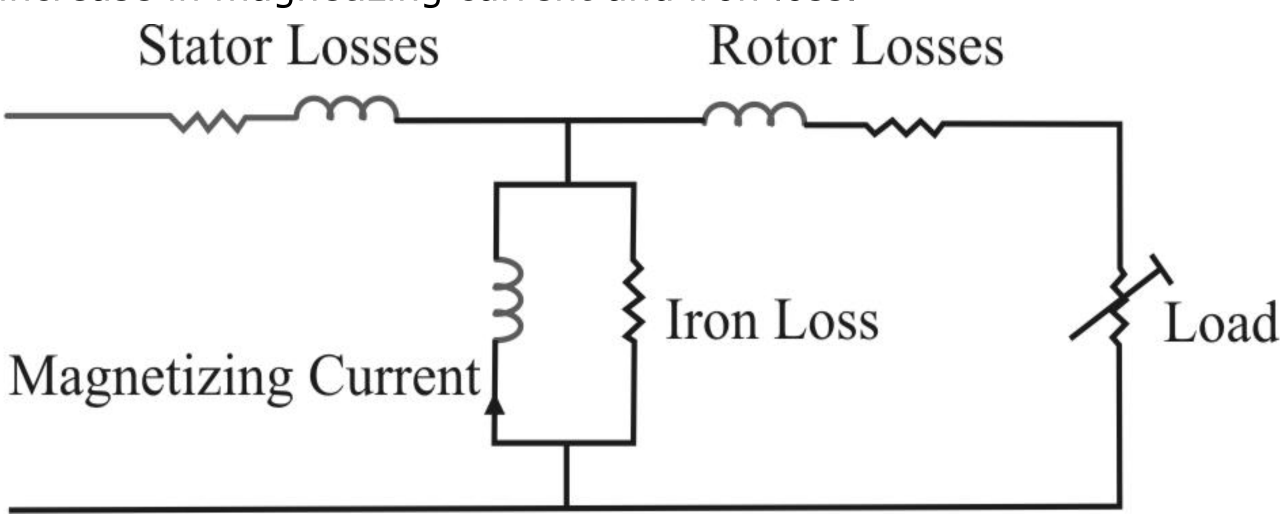


The rotor can never rotate at the synchronous speed because there would be no relative motion between the magnetic field and the rotor windings and no current could be induced. The induction motor has a high starting torque.

Equivalent Circuit:

The induction motor can be treated essentially as a transformer for analysis. The induction motor has stator leakage reactance, stator copper loss elements as series components, and iron loss and magnetizing inductance as shunt elements. The rotor circuit likewise has rotor leakage reactance, rotor copper (aluminum) loss and shaft power as series elements. The transformer in the centre of the equivalent circuit can be eliminated by adjusting the values of the rotor components in accordance with the effective turn's ratio of the transformer. From the equivalent circuit and a basic knowledge of the operation of the induction motor, it can be seen that the magnetizing current component and the iron loss of the motor are voltage dependant, and not load dependant.

Additionally, the full voltage starting current of a particular motor is voltage and speed dependant, but not load dependant. The magnetizing current varies depending on the design of the motor. For small motors, the magnetizing current may be as high as 60%, but for large two pole motors, the magnetizing current is more typically 20 - 25%. At the design voltage, the iron is typically near saturation, so the iron loss and magnetizing current do not vary linearly with voltage with small increases in voltage resulting in a high increase in magnetizing current and iron loss.



Equivalent Circuit of Three Phase Induction Motor

Starting of Induction Motor:

In a three phase induction motor, the induced e.m.f in the rotor circuit depends on the slip of the induction motor and the magnitude of the rotor current depends upon this induced e.m.f. When the motor is started, the slip is equal to 1 as the rotor speed is zero, so the induced e.m.f in the rotor is large. As a result, a very high current flows through the rotor. This is similar to a transformer with the secondary coil short circuited, which causes the primary coil to draw a high current from the mains. Similarly, when an induction motor starts, a very high current is drawn by the stator, on the order of 5 to 9 times the full load current. This high current can damage the motor windings and because it causes heavy line voltage drop, other appliances connected to the same line may be affected by the voltage fluctuation. To avoid such effects, the starting current should be limited. A starter is a device which limits the starting current by providing reduced voltage to the motor. Once the rotor speed increases, the full rated voltage is given to it.

Methods of Starting:

There are two important factors to be considered in starting of induction motors:

- The starting current drawn from the supply, and
- The starting torque.

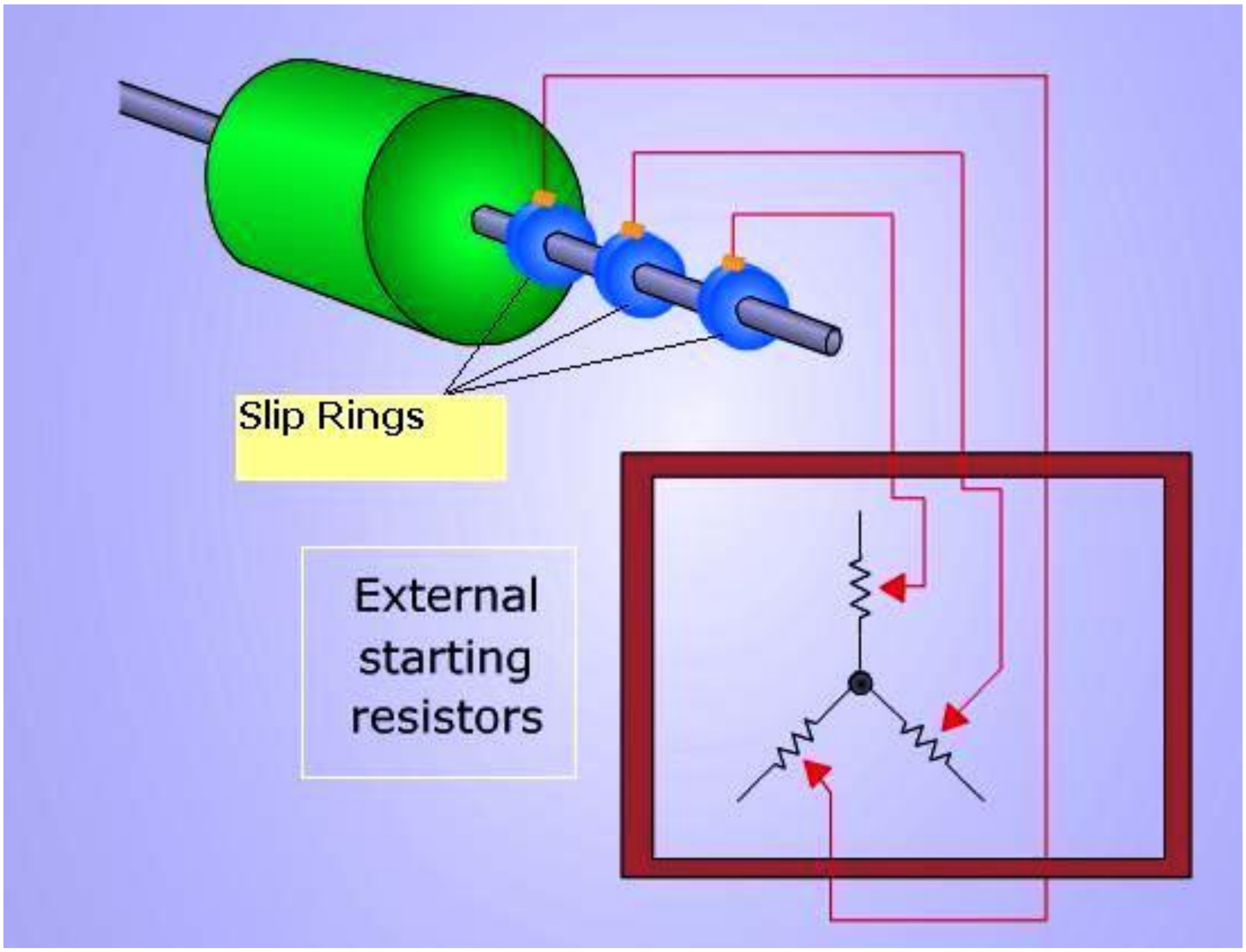
The starting current should be kept low to avoid overheating of motor and excessive voltage drops in the supply network. The starting torque must be about 50 to 100% more than the expected load torque to ensure that the motor runs up in a reasonably short time.

The most usual methods of starting 3-phase induction motors are:

- For Slip-Ring Motors
- Rotor resistance starting
- For Squirrel-Cage Motors
- Direct-on -line starting (starting from the fixed voltage).
- Star-delta starting (starting from the fixed voltage).
- Autotransformer starting.(starting from the lower voltage to higher voltage).

Rotor Resistance Starting :

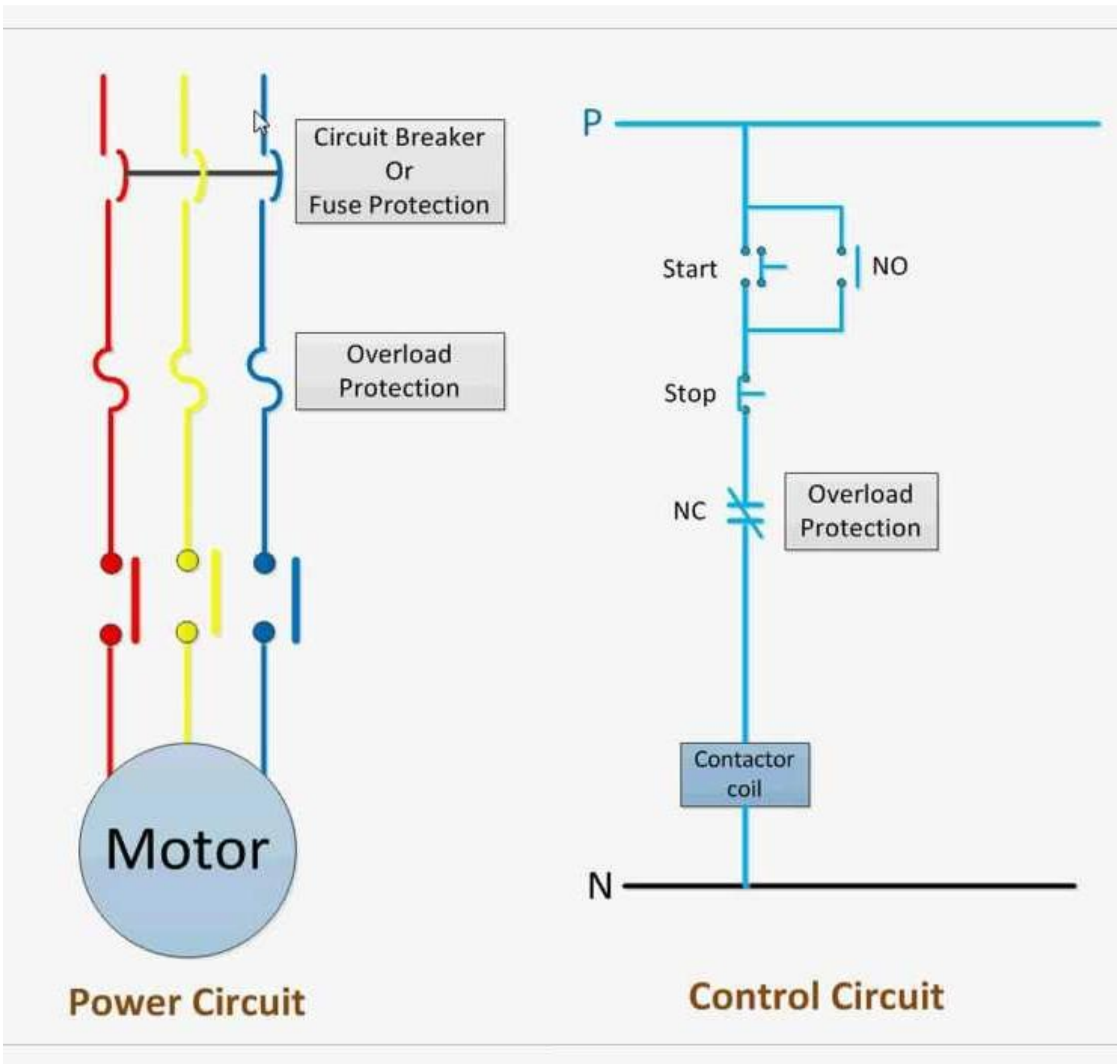
By adding eternal resistance to the rotor circuit any starting torque up to the maximum torque can be achieved; and by gradually cutting out the resistance a high torque can be maintained throughout the starting period. The added resistance also reduces the starting current, so that a starting torque in the range of 2 to 2.5 times the full load torque can be obtained at a starting current of 1 to 1.5 times the full load current.



Rotor Resistance Starting

Direct-On-Line Starting :

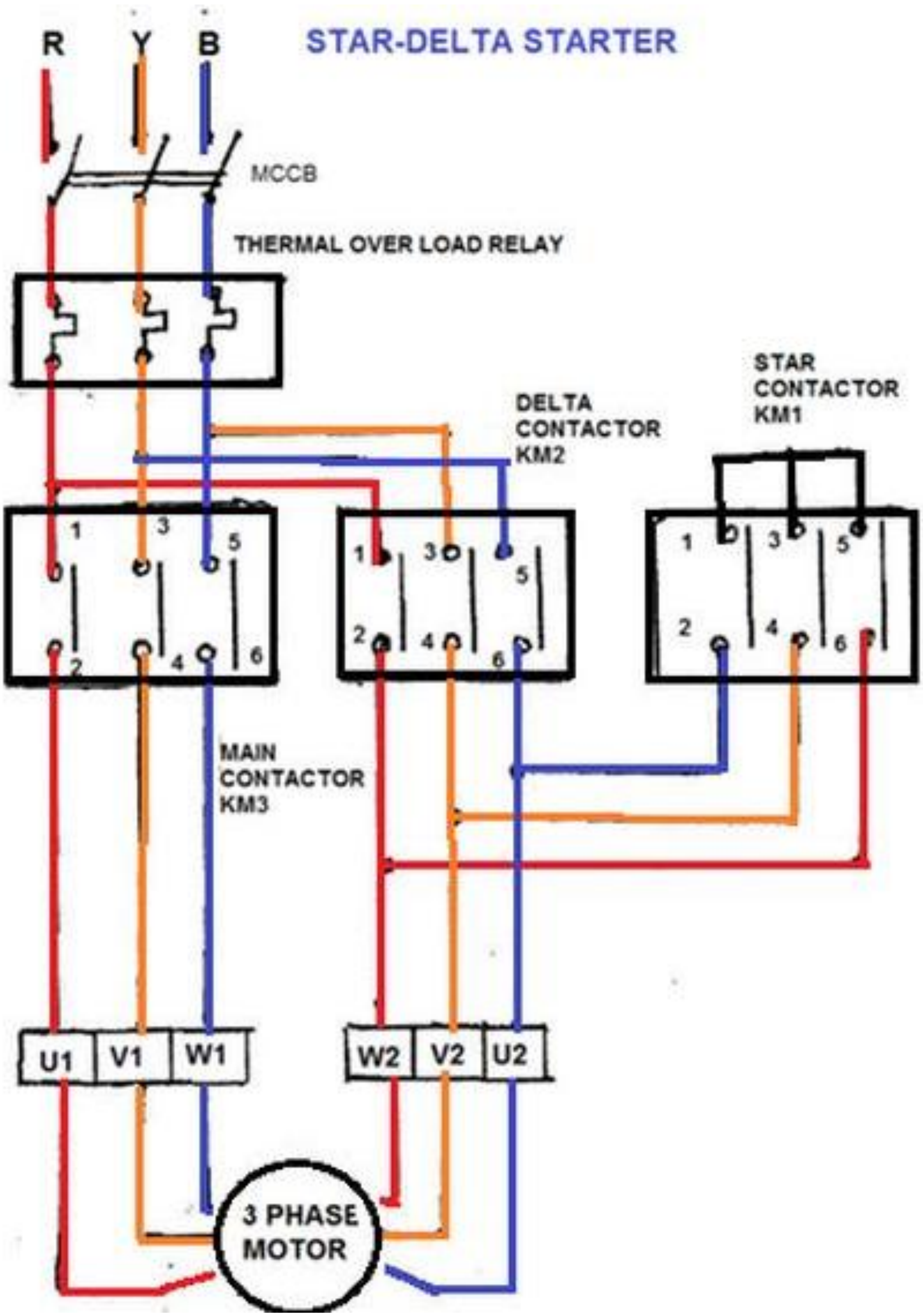
This is the most simple and inexpensive method of starting a squirrel cage induction motor it is switched on directly to full supply voltage. The initial starting current is large, normally about 5 to 7 times the rated current but the starting torque is likely to be 0.75 to 2 times the full load torque. To avoid excessive supply voltage drops because of large starting currents the method is restricted to small motors only. To decrease the starting current cage motors of medium and larger sizes are started at a reduced supply voltage. The reduced supply voltage starting is applied in the next two methods.



Direct On Line Starting

Star-Delta Starting :

This is applicable to motors designed for delta connection in normal running conditions. Both ends of each phase of the stator winding are brought out and connected to a 3-phase change -over switch. For starting, the stator windings are connected in star and when the machine is running the switch is thrown quickly to the running position, thus connecting the motor in delta for normal operation. Phase voltages & the phase currents of the motor in star connection are reduced to $1/\sqrt{3}$ of the direct -on -line values in delta. The line current is 1/3 of the value in delta. A disadvantage of this method is that the starting torque (which is proportional to the square of the applied voltage) is also reduced to 1/3 of its delta value.



Star Delta Starting

Auto-Transformer Starting :

This method provides the lower initial voltage applied to the motor with the help of autotransformer and therefore the starting current and torque. The motor, which can be connected permanently in delta or in star, is switched first on reduced voltage from a 3-phase tapped autotransformer and when it has accelerated sufficiently, it is switched to the running (full voltage) position. The principle is similar to star/delta starting and has similar limitations. The advantage of the method is that the current and torque can be adjust.

Three Phase Auto Transformer

Slip of Induction Motor:

There must be a relative difference in speed between the rotor and the rotating magnetic field. If the rotor and the rotating magnetic field were turning at the same speed no relative motion would exist between the two, therefore no lines of flux would be cut, and no voltage would be induced in the rotor. The difference in speed is called slip. Slip is necessary to produce torque. Slip is dependent on load. An increase in load will cause the rotor to slow down or increase slip. A decrease in load will cause the rotor to speed up or decrease slip. Slip is expressed as a percentage and can be determined with the following formula.

% Slip = (Ns - Nr) x 100/Ns

For example, a four-pole motor operated at 50 Hz has a synchronous speed (NS) of 1500 RPM. If the rotor speed at full load is 1465 RPM (NR), then slip is 2.3%.

% Slip = (1500 - 1465) x 100 / 1500

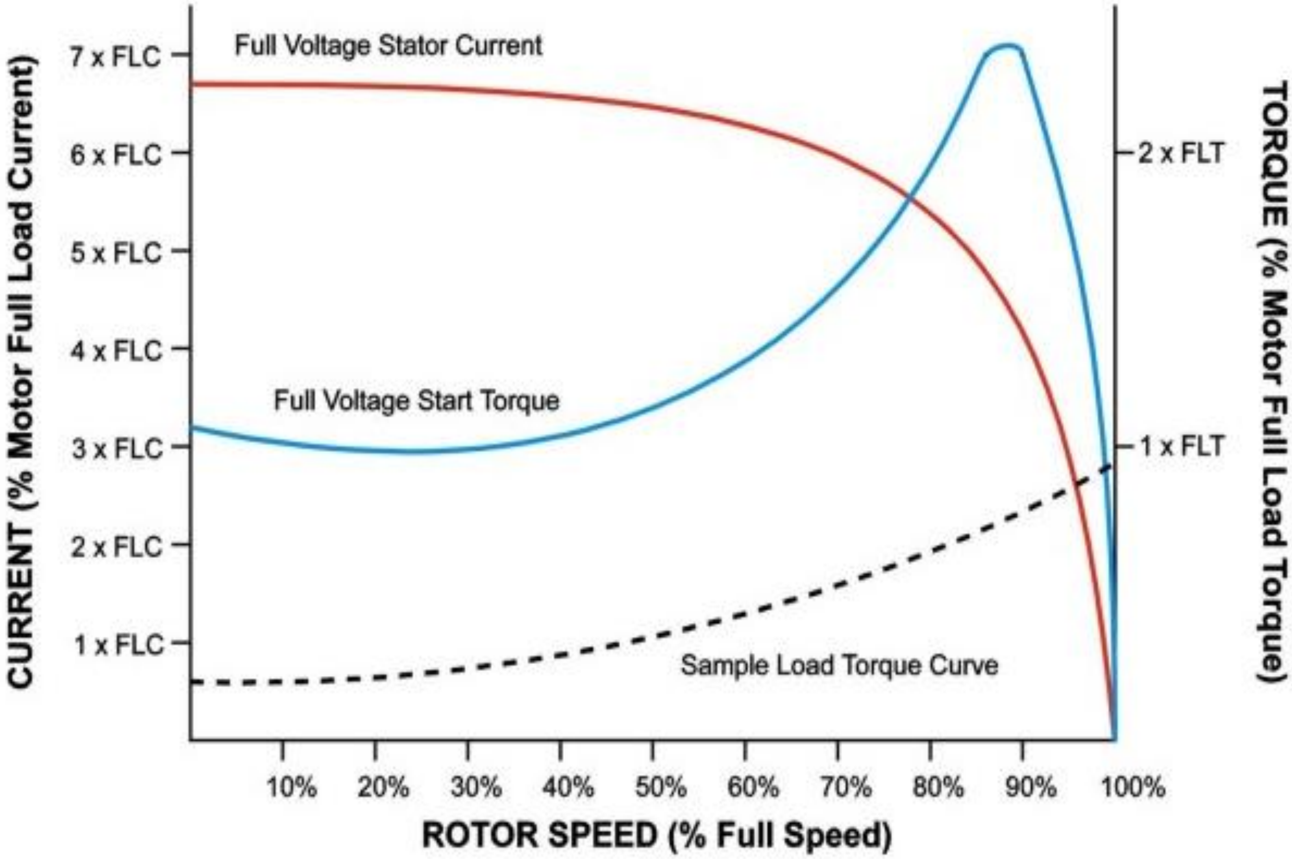
% Slip = 2.3%

Characteristic of Induction Motor:

Starting Characteristics:

In order to perform useful work, the induction motor must be started from rest and both the motor and load accelerated up to full speed. Typically, this is done by relying on the high slip characteristics of the motor and enabling it to provide the acceleration torque. Induction motors at rest, appear just like a short circuited transformer, and if connected to the full supply voltage, draw a very high current known as the "Locked Rotor Current". They also produce torque which is known as the "Locked Rotor Torque". The Locked Rotor Torque (LRT) and the Locked Rotor Current (LRC) are a function of the terminal voltage to the motor, and the motor design. As the motor accelerates, both the torque and the current will tend to alter with rotor speed if the voltage is maintained constant. The starting current of a motor, with a fixed voltage, will drop very slowly as the motor accelerates and will only begin to fall significantly when the motor has reached at least 80% full speed.

The actual curves for induction motors can vary considerably between designs, but the general trend is for a high current until the motor has almost reached full speed. The LRC of a motor can range from 500% Full Load Current (FLC) to as high as 1400% FLC. Typically, good motors fall in the range of 550% to 750% FLC.



The starting torque of an induction motor starting with a fixed voltage, will drop a little to the minimum torque, known as the pull up torque, as the motor accelerates and then rise to a maximum torque, known as the breakdown or pull out torque at almost full speed and then drop to zero at synchronous speed. The curve of start torque against rotor speed is dependant on the terminal voltage and the motor/rotor design. The LRT of an induction motor can vary from as low as 60% Full Load Torque (FLT) to as high as 350% FLT. The pull-up torque can be as low as 40% FLT and the breakdown torque can be as high as 350% FLT. Typical LRTs for medium to large motors are in the order of 120% FLT to 280% FLT. The power factor of the motor at start is typically 0.1 - 0.25, rising to a maximum as the motor accelerates, and then falling again as the motor approaches full speed.

A motor which exhibits a high **starting** current i.e., 850% will generally produce a low starting torque, whereas a motor which exhibits a low starting current, will usually produce a high starting torque. This is the reverse of what is generally expected. The induction motor operates due to the torque developed by the interaction of the stator field and the rotor field. Both of these fields are due to currents which have resistive or in phase components and reactive or out of phase components. The torque developed is dependant on the interaction of the in phase components and consequently is related to the I^2R of the rotor. A low rotor resistance will result in the current being controlled by the inductive component of the circuit, yielding a high out of phase current and a low torque.

Figures for the locked rotor current and locked rotor torque are almost always quoted in motor data, and certainly readily available for induction motors. Some manufactures have been known to include this information on the motor name plate. One additional parameter which would be of tremendous use in data sheets for those who are engineering motor starting applications, is the starting efficiency of the motor. By the starting efficiency of the motor, I refer to the ability of the motor to convert amps into Newton meters. This is a concept not generally recognized within the trade, but one which is extremely useful, when comparing induction motors. The easiest means of developing a meaningful figure of merit is to take the locked rotor torque of the motor (as a percentage of the full load torque) and divide it by the locked rotor current of the motor (as a percent age of the full load current).i.e.,

Starting efficiency = Locked rotor torque / Locked rotor current

If the terminal voltage to the motor is reduced while it is starting, the current drawn by the motor will be reduced proportionally. The torque developed by the motor is proportional to the current squared, and so a reduction in starting voltage will result in a reduction in starting current and a greater reduction in starting torque. If the start voltage applied to a motor is halved, the start torque will be a quarter; likewise a start voltage of one third will result in a start torque of one ninth.

Running Characteristics:

Once the motor is up to speed, it operates at low slip, at a speed determined by the number of stator poles. The frequency of the current flowing in the rotor is very low. Typically, the full load slip for a standard cage induction motor is less than 5%. The actual full load slip of a particular motor is dependant on the motor design with typical full load speeds of four pole induction motor varying between 1420 and 1480 RPM at 50 Hz. The synchronous speed of a four pole machine at 50 Hz is 1500 RPM and at 60 Hz a four pole machine has a synchronous speed of 1800 RPM.

The induction motor draws a magnetizing current while it is operating. The magnetizing current is independent of the load on the machine, but is dependant on the design of the stator and the stator voltage. The actual magnetizing current of an induction motor can vary from as low as 20% FLC for large two pole machines to as high as 60% for small eight pole machines. The tendency is for large machines and high speed machines to exhibit a low magnetizing current, while low speed machines and small machines exhibit a high magnetizing current. A typical medium sized four pole machine has a magnetizing current of about 33% FLC. A low magnetizing current indicates a low iron loss, while a high magnetizing current indicates an increase in iron loss and a resultant reduction in operating efficiency.

The resistive component of the current drawn by the motor while operating, changes with load, being primarily load current with a small current for losses. If the motor is operated at minimum load i.e., open shaft, the current drawn by the motor is primarily magnetizing current and is almost purely inductive. Being an inductive current, the power factor is very low, typically as low as 0.1. As the shaft load on the motor is increased, the resistive component of the current begins to rise. The average current will noticeably begin to rise when the load current approaches the magnetizing current in magnitude. As the load current increases, the magnetizing current remains the same and so the power factor of the motor will improve. The full load power factor of an induction motor can vary from 0.5 for a small low speed motor up to 0.9 for a large high speed machine. The losses of an induction motor comprise: iron loss, copper loss, windage loss and frictional loss. The iron loss, windage loss and frictional losses are all essentially loading independent, but the copper loss is proportional to the square of the stator current. Typically the efficiency of an induction motor is highest at 3/4 load and varies from less than 60% for small low speed motors to greater than 92% for large high speed motors. Operating power factor and efficiencies are generally quoted on the motor data sheets.

Torque of Three Phase Induction Motor:

As previously stated, torque in an induction motor is caused by the interaction of the rotor and stator fields. In order that an EMF and corresponding currents are induced in the rotor, it rotates at a slip. At no-load, the rotor will lag behind the stator flux by a small amount necessary to produce the minimum torque required to overcome the rotor weight and motor losses. As load is added, the rotor speed will naturally increase. This decrease in speed (increase in slip) allows the stator field to rotate past the rotor bars at a faster rate, inducing larger rotor currents and a larger rotor field. The result is a larger torque at a slower speed.

Since the rotor impedance is low, a small decrease in rotor speed results in a large increase in rotor current and a large increase in the strength of the rotor field. As the load increases, the larger rotor currents are in such a direction as to decrease the stator flux. This results in a temporary decrease in counter EMF in the stator windings. This, in turn, allows more current to flow into the stator and increases the power input to the motor.

The strength of the rotor and stator fields, as well as the phase relationships between them, governs torque.

The power factor of the rotor is dependent on the phase relationship, since power factor is the cosine of the phase angle.

During normal operations, K, β, and pf are nearly constant. The torque will increase directly with the rotor current. The rotor current increases almost directly with slip. Increases in slip cause an increase in rotor frequency and rotor reactance.

To understand this, consider a two-pole induction motor. Synchronous speed is calculated at 3,600 rpm. If this motor operates at a 5 percent slip, then the slip in rpm is:

3,600 x .05 = 180 rpm

Physically, this means that a pair of stator poles will pass a certain rotor conductor 180 times a minute, or three times a second. Each time a pair of poles moves across a certain conductor, one cycle of EMF will be induced, resulting in a frequency of three cycles per second. If the slip were to increase to ten percent, or 360 rpm, the frequency of the rotor voltage and current is increased to six cycles per second. If the slip were to increase to 100 percent, the rotor frequency would be 60 Hz.

From this, you can see how rotor frequency is dependent on slip.

$$\text{Rotor Frequency} = \text{Stator Frequency} \times \text{Slip}$$

The frequency of the rotor is important insofar as its affect on rotor reactance. Rotor reactance will be almost directly proportional to rotor impedance, thus:

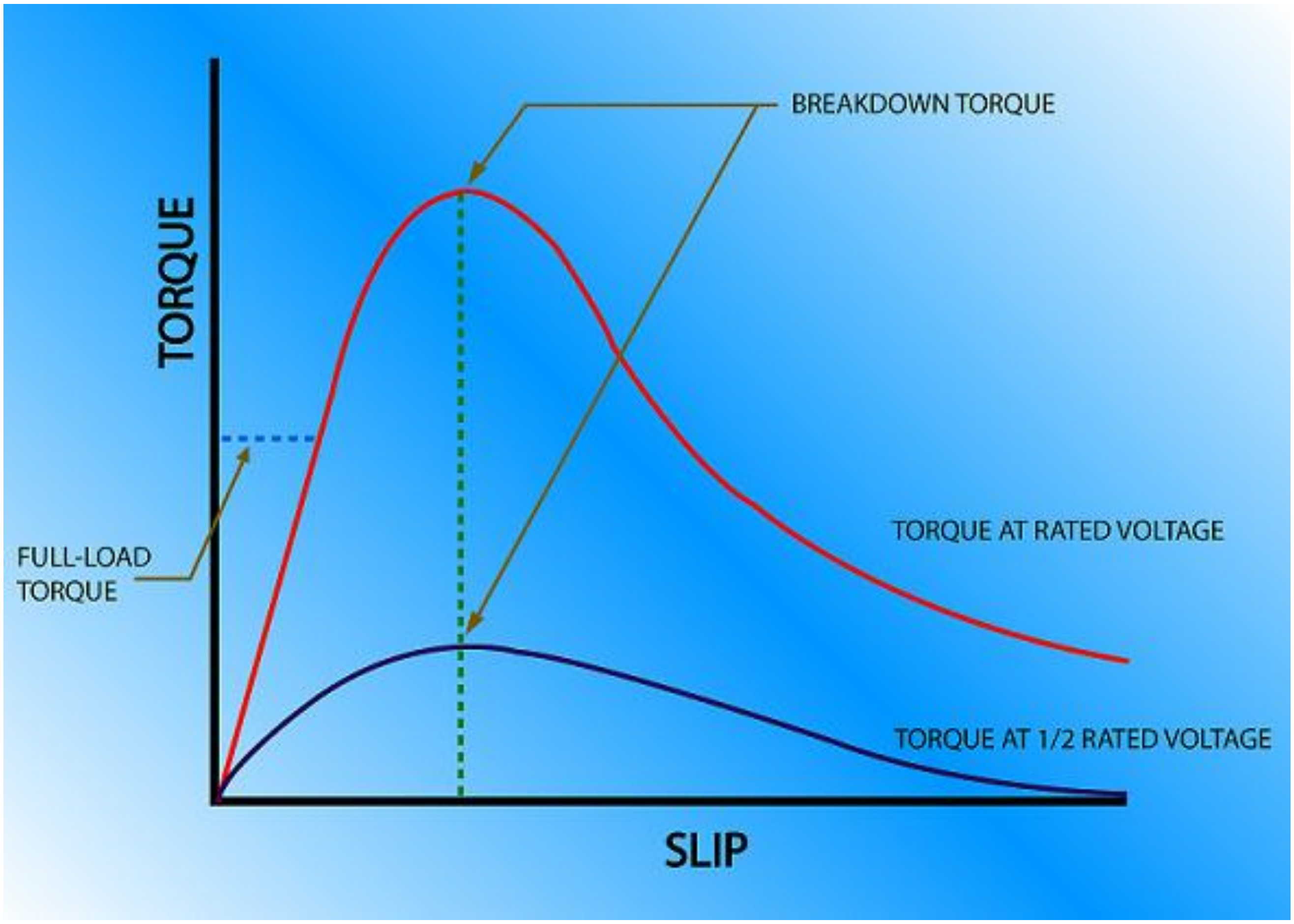
$$\text{Rotor Reactance} = 2\pi f L$$

From this, we see how increases in slip cause an increase in rotor frequency and rotor reactance. The rotor resistance will be constant, so an increase in rotor reactance means a decrease in rotor power factor since:

$$\text{Rotor Power Factor} = \frac{\text{Rotor Resistance}}{\text{Rotor Reactance}}$$

(Since it is proportional to impedance)

During normal operations, the change in slip is very small as load is added from an unloaded to a fully loaded condition. This means that changes in rotor impedance and reactance are tactically negligible. However, as the load is increased beyond rated and full-load values, the slip increases appreciably. This increase will lower the rate that rotor current increases in such a manner as to result in a torque that does not increase directly with slip. The decreasing power factor and the lowered rate of current increase will result in torque increases that become less rapid and will finally reach a maximum value. This is usually about 20 percent slip in squirrel cage induction motors. This maximum value of torque is known as *pullout torque*. If the load increases even further, the rotor power factor will decrease faster than the rotor current increases, resulting in a decreasing torque and stalling the motor. **Figure 10** shows the relationship between torque and slip.



Torque vs. Slip of Induction Machine

Starting Current of Induction Machine:

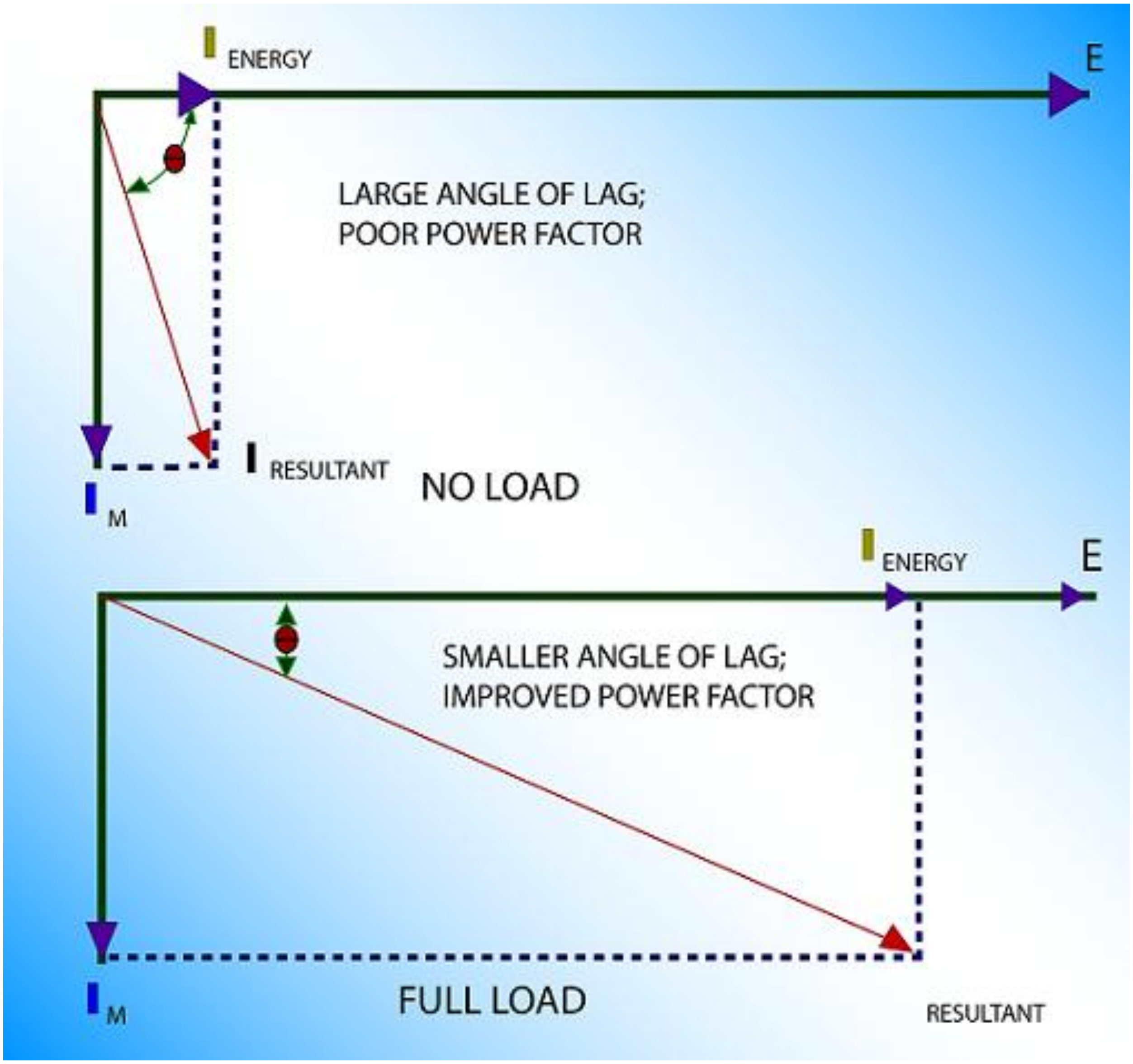
At the moment a three-phase induction motor is started, the current supplied to the motor stator terminals may be as high as six times the motor full-load current. This is because at starting, the rotor is at rest; therefore, the rotating magnetic field of the stator cuts the squirrel cage rotor at the maximum rate, inducing large amounts of EMF in the rotor. These results in proportionally high currents at the input terminals of the motor, as previously discussed. Because of this high inrush, current starting protection as high as 300 percent of full-load current must be provided to allow the motor to start and come up to speed.

Since there exists 100 percent slip at the instant the motor is energized, the rotor current lags the rotor EMF by a large angle. This means that the maximum current flow occurs in a rotor conductor at a time after the maximum amount of stator flux has passed by. This results in a high starting current at a low power factor, which results in a low value of starting torque. As the rotor speeds up, the rotor frequency and rotor reactance decrease, causing the torque to increase up to its maximum value, then decrease to the value needed to carry its load.

Power Factor of Induction Machine:

The power factor of a squirrel cage induction motor is poor at no-load and low load conditions. At no-load, the power factor can be as low as 15 percent lagging. However, as load is increased, the power factor increases. At high rated load, the power factor may be as high as 85 to 90 percent lagging. The power factor at no-load is low because the magnetizing component of input current is a large part of the total input current of the motor. When the load on the motor is increased, the in-phase current supplied to the motor increases, but the magnetizing component of current remains practically the same. This means that the resultant line current is more nearly in-phase with the voltage and the power factor is improved when the motor is loaded compared with an unloaded motor, which mainly draws magnetizing current.

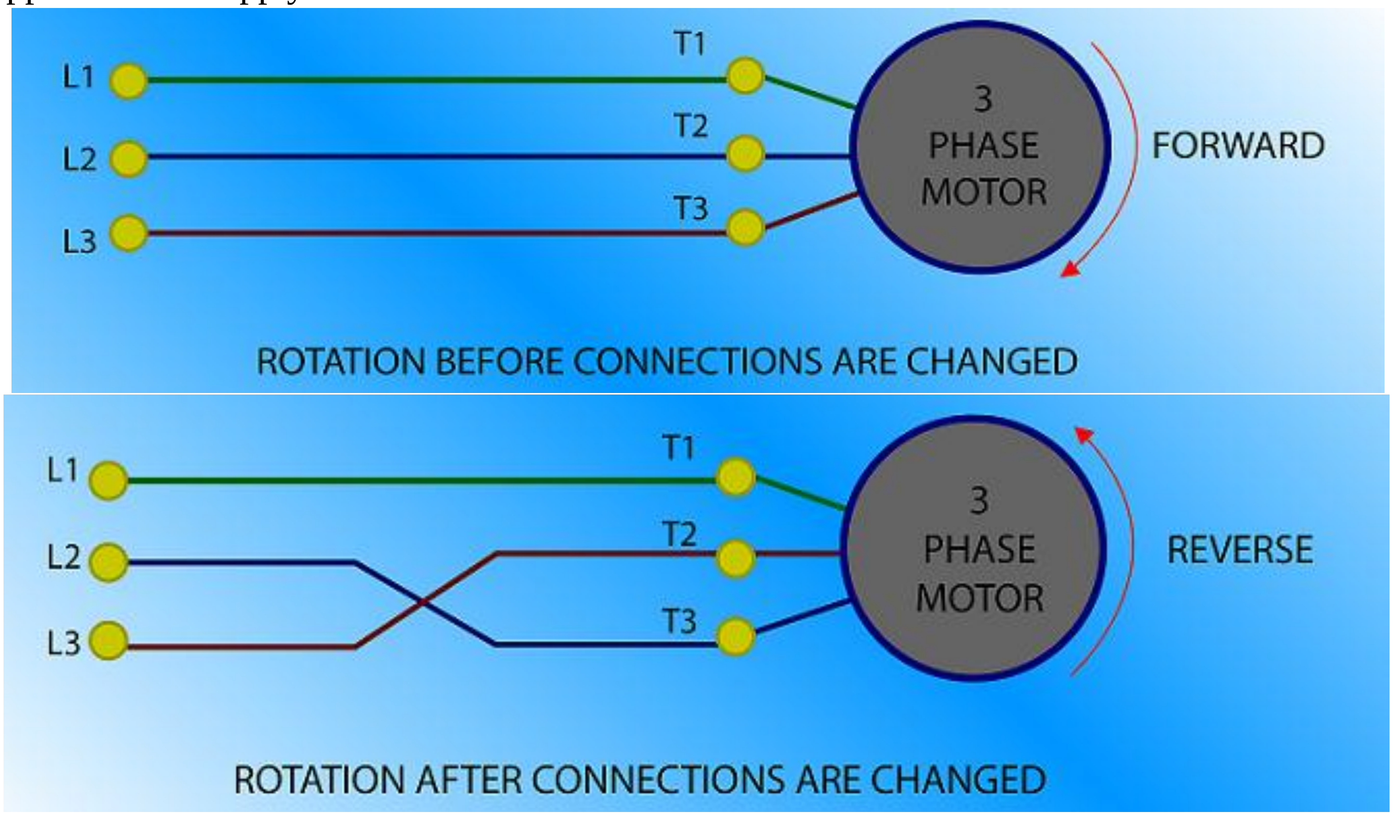
Figure shows the increase in power factor from a no-load condition to full-load. In the no-load diagram, the in-phase current (I_{ENERGY}) is small when compared to the magnetizing current (I_M); thus, the power factor is poor at no-load. In the full-load diagram, the in-phase current has increased while the magnetizing current remains the same. As a result, the angle of lag of the line current decreases and the power factor increases.



PF vs. Load for an Induction Motor

Running and Reversing of Three Phase Induction Machine:

Reversing the connections to any two of the three motor terminals can reverse the direction of rotation of three phase induction motor. Reverse the direction of rotation of the motor by reversing of two phases at the terminal box. The reversal has to be made when the motor is stopped and the supply switched off.



Three-Phase Induction Motor Rotational Direction Change

Difference between Induction and other AC Motor:

The basic difference between an induction motor and a synchronous AC motor is that in the latter a current is supplied onto the rotor. This then creates a magnetic field which, through magnetic interaction, links to the rotating magnetic field in the stator which in turn causes the rotor to turn. It is called synchronous because at steady state the speed of the rotor is the same as the speed of the rotating magnetic field in the stator.

The induction motor does not have any supply onto the rotor; instead, a secondary current is induced onto the rotor. Conductors in the rotor induce a current as the rotating magnetic field created by the stator windings sweep past them much in the same way as in a transformer. For this to happen, the speed of the rotor and the speed of the rotating magnetic field in the stator must be different, or else the magnetic field will not be moving relative to the rotor conductors and no current will be induced. If this happens, the rotor slows slightly until a current is re-induced and then the rotor continues as before. This difference between the speed of the rotor and speed of the rotating magnetic field in the stator is called slip. It is unit less and is the ratio between the relative speeds of the magnetic field as seen by the rotor to the speed of the rotating field. Due to this an induction motor is sometimes referred to as an asynchronous machine.

Advantage of AC over DC Motor:

Most of the power-generating systems produce AC. For this reason, a majority of the motors used, operate on AC. There are other advantages for using AC. In general, AC motors are less expensive and easier to maintain than DC machines. An AC motor is particularly well suited for constant speed operations. This is because its speed is determined by the frequency of the power source and the number of poles constructed in the motor alternating current motors is built in different sizes, shapes, and ratings for many different applications. It is impossible to address all forms of AC motors in this text. This article will address only the squirrel cage induction motor.