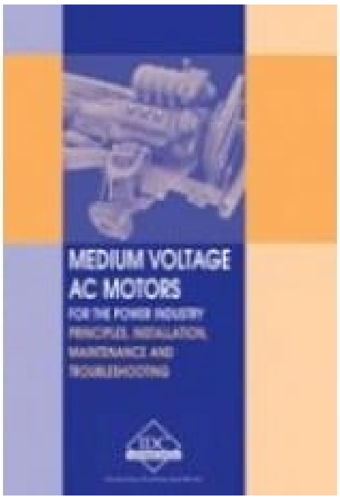
VM-E - Medium Voltage AC Motors for the Power Industry Principles, Installation, Maintenance and Troubleshooting



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Short Description

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Typical applications of electric motors in mining, manufacturing, materials handling, process control are covered in detail. You will learn the basic steps in specifying, installing and wiring and commissioning motors. The concluding section of the book gives you the fundamental tools for troubleshooting motors confidently and effectively.

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Fundamentals of Motor Technology

1 Fundamentals of Motor Technology

Learning Objectives

- To refresh basic principle of rotating electrical machines
- To study fundamental principle of speed control
- To study about efficiency, torque, inertia, horsepower and power factor
- To refresh 3-phase power concepts
- To study about torque speed curves
- To study about principle of torque production
- To study about Frame size and standardization
- To study about types of motors and their characteristics
- To study merits of each type of motors
- Reason for using cage type of motor
- To study relation between output of motor and voltage of operation
- Medium voltage motors and features

Introduction

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

Let's start by looking at a simple 2-pole DC electric motor. See Figure 1.4.

Figure 1.4

2-pole DC motor

Every DC motor has six basic parts – axle, rotor (aka the armature), stator, commutator, field magnet(s), and brushes. In most common DC motors the external magnetic field is produced by high-strength permanent magnets. The stator is the stationary part of the motor – this includes the motor casing, as well as two or more permanent magnet pole pieces. The rotor (together with the axle and attached commutator) rotates with respect to the stator. The rotor consists of windings (generally on a core), the windings being electrically connected to the commutator. Figure 1.4 shows a common motor layout – with the rotor inside the stator (field) magnets.

The geometry of the brushes, commutator contacts, and rotor windings are such that when power is applied, the polarities of the energized winding and the stator magnet(s) are misaligned, and the rotor will rotate until it is almost aligned with the stator's field magnets. As the rotor reaches alignment, the brushes move to the next commutator contacts, and energize the next winding. Given our example two-pole motor, the rotation reverses the direction of current through the rotor winding, leading to a ‘flip’ of the rotor's magnetic field, and driving it to continue rotating.

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. Figure 1.5 shows diagrammatically in cross section the armature of four-pole dc machine.

The field winding produces alternate north-south polarity, and the armature conductors are distributed in four belts of slots carrying currents alternatively towards and away from the reader, as symbolized by crosses and dots.

Figure 1.5

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 1.6, 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 1.6

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 are 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 1.7.

Figure 1.7

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 1.8.

Figure 1.8

Commutator of a DC machine

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

The current induced in armature conductors of DC generator are alternating. To make their flow unidirectional in the external circuit we need commutator. The process by which currents in the short circuit coil is reversed while crossing the magnetic neutral axis is called commutation.

The cross sectional view of a DC machine is as shown in Figure 1.9.

Figure 1.9

Simple cross sectional view of a DC machine

Interpoles: Interpoles are small poles fixed to the yoke and spaced between main poles. They are wound with comparatively few heavy gauge Cu wire turns and are connected in series with armature so that they can carry armature current. The polarity in the case of a DC generator is same as main pole ahead in direction of rotation.

The functions of interpoles are:

- Since polarity of interpole is same as main pole, they induce e.m.f. in coil ,which helps in reversal of current. This e.m.f. is called as commutating e.m.f. This e.m.f. neutralizes the reactance e.m.f. thereby making commutation sparkles. Interpole raises sparking limit of a machine to almost same as heating limit. Hence for given output interpole machines are made smaller than non-interpole machines.
- Other function of interpole is to neutralize the cross magnetizing effect of armature reaction. So brushes are not shifted from original position

In the case of an AC machine, as shown in Figure 1.10, 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 1.10

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 AC Motors

The following relation gives the synchronous speed of an AC motor:

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 the 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 and controllers.

1.4 Efficiency, torque, inertia, horsepower/power factors

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: Table 1.1 shows classification of losses in rotating machines.

Table 1.1

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 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 Friction losses
Variable losses	**Copper (I^2R) loss,** includes even the losses in the field windings of DC motors / synchronous motors.	Stator Cu losses Rotor Cu losses 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 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 kg 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 them.

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:

- **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.
- **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 Resultant power (kVA). 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 cannot 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 Frame size and its standardization

Frame of an electrical machine is a structure in which the stator core is assembled. The frame serves the following purpose:

- It encloses the core and windings
- It shields live and moving parts from human contact and from injury caused by intruding objects or weather exposures
- It transmits torque to the machine support, and therefore designed to withstand twisting forces and shocks
- It serves as ventilating housing or means of guiding the coolant into effective channels

Many varieties of designs are employed to meet the above requirements, and to adapt machines to particular service condition. An induction motor of large dimensions has a very small air gap and designing the frame for such machines has special significance. For induction motors the frame should be strong and rigid both during construction and after assembly of the machine. This is because length of air gap is small and if frame is not rigid, the rotor will not remain concentric with stator giving rise to unbalanced magnetic pull.

The frame may be die cast or fabricated. Machines up to about 50 kW rating usually have their frames die- cast in a strong silicon aluminum alloy and some cases with stator core cast in .The process of die-casting has advantage that it facilitates the use of thicker cross section of frames at places where grater mechanical strength is required. These die-cast frames do not require machining.

The frames of large sizes of machines are fabricated by welding steel plates. The advantage of fabrication is its adaptability to new design modifications.

Frames of small machines are made up of single unit. They are provided with feet by which they are fixed to base plate. In machines, which have radial ventilating ducts, the stator core is placed inside the frame on axial ribs thereby providing an annular space for air between core and frame.

The frames of totally enclosed machines are provided with axial fins in order to increase the heat-dissipating surface. Figure 1.13 shows a die-cast frame provided with axial fins.

Figure 1.13

Die--cast frame with axial fins

The stator laminations in small machine are fixed to the frame with the help of clamping ring as shown in Figure 1.14.

Figure 1.14

Assembly of stator core with clamp rings

The frames of medium and large sized machines are fabricated as stated earlier. The frame is short cylinder, or a box, with end plates axial ribs. The stator core is inserted into frame after inner surface of ribs have been machined and ends turned where necessary for end covers.

Medium sized machines (i.e. Machines whose stator core diameter exceeds 1 m, but is not more than 2.5 to 3.0m) are provided with radial ventilating ducts. In this case, ring chambers with large radial dimensions are required in order to obtain proper rigidity of frame and sufficient cross section for ducts for air. As stated earlier, the stator core of this machine is assembled from segmental lamination and fixed to dovetails welded or screwed on inside surface of frame. The frame is usually made in the form of a box or T shaped in order to increase its rigidity .In machine of large axial length the box has intermediate walls in addition to two sides of walls. These walls are designed such that the two consecutive walls are not more than 0.5 m apart (see Figure 1.15). This connection gives additional rigidity to frame.

The frames of larger horizontal shaft machines are made up of joints located in the horizontal plane. Openings are located in the outside surface of frame for providing outlet to cooling air in radial direction.

Figure 1.15

Box type of stator frame

1.6 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 1.16.

Shunt motor: The speed of the motor maintains to be almost constant with a slightly drooping characteristic, i.e., 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 1.16

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 1.17.

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 1.18. 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 1.17

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 1.18

Torque characteristic of a Synchronous Motor

1.7 Production of torque

Consider a 3-phase induction motor. Let the stator windings be supplied from a balanced 3-phase source. As already studied, current flows in the stator windings and a rotating magnetic field develops. The rotating magnetic field revolves in space around the stator, at synchronous speed given as $N_s = 120f/ P$. Assume that this stator magnetic field rotates in clockwise direction.

The rotor is stationary. There is relative motion between the stationary rotor and rotating magnetic field. Due to this relative motion, the stator field flux is cut across by the rotor conductors. By electromagnetic induction, e.m.f.s are set up in rotor conductors. Since the rotor forms a close circuit, currents are induced in rotor conductors. Due to interaction between stator flux and the rotor-induced conductors, a torque is produced. This is driving torque, which puts the rotor into motion. The rotor rotates.

Rotor rotates in clockwise direction according to Lenz's law. Since the torque acting on rotor is produced due to relative motion between stator flux and rotor conductors, and the torque must act such that it should reduce relative motion. Figure 1.19 shows relative motion of rotor respective of stator.

Figure 1.19

Production of torque

1.8 Types of motors

The induction type motor is an important class of motor and finds wide applicability as a 3-phase 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.

1.8.1 Squirrel cage induction motor

It is the most common type of AC motor 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 conductors are usually thick bars of copper or aluminum. 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. By this arrangement, the rotor forms a closed circuit. This type of construction is called Squirrel cage construction. See Figure 1.20.

Figure 1.20

Simple view of squirrel cage induction rotor

The rotor bars are permanently short-circuited on themselves; hence it is not possible to add any external resistance in series with the rotor circuit for starting purpose.

The rotor slots are not parallel to the shaft but purposefully given a slight skew. This is useful in two ways.

- It helps to run motor quietly and thus reduces magnetic hum.
- It helps in reducing locking tendency of rotor.

1.8.2 Wound rotor (Slip ring) induction motor

A wound rotor (Slip ring) 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. Consequently, this type of motor is often referred to as a slipring motor (see Figure 1.21).

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 1.21

Simple view of slip ring induction rotor

1.8.3 Synchronous motor

Synchronous motor is a constant speed motor; which can be used to correct the power factor of the 3-phase system. 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 'locks in' to the synchronous speed.

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 a preformed unit consisting of 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.

1.9 Relative merits of each type of motor

The advantages of each type of motor are given in Table 1.2.

Table 1.2

Merits of each type of motor

Advantages of Squirrel Cage induction Motor	Advantages of Wound Rotor Induction Motor	Advantages of Synchronous Motor
These are cheaper and more robust as Compared to wound rotor Motor	These motor have higher starting torque	These are constant speed Motors and independent on load
These motor have slightly higher efficiency and power factor	These motors have a much lower starting current	These type of motor can act as Motor or Generator depending on excitation current
These are made explosion proof, the risk of sparking is reduced by the absence of slip rings and brushes	These motors have a mean of varying speed by use of external rotor resistance. This cannot be done in Squirrel cage induction motor	Power factor can be controlled very easily

The cage rotor motor is preferred over other motors because, this motor is

- Cheaper and more robust
- Slightly has higher efficiency and power factor
- Explosion proof

1.10 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 1.22 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 1.22

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 maintaining 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 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.

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 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 at which it is capable of delivering the load torque. Once the torque crosses this value, it goes out of synchronism 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.

1.11 Relationship between output of motor and voltage of operation

No-load test

The no-load test is carried out at different voltages and the value of voltage; no-load current and no-load input are measured (U, I_0 and P_0) at each voltage value. A total of six measurements are to be taken three between 100% and 125% of rated voltage and three between 20% and 50% of rated voltage. The test is to be carried out in the descending order of voltage after running the machine at no-load at rated voltage and frequency (with the motor in uncoupled condition) till the no-load input power value P_0 becomes stable (variation of <3%) at two successive 30 min. intervals. Value of R before and after the test is to be measured and the arithmetic mean calculated for use with the test values.

The watt input at rated voltage will be the sum of the friction and windage, core loss, and no load primary I^2R loss. Subtracting the primary I^2R loss at the temperature of the test from the inputs gives the some of friction and windage and core loss.

Plotting the input watts, less primary I^2R, against the square of the voltage and extrapolating the lower part of curve in a straight line to intercept the zero-voltage axis determines the friction and windage loss. Figure 1.23 shows typical data of the test.

Figure 1.23

Computing friction and windage loss (Reference: AS/NZS 1359.102.3:2000)

1.12 Medium voltage motors and its features

These are available for indoor and outdoor installation to various degrees and types of protection. These machines are characterised by high efficiency and low noise level, and are fitted with short-circuit and shatterproof terminal boxes. Windings are insulated, using the well-known VPI system.

1.12.1 VPI system of insulation

VPI treatment normally meant impregnating individual coils in a small vessel. These had to be partially or fully cured before winding into a stator. That, too, is still practical for large machines. This global vacuum pressure impregnation insulation system exhibits various merits in insulation performance and reliability for operation including maintenance, and therefore suitable for the generators used at geothermal power plant. Additionally, the global vacuum pressure impregnation insulation system is attracted as a leading system for the insulation in future.

By means of various attachments, these machines can be adapted to almost any application. Designs for difficult and severe site and operating conditions, both conventional and explosion-protected, are also available.

The range includes surface-ventilated motors with ribbed frame, tube-cooled and modular-design motors, all of which are available with the customary cooling methods and degrees of protection. In the development of these motors special emphasis was laid on high efficiencies, low noise and vibration levels, ease of maintenance and long service life. This is ensured by a sturdy design with a high degree of adaptability to various applications.

Uses:

- Thermo electric power plant and nuclear power plants
- Cement Industry
- Coal extractions
- Air compressor and pump
- Hazardous areas

Basic technical characteristics are as shown in Table 1.3.

Table 1.3

Basic Technical Characteristics

Rated outputs range:	132 - 3000 kW
Rated voltage:	3; 3.3; 5; 5.5; 6; 6.3; 6.6; 10; 10.5; 11; 13.8 kV
Synchronous speed:	300 - 3600 rpm at 50 Hz or 60 Hz
Class of insulation:	F
Protection degree:	IP23; IPW24; IP44; IP54; IPW54; IP55; IPW55; IP56

Rotor type:	Squirrel-cage or wound
Construction shape:	Horizontal or vertical

1.12.2 Squirrel-cage Induction Motors

Destination

The motors described herein are meant for driving some main equipment in thermoelectric power plants: coal mills, gas and air fans, and pumps. They can operate in normal temperate climate, dusty and ashy environment.

Designation

Motors designation consists of groups of capital letters and figures, which are marked on the motor nameplate. Their significances are the following:

M	3-phase induction motor
I	Closed construction
P	Slip-ring rotor
Number	Constructive version
A	Water cooled
X	Special construction

Horizontal Motors

Number	Height of rotating axis (H quota in mm)
Letter	Frame length
Number	Shaft end diameter
Number	Number of poles

Designation example: MIP3X 355X 90-4

Vertical Motors

V	Vertical construction
Number	Axial external thrust [tf]
Letter	Frame length
Number	Shaft end diameter
F, FF, FD	Flange symbol (IEC 72-1,2)
Number	Circle diameter on which are placed the ho centers in flange

Number	Number of poles

Designation example: MIP V 12Y 120F 1180-6

Technical characteristics. Performances

Motors meet the general technical conditions in IEC 34-1 standards. They are designed to run in continuous duty, type S1, at 6 kV and 50 Hz.

Noise and vibrations levels meet the IEC 34-9 respectively IEC 34-14 standards.

Maximum safe working is ensured as a result of the following solutions:

- Vacuum and pressure impregnation (VPI process) of the stator windings,
- 50000 hours lifetime of the rolling bearings - calculated according to SKF method,
- Windings and bearings heating monitoring by means of platinum RTDs and thermistors.
- Space heaters meant to prevent moisture formation during non-working time.

1.12.3 Slip-ring Induction Motors

Destination

The motors described herein are meant to drive equipment with standard conditions of starting and running; some of the motors in B and C chapters are intended for industrial drives: tube mills, crushers, blowers, rotary calciner kilns, compressors, pumps, fans, conveyer belts and other equipment with similar features. They can operate indoor or outdoor, in the following conditions: temperate or tropical climate, dusty environment, free of chemical, corrosive or inflammable agents.

Designation

An individual motor designation consists of groups of capital letters and numbers, which are marked on the motor nameplate. Their significance is as following:

M	3-phase induction motor
I	Closed construction
P	Slip-ring rotor
Number	Constructive version

A	Water cooled
X	Special construction

Horizontal Motors

Number	Height of rotating axis (H quota in mm)
Letter	Frame length
Number	Shaft end diameter
Number	Number of poles

Designation example: MIP3X 355X 90-4

Vertical Motors

V	Vertical construction
Number	Axial external thrust [tf]
Letter	Frame length
Number	Shaft end diameter
F, FF, FD	Flange symbol (IEC 72-1,2)
Number	Circle diameter on which are placed the hole centers in flange
Number	Number of poles

Designation example: MIP V 12Y 120F 1180-6

Technical characteristics - performances

The motors meet the general technical conditions in IEC 34-1 standards. They are designed to run in continuous duty, type S1.

Noise and vibrations levels are in accordance with IEC 34-9, respectively IEC 34-14 standards.

The maximum safety in working is ensured as a result of the following solutions:

- Vacuum and pressure impregnation (VPI) of the windings
- Working life of bearings is min. 50,000 working hours, calculated according to SKF method,
- Special system of brush holders (constant pressure springs),
- Windings and bearings heating monitoring by means of platinum RTD-s (on request),
- Prevention of the moisture condensation during stand still conditions, by means of space heaters.

1.13 Summary

In this chapter we have seen fundamentals of motor technology. We have learned basic principles of rotating electric machines. Electrical machines utilize the concepts of electromagnetism. In a motor, a magnetic field and an electric field interact with each other to produce a mechanical force, which rotates rotor and converts electrical energy into mechanical energy.

Fundamental principle of speed control of motor is discussed in detail. 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 AC motors can be varied.

Motor efficiency, torque, inertia and horsepower and power factor is discussed in next section. In selecting a motor for a particular application, its speed-torque characteristic is needed to be known to a fair degree of accuracy. Torque speed characteristics of different motors are discussed in detail. How torque is produced is explained in detail.

Frame of electrical machines are structures in which stator core is assembled. They serve different purposes.

We have seen different types of motors, i.e. cage type, slip ring and synchronous motors. Relative merits of each type of motor over others. Relationship between output of motor and the voltage of operation is also explained. Medium voltage motor and their features are discussed in detail.