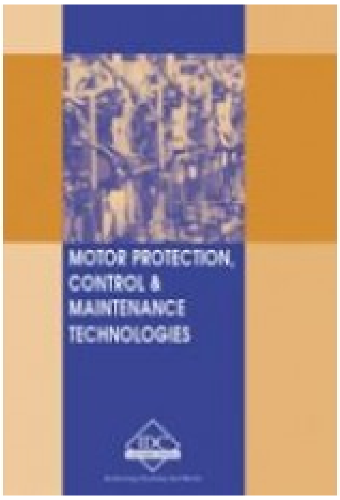
IDC Technologies - Books - 1031 Wellington Street West Perth WA 6005

Phone: +61 8 9321 1702 - Email: books@idc-online.com

# MP-E - Practical Motor Protection, Control and Maintenance Technologies




**Price: $127.22**

**Ex Tax: $127.22**

## Short Description

It is estimated that electrical drives and other rotating equipment consume about 50% of the total electrical energy consumed in the world today (and this figure increases to 70% if you only consider industry). The cost of maintaining electrical motors can be a significant amount in the budget item of manufacturing and mining industries.

## Description

It is estimated that electrical drives and other rotating equipment consume about 50% of the total electrical energy consumed in the world today (and this figure increases to 70% if you only consider industry). The cost of maintaining electrical motors can be a significant amount in the budget item of manufacturing and mining industries.

This manual gives you a thorough understanding of electrical motor's protection, control and maintenance and gives you the tools to maintain and troubleshoot electrical motors. You will gain a fundamental understanding of the protection, control and maintenance of electric motors and drives. Typical applications of electric motors in mining, manufacturing, materials handling and process control are covered in detail. The concluding section of the manual gives you the fundamental tools in troubleshooting motors confidently and effectively.

**Table of Contents**
Download Chapter List

Table of Contents

**First Chapter**
**Electric Motors**

# 1 Electric Motors

## 1.1 Fundamentals of Motor Technology

Electrical machines are ubiquitous in the modern world, as electric power has turned out to be the most efficient source of energy. Another universal phenomenon is the employment of magnetic field, the media for energy conversions in these electrical machines. It is a clean mechanism, without employing any particulate matter for the energy transformations involved. This factor alone makes a motor, as against an internal combustion engine, highly suitable for even the most demanding of environments where pollutants associated with combustion are undesirable.

An electric motor converts electrical energy into mechanical energy; in much the same way as a generator that converts mechanical energy into electrical energy. The basic commonality between them is that these machines convert energy from one form to another through the utilization of a magnetic field.

Another electrical device that is very closely related to these and is usually studied along with generators and motors is the transformer. A transformer is a device that converts AC electric energy at one voltage level to AC electric energy at another voltage level. This phenomenon of transforming the voltages is an inherent feature of generators and motors as well.

## 1.2 Basic Principles of Rotating Electrical Machines

Electrical machines utilize the concepts of electromagnetism. In the case of rotating electrical machinery, a magnetic field interacts with either an electric field or a mechanical force to produce the other. For example, in a motor, a magnetic field and an electric field interact with each other to produce a mechanical force.

The basic principles connected with magnetic fields can be summarized as follows:

- A current carrying conductor produces a magnetic field in its vicinity and will be as shown in Figure 1.1.

**Figure 1.1**

*Magnetic field lines around a current carrying conductor*

- A time varying magnetic field crossing a coil of wire induces a voltage in the coil. This is the basic guiding principle for a transformer.
- A magnetic field crossing a current carrying conductor develops a force on the conductor. This is because the current carrying conductor produces a magnetic field that interacts with the external magnetic field to develop the mechanical force. This is the basic guiding principle for a motor.
- Voltage gets induced in a conductor moving in a magnetic field. This is the basic guiding principle for a generator.
- All these principles put together, generate the motoring action, as shown in Figure 1.2. The process can be summed up as follows:
- As a voltage is applied to the stationary conductors, a magnetic field is produced.
- This magnetic field, in turn, induces a voltage in the rotor conductors in case of some motors (induction motors) or a voltage is externally applied to the rotor conductors.
- This voltage also produces a magnetic field.
- The magnetic field of the stator and rotor, together, put the rotor in running condition.

**Figure 1.2**

*A motor action*

Electrical machines (either a motor or a generator) typically have an overall appearance as shown in Figure 1.3 and can be broadly classified as DC machines and AC machines, depending on the nature of supply given to them. One has to appreciate the fact that the study of an electrical machine can be interchangeably associated with either a motor or a generator. The fundamentals for a particular category (like DC or Synchronous) are identical for both the generator and motor.

***Figure 1.3***

*Simple depiction of a motor*

For the sake of clarity, it is more appropriate to study the details of a DC machine, as the underlying principle of operation is simpler to comprehend. A simple DC machine, as shown in Figure 1.4, has a current carrying coil supported in between two permanent magnets (opposite poles facing each other) so the coil can rotate freely inside.

**Figure 1.4**

*A simple DC machine with two pairs of poles*

When the coil ends are connected to a DC source then current flows through it and it behaves like a bar magnet. As the current starts flowing, the magnetic flux lines of the coil, as shown in Figure 1.5, interact with the flux lines of the permanent magnet. This causes motion of coil due to forces of attraction / repulsion between two fields. The coil rotates in order to achieve a position where there is no force of attraction or repulsion.

**Figure 1.5**

*Electromagnetic circuit of a DC machine*

As the commutator segments are mounted on the same shaft, the commutator-to-brushes contact changes and the polarity of DC supply connected to the coil is reversed. This causes change in the direction of current, thereby changing the direction of the resultant mechanical force. Hence the coil rotates by another 180 degrees and the process continues forever. The mechanical features and electrical connection diagram of such a machine is as shown in Figure 1.6.

**Figure 1.6**

*Electromechanical features of DC machines*

The brush contacting positions will keep on changing like this and a continuous rotation of the coil (on the rotor) is achieved. The changes in the contact making combinations - of the brush and commutator segments - make the coil supply (even though DC) to alternate continuously. It is, therefore, apt to say that a commutator is the heart of a DC machine. A commutator looks as shown in Figure 1.7.

**Figure 1.7**

*Commutator of a DC machine*

The resulting alternating electric current flows through the coil and produces necessary rotation.

The cross sectional view of a DC machine is as shown in Figure 1.8.

**Figure 1.8**

*Simple cross sectional view of a DC machine*

In the case of an AC machine, as shown in Figure 1.9, the magnetic field itself revolves at a speed corresponding to the supply frequency. The electric current in the rotor coils is either induced (in case of asynchronous machines) or supplied through an external source (synchronous machines). In either case, the current in the coil is alternating thereby producing the rotating motion.

**Figure 1.9**

*Simple cross sectional view of an Alternator / Synchronous motor*

## 1.3 Fundamental Principles of Speed Control

Speed control of a motor is necessitated by the need for operability of the connected load at various speeds or at some pre-determined set of speeds to suit the process requirements. To deal with the speed control of various types of motors, a good understanding about the motor's constructional features and their operational characteristics is needed.

Depending on the type of combinations of windings used on the stator and the rotor, DC and AC motors can further be classified into different types and each of them has a significant role to play in delivering the power.

The speed regulation (much like the voltage regulation of a generator) of a motor is defined by:

### 1.3.1 DC Motors

The speed of a shunt motor is proportional to the armature voltage and is inversely proportional to the field current (excitation) of the motor. An overview of the different types of DC motors has been given below:

**Shunt motor** has field winding mounted on a yoke and the armature winding is mounted on the rotor. The shunt motor is used where speed regulation is important.

**Self-excited motor** has the field winding connected in parallel (shunt) with the armature winding and hence draws current from the same supply.

The speed control can be achieved by only adjusting the terminal voltage. The series resistance in the field circuit can be adjusted, but can naturally be done off-line.

**Separately excited shunt motor** has the field winding connected to a separate constant voltage power supply.

The speed control can be achieved by only adjusting the armature voltage as well as the field (excitation) current separately. The armature voltage control mode is the constant torque operation zone and the field current control mode is called as constant power operation. This is also known as field weakening mode.

**Series motor** has the field winding connected in series with the armature winding. Naturally, heavy current will pass through it, so field winding is of a thicker gauge. Series motor is used where speed regulation is not important and the torque requirement is very high.

In case of series motor, the field current cannot be controlled separately and is equal to the armature current. Hence under no load condition the excitation becomes very weak. The most important precaution required to be taken while using a series motor is that the motor cannot be run in no-load as it can speed up to very dangerous levels and can cause serious damage to itself.

**Compound motor** combines both series and shunt motor features. This combines the good features of both types such as high torque characteristics of series motor and the speed regulation of shunt motor. The level of compounding can be decided based on the particular application. These motors are generally used where severe starting conditions are met and constant speed is required at the same time.

The speed versus load current of various types of DC motors can be summarized as shown in Figure 1.10.

**Figure 1.10**

*Speed characteristics of various types of DC Motors*

### 1.3.2 AC Motors

The synchronous speed of an AC motor is given by the following relation:

For example, if the motor has two poles, then at 50 Hz frequency motor rpm will be 3000 rpm.

However, all AC motors do not run at synchronous speeds. Only synchronous motors run at these speeds. Induction motors run at speeds slightly lower than the synchronous speed and hence are known as asynchronous motors. By varying the frequency of the supply, synchronous speed of these AC motors can be varied.

A simple definition for an AC induction motor is that it is essentially a rotating transformer. Each of these different types of motors has specific benefits to offer over the other. Even though they have different performance characteristics to offer, the AC motors are virtually taking over the domain of DC motors for various reasons like ease of maintenance and recent developments in the manufacturing of reliable power components & controllers.

## 1.4 Efficiency, Torque, Inertia, Horsepower / Power Factor

### 1.4.1 Efficiency

The study of efficiency is essential for design purposes because it directly influences the economy of operation of the machine. In simple terms,

The stator input can be directly measured, but the rotor output needs to be measured by some indirect methods. However it is more accurate to determine the efficiency of a rotating machine by determination of its losses rather than by the direct load test, in which the input and output are to be measured. Furthermore, in large and even medium size machines, it is not practically possible to arrange for the actual loading of the machine. Once the losses are determined,

**Classification of losses in rotating machines:**

| Type of Loss | Causes | Example |
|---|---|---|
| **Constant losses** | **No load core (iron) loss**, mainly due to leakage fluxes and largely confined to the armature in case of DC and synchronous machines and to the stator of an induction motor. Mainly a result of the time variation of flux density and rotation of its axes. | Hysteresis losses<br>Eddy current losses |
| | **Mechanical loss,** comprises losses due to brush friction, bearing friction, windage and ventilation system losses. These will be relatively large in a machine of large diameter or of high speed. | Windage losses<br>Friction losses |
| **Variable losses** | **Copper ($I^2R$) loss,** includes even | Stator Cu losses |

| | | |
|---|---|---|
| | the losses in the field windings of DC motors / synchronous motors. | Rotor Cu losses<br>Brush contact losses |
| | **Stray load loss**, mainly due to skin effect (increased effective resistance of conductors due to non-uniform distribution of alternating currents) and due to distorted flex pattern in the teeth of the core. | Copper stray load losses<br>Core stray load losses |

As the voltage can be assumed to be constant, the core loss can also be approximated as a constant. The stator resistance can be measured by DC methods. However, hysteresis and eddy current loss in the conductors increase the resistance, and hence the effective resistance is normally taken as 1.2 times the DC resistance. The rotor copper loss is calculated by subtracting stator copper loss from the total measured loss or the rotor $I^2R$ loss. Friction and windage loss may be assumed constant irrespective of the load.

Because of the fixed and variable losses, the motor efficiency continuously increases with the load. The efficiency is maximum at a particular designed load. This full load efficiency also varies with the rating of a motor and is higher for large size machines varying between 75 % (typically for a 1 kW motor) and as high as 97 % (for a 3500 kW motor). Similarly efficiency of a low speed motor is usually lower than that of a high speed motor, the difference being as high as 3 to 4 %.

### 1.4.2 Torque

The torque on an object is defined as the product of the force applied to the object and the smallest distance between the line of action of the force and the object’s axis of rotation.

Torque is a force applied in a manner that tends to produce rotation, such as a pipe wrench on a shaft. Torque without rotation is termed static torque, since no motion is produced. Torque is measured in kg-m or lb-ft which is the product of the force in kgs or in pounds (lb) x the distance in meters (m) or in feet (ft) from the center of the point of apparent rotation. Because most power transmission is based upon rotating elements, torque is important as a measurement of the effort required to do work (horsepower).

When the stator and rotor windings of an AC motor both carry currents, they produce their own magnetic fields along their respective axes which are sinusoidally distributed along the air gap. A torque results from the tendency of these two fields to align themselves.

### 1.4.3 Inertia

Inertia in a rotational motion, as in case of a motor, is analogous to mass in a linear motion.

Newtonian physics teaches us that F (force) = M (mass) x A (acceleration). In rotary terms, the same is expressed as T (torque) = J (inertia) x A (acceleration). This fundamental equation shows us that the less inertia a system has the less torque it will take to meet a desired acceleration rate. For this reason it is advantageous to minimize inertia to the greatest extent to maximize acceleration. For a fixed amount of load inertia this means minimizing motor inertia. Stated another way, minimizing motor inertia would allow most of the motor's torque to accelerate the load not 'wasting' much of the motor's torque accelerating its own inertia. This is one of the main reasons for preferring AC motors over DC motors, to the possible extent, as "inertia of AC motor is lower compared to DC motor of similar rating". Minimizing motor inertia for a given rating of torque will theoretically maximize acceleration, increase system bandwidth, but at the same time, increases load to motor inertia mismatch and needs to a careful evaluation.

### 1.4.4 Horsepower

Power (Horsepower) is the rate of doing work and is a force applied in a manner that produces motion and, therefore, is work over a specified time period. A common unit of power is horsepower. One horsepower (HP) is defined as the force required to lift 33,000 lbs, one foot in one minute and is approximately 0.75 kW. Torque is constant at any speed while there is a directly proportional relationship between power and speed. Therefore, power is motion dependent but torque is not.

### 1.4.5 Power Factor

Motors achieve the transformation of electrical power into mechanical power by magnetizing its stationary, as well as rotating parts, to create necessary magnetic field. The relative magnetic fields between the rotating and stationary parts create the necessary mechanical forces to drive the shaft. So the input power to the motor gets converted into an output comprising of magnetization and mechanical components and manifests in two forms:

1). **Real power**: This is absorbed by the active loads – fans, compressors, pumps – connected to the motor and to meet any active power losses like frictional / windage ones.

2). **Reactive power**: This is due to the inductive load and is a function of the internal quality of the electrical machine's components / material. It is solely consumed by the electrical equipment and does not result in any mechanical work. Magnetizing circuits, the main infrastructure supporting the creation of magnetic field is basically inductive in nature. Theoretically an inductive circuit draws no real current. It draws only reactive current.

The sum (not algebraic) of these two components is the input power to the motor and is called as the apparent power. The ratio between active power (W) and apparent power (VA) is power factor.

True or Real Power is measured in watts (W). It is the power drawn by the electrical resistance of a system that does useful work. Reactive Power is measured in volt-amperes reactive (VAR) and is the power stored in and discharged by the inductive motors, transformers or solenoids. Reactive power required by inductive loads increases the amount of apparent power - measured in kilovolt amps (kVA) - in the distribution system. Increasing the reactive and apparent power causes the power factor, PF, to decrease. Apparent Power is measured in volt-amperes (VA) and is the voltage on an AC system multiplied by all the current that flows in it. It is the vector sum of the true and the reactive power and can be represented as shown in Figure 1.11

**Figure 1.11**

*Representation of apparent power and real power*

Power factor is the cosine of angle between the Resultant power and Real power. In the above triangle, power factor is a fraction obtained by dividing the real power in the system by (real power + apparent power). So it implies that Real power is equal to product of resultant power and PF. Hence if we increase the PF we will get more real power. But that is not so. We can not change the PF of individual equipment but we can change the PF of the system.

Consider a 750 kVA load operating at 80% lagging PF. Construct a power triangle to help determine the kW and kVAR components of the power

Solving for the real and reactive power values yields 600 kW and 450 kVAR, respectively.

**Figure 1.12**

*An example of representing apparent power and real power*

So of the 750 kVA drawn from the source, only 600 kW, or 80% of it, can do useful work. The reactive power, necessary to establish electromagnetic fields, adds a considerable burden to the source.

Low power factor is caused by inductive loads such as transformers and electric motors. Unlike resistive loads that create heat by consuming kilowatts, inductive loads require the current to create magnetic fields to produce the desired work.

A pure inductor dissipates no heat, so it has a power factor of zero.

Power factor is a measure of a particular motor's requirements for magnetizing amperage can be expressed as (for a three-phase electric motor):

Appliances are energy conversion devices. As dictated by the rules of power factor and efficiency, the energy consumed by an appliance is always greater than the energy provided by it.

## 1.5 Torque-speed Curves

In selecting a motor for a particular application, its speed-torque characteristic is needed to be known to a fair degree of accuracy. Further, this has to be properly matched to the speed-torque characteristic of the mechanical load. Typically the torque versus load characteristics of DC motors will be as shown in Figure 1.13.

**Shunt motor**: The speed of the motor maintains to be almost constant with a slightly drooping characteristic, ie., it reduces slightly with the increasing torque.

**Series motor**: The speed of the motor varies as the reciprocal of the square root of the torque. When the torque goes to zero, its speed goes to infinity.

**Compound motor**: Combines both the features of shunt and series motors, the torque doesn't cross that of a series motor but starting torque higher than that of a shunt motor.

**Figure 1.13**

*Torque characteristics of various types of DC Motors*

**Induction motor:** The speed-torque characteristics and torque-slip characteristics of an induction motor are important parameters for determining the performance of the motor. Typical speed-torque characteristic and torque-slip characteristics of a 3-Phase induction motor are shown in figure 1.14.

It can be seen that when motor starts from zero speed, start torque is lower than the full load torque and the motor can start at light to no load.

The normal full load torque is achieved at a point where the rotor speed is only 5% less than synchronous speed. From this point onwards, torque drops to zero value since there is no relative motion or slip between stator and rotor.

In order to achieve high starting torque rotor is made with high resistance conductors or external resistance is inserted in rotor circuit.

The nature of the characteristic curve can be changed in case of a slip-ring type induction motor by inserting an external resistance in the rotor circuit. If the rotor resistance is increased from $r_2$ to $r_2''$, $r_2'''$ ($r_2 < r_2'' < r_2'''$), then the maximum torque remains the same, but the slip at which the maximum torque occurs is shifted as shown in figure 1.14. The method of introducing an external resistance in rotor circuit is used to obtain a higher starting torque as required up to the maximum torque limit that the motor can produce. This method of increasing the starting torque can be used only in case of slip ring or wound rotor induction motors.

**Figure 1.14**

*Torque characteristics of AC Induction Motors*

**Synchronous motor:** Torque in a synchronous motor is developed only at synchronous speed when the locking of the two fields takes place.

**Figure 1.15**

*Torque characteristic of a Synchronous Motor*

## 1.6 Induction / Wound rotor / Synchronous Motor Types

The induction type motor is an important class of motors and finds wide applicability as a motor in industry and in its single-phase form in several domestic applications. Induction motor, in general, is known as the industrial horse of the modern industry. Hence due importance is given to induction motors throughout this course.

### 1.6.1 Squirrel cage induction motor

It is the most common type of AC motors and is the most cost effective motor that can be designed for any kind of environment. The typical construction of the rotor gives it its name. The rotor consists of a series of conducting bars laid into slots carved in the face of the rotor and shorted at either end by large shorting rings.

**Figure 1.16**

*Simple view of squirrel cage induction rotor*

### 1.6.2 Wound rotor motor

A wound rotor has a complete set of three-phase windings that are mirror images of the windings on the stator. The three phases of the rotor windings are usually Y-connected and the other three ends are tied to slip rings on the rotor's shaft. The rotor windings are connected in series with some external resistors – through brushes riding on the slip rings.

The motor starts with a full resistance bank, but as the speed of the motor increases, the resistances are shorted, one by one. As the motor reaches full speed, the whole bank of resistance is shorted out and the motor now runs like a squirrel cage induction motor.

**Figure 1.17**

*Simple view of slip ring induction rotor*

### 1.6.3 Synchronous motor

Synchronous motor is a constant speed motor; which can be used to correct the power factor of the 3-phase system. Like the induction motor in terms of the stator, the synchronous motor has either a permanent magnet arrangement or an electromagnet (with current supplied via slip rings) rotor. In simple terms, the rotor will keep locking with the rotating magnetic field in the stator. So, a 2-pole machine will run at exactly 3000 RPM. In many synchronous machines, a squirrel cage is incorporated into the rotor for starting. Therefore, the machine acts as an induction motor when starting and as it approaches synchronous speed, it suddenly 'locks in' to the synchronous speed.

### 1.6.4 Single phase induction motor

This motor is used mostly in small sizes, where polyphase current is not available. Characteristics are not as good as the polyphase motor and for sizes larger that 10 HP, the line disturbance is likely to be objectionable. These motors are commonly used for light starting and for running loads up to 1/3 HP Capacitor and repulsion types provide greater torque and are built in sizes up to 10 HP.

**Figure 1.18**

*Shaded pole single phase induction motor*

## 1.7 Basic Construction of a Motor

A Motor (whether DC or AC) comprises of 2 electromagnetic parts:

- Stationary part called the Stator consists of the frame, which provides the physical support.
- Rotating part called the Rotor, supported at each end on bearings.
- The other parts, which are required to complete a motor are:

- *Two end-flanges* to support the two bearings ..... one at the Drive-End (DE) and the other at the *Non Drive-End* (NDE)
- *Two Bearings* to support the rotating shaft .... at DE and NDE
- *Steel shaft* for transmitting the torque to the load
- *Cooling fan* located at the NDE to provide forced cooling for the stator and rotor
- *Terminal box* on top or either side to receive the external electrical connections

Both the Stator and the Rotor are made up of:

- An Electric circuit, usually made of insulated copper or aluminium, to carry current.
- A Magnetic circuit, usually made from laminated steel, to carry magnetic flux.

However, the constructional details of DC and AC motors differ and are to be dealt with separately.

### 1.7.1 DC Motors

The *Stator,* apart from providing physical support, houses the pole pieces, which project inward and provide a path for the magnetic flux. The ends of the pole pieces that are near the rotor spread out over the rotor surface to distribute the flux evenly over the rotor surface. These ends are called the ‘pole shoes’. The exposed surface of a pole shoe is called the ‘pole face’, and the distance between the pole face and the rotor is called the ‘air gap’. The poles on DC Motors are called salient poles, because they stick out from the surface of the stator.

There are two main windings on a DC motor:

- **Field windings** are the windings that produce the main magnetic flux in the motor. These are located on the Stator. The pole shoes occupy a major part of the pole-pitch.
- **Armature windings** are the windings in which a voltage is induced. A DC Motor’s rotor is often referred to as armature because the armature windings are located on the rotor.

The two ends of the coil are connected to two conducting segments mounted on the shaft and are insulated from each other and also from the shaft. This arrangement is called the commutator. Current is collected from the commutator segments by means of carbon brushes. The connections of the coil to the outside circuit reverse in a regular manner – each half cycle in case of 2 pole motor. This is the rectification action of the commutator-bruch arrangement in a generator.

### 1.7.2 AC Motors

**Synchronous Motor:** The rotor is essentially a large electromagnet. The magnetic poles on this rotor can be of either salient (“protruding” or “sticking out” of the surface of the rotor) or non-salient construction (constructed flush with the surface of the rotor). Non-salient pole rotors are normally used for rotors two and four pole rotors. Salient pole rotors are normally used for rotors with four or more poles. Because the rotor is subjected to changing magnetic fields, it is constructed of thin laminations to reduce eddy current losses. As the field circuit on the rotor must be fed with DC current, special arrangement must be made to transfer the power. Normally slip rings and brushes are employed for this purpose.

The Stator is normally made of preformed stator coils in a double layer winding. It consists of several coils in each phase, distributed in slots around the inner surface of the rotor, because it is simply impossible to put all the conductors into a single slot. In large motors, each coil is preformed units consisting of a number of turns, each turn insulated from the others and from the side of the stator itself. The voltage in any single turn of wire is very small, and it is only by placing many of these turns in series that reasonable voltages can be produced.

**Induction Motor:** The Stator is the outer cylindrical frame of the motor, which is made either of welded sheet steel, cast iron or cast aluminium alloy.  This may include a feet or a flange for mounting. It comprises:

- The *magnetic path,*which comprises a set of slotted steel laminations pressed into the cylindrical space inside the outer frame. The magnetic path is laminated to reduce eddy currents, lower losses and lower heating
- A set of *insulated electrical windings,*which are placed inside the slots of the laminated magnetic path.  The cross-sectional area of these windings must be large enough for the power rating of the motor.  For a 3-phase motor, 3 sets of windings are required, one for each phase

**Figure 1.19**

*Stator and rotor laminations*

**The rotor**

This is the rotating part of the motor. As with the stator above, the rotor consists of a set of *slotted steel laminations* pressed together in the form of a cylindrical magnetic path and the electrical circuit. The electrical circuit of the rotor can be either:

- *Wound Rotor type*, which comprises 3 sets of insulated windings with connections brought out to 3 sliprings mounted on the shaft. The external connections to the rotating part are made via brushes onto the sliprings. Consequently, this type of motor is often referred to as a *slipring motor*
- *Squirrel Cage Rotor type,* which comprises a set of copper or aluminium bars installed into the slots, which are connected to an end-ring at each end of the rotor. The construction of these rotor windings resembles a '*squirrel cage*'. Aluminium rotor bars are usually die-cast into the rotor slots, which results in a very rugged construction. Even though the aluminium rotor bars are in direct contact with the steel laminations, practically all the rotor current flows through the aluminium bars and not in the laminations

**Figure 1.20**

*Assembly details of a typical AC induction motor*

## 1.8 Principles of Operation and Performance

The machine and the load are the two components of an electro-mechanical energy conversion system. In particular, the machine characteristics play a very important role in the operating behavior of the entire system. The steady operating point is the point where the speed torque characteristics of the load and the motor intersect each other. Figure 1.21 shows the speed torque characteristic of a squirrel cage induction motor and that of a typical linear load. The drive system settles at a speed corresponding to the point of intersection of these two curves.

**Figure 1.21**

*Speed-Torque curves of Motor Vs Load*

At the time of engineering the drive system, the speed / torque / power characteristics developed at the motor shaft and how well these characteristics suit the driven machine must be considered. The four essential parameters that must be considered are:

- **Breakaway Torque**, the torque required to put the machine into motion. Normally it is greater than the torque required to maintain motion (running torque). Very often, the breakaway torque combined with process torque determines a drive selection.
- **Process Torque**, the torque required to pull, push, compress, stretch or otherwise process or act upon the material being transported by or through the machine. On some machines, process torque may be so significant as to determine the drive power rating. On other machines, this load may be insignificant. The process torque load is superimposed on all other static and dynamic torque requirements of the machine.
- **Accelerating Torque**, the torque required to bring the machine to its operating speed within a given time. With most machines, the load is largely frictional and a standard drive rating may have adequate torque for satisfactory acceleration. However, certain machines classified as "high inertia" with flywheels, bull gears or other large rotating masses may require drive selection based upon the power required to accelerate the load within a given time.
- **Running Torque**, the torque required to maintain the motion of the machine in a steady state condition, after getting accelerated to the desired operating speed.

The characteristics (especially the speed - torque curves) of both the driven machine and the driving machine play very important role in the selection process. Broadly loads can be classified into four basic categories and their characteristics will be as follows:

- Constant Torque
- Constant Horsepower
- Squared-Exponential Loads - torque varies directly as the speed, and power as the square of speed.
- Cubed-Exponential Loads - torque varies as the square of speed, and power as the cube of speed.

A limited number of machines may have operating characteristics which are a composite function of these basic types and hence need a careful evaluation before selecting the drive system.

To select a motor for a specified application it is imperative to study the operational performance of the various types of motors, thereby making it possible to evaluate various possible alternatives.

**DC Shunt motor**

The speed of a shunt motor (up to the rated speed) displays a drooping characteristic with respect to the torque delivered. It means that the speed decreases slightly as the torque increases. The rate of decrease in the speed is normally directly proportional to the torque demanded by the load. The torque developed by a shunt motor is proportional to the armature current, but with a deviation from the linear characteristic due to the effect of armature reaction. Because of its excellent speed regulation the shunt motor was the most preferred drive for variable speed applications. The ease of manipulating the speed by varying either the field current (using separately excited DC motor) or armature voltage gives it a great edge over other kind of motors for high rating variable speed applications. Normally by increasing the armature voltage applied to the rotor the speed is increased till the rated speed of the motor is attained. Further speed increase is achieved by reducing the field current. The power developed by a shunt motor varies in proportion with the speed as long as it is under the armature voltage control. In the field weakening mode, the power developed by the motor remains constant. This is because, in this zone of operation the torque developed by the motor decreases as the speed increases.

**DC Series motor**

The speed torque characteristic of a series motor is hyperbolic, with the speed decreasing as the torque increases. The motor develops very high torque at low speeds and very high speed at low torques. Hence the motor finds application where the load remains connected forever, without any possibility of even accidental load throw off. Also the very high initial torque makes it ideally suitable for traction duty of a locomotive.

**DC Compound motor**

This motor has both series field winding and shunt field winding and is used to obtain an intermediate performance, which is between that of a shunt motor and that of a series motor. It means that the characteristics of such a motor lie in between those of shunt and series motors. Even though cumulatively compounded – shunt and series fields aid each other – motor is the only one that can be seen being used, differentially compounded – series field winding opposes the shunt field winding – motor can also be used, but suffers from lack of stable operation.

**Synchronous motor**

As constant speed drives, these motors find application in driving large compressors, crushers etc. Even though they develop torque only at synchronous speed, their efficiency, inherent ability to correct power factor – even of the local power system – make them economically attractive. The speed of a synchronous motor is a constant irrespective of the torque developed by the motor up to the pull-out (maximum) value. It means that a synchronous motor runs at a constant speed till the point to which it is capable of delivering the load torque. Once the torque crosses this value, it goes out of synchronsim and comes to a stop. However some of these motors are fitted with damper windings in the rotor to make them self-starting. With this winding in place, the motor can be started as an induction motor and can be accelerated up to the synchronous speed

**Induction motor**

Torque-slip (speed) characteristic of an induction motor is a quite interesting operational characteristic. This is a very important factor in the selection of an induction motor drive. Additionally, the ratio of maximum torque to rated torque, ratio of starting current to rated current, ratio of starting torque to rated torque and the ratio of no load current to rated current are of equal significance. By adding external resistance the torque slip characteristic of a slip ring induction motor can be easily modified. Even though the maximum torque remains unaltered, the corresponding slip increases proportional to the resistance added to the rotor circuit. The peculiarities in the characteristic of an induction motor can be appreciated better by understanding the way it functions.