**UNIT 2**

**ELECTRIC MOTORS**

**INTRODUCTION**

The working principle of motors is based on the electromechanical energy conversion process. This process involves the conversion of electrical energy into mechanical energy or vice versa by interchanging of energy between an electrical system and a mechanical system through a medium. The medium may include a coupling system of either electric field or magnetic field. To create a rotating motion between a magnetic field and electric current carrying conductors, motors should essentially have two major parts stator and rotors, separated by an air gap. Due to interaction between the magnetic fields set up in the stator and rotor, motors convert electrical energy into mechanical energy. The most commonly used electric motors are induction motors, direct current motors and synchronous motors. All types of electric motor have the same general construction consisting four principal components: stator (stationary windings), rotor (rotating windings), bearings, and frame (enclosure).

**2.1 MOTOR TYPES, CHARACTERISTICS, EFFICIENCY**

2.1.1

**Induction Motor:**

Induction motors have extensive use in industrial sectors as well as domestic sectors. When an induction motor is energised from a given supply, a magnetic field is induced in stator winding which induces a current in the rotor. Due to this induced current a second magnetic field is produced, which tries to oppose the stator magnetic field, for which rotor starts to rotate. There are two types of induction motors viz. 3-phase induction motors and single-phase induction motors. Single phase motors are fed from single phase whereas 3-phase motors are fed from 3 phase power supply. The single phase induction motors are less efficient, which are widely used in home appliances, shops, offices etc. On the other hand the use of 3-phase motors is seen in only large commercial and industrial sectors. The induction motor which carries Squirrel cage type rotor is called squirrel cage induction motors. Most of 3-phase induction motors are found to be squirrel cage induction motors which are extremely simple and robust in construction and enable to handle it in the most adverse situations. A single phase induction motor is similar to a 3-phase squirrel cage induction motor. It always consists of a squirrel cage type rotor. In case of single phase induction motor, a single phase supply cannot induce a rotating magnetic field, for which it is not considered as a self starting motor. So additional windings are provided and converted it into two phase supply and thus make it self-starting.

**Direct-Current Motors**

Direct-Current motors uses direct-unidirectional, current and convert d.c. power into mechanical power. These type of motors generally depend upon the mechanical load they have to withstand. There are three types of d.c. motors viz. (i) shunt-wound motor (ii) series wound motor (iii) compound wound motor.

**Synchronous Motors**

3 phase synchronous motors are most commonly used and it converts 3-phase power into mechanical power. The stator of synchronous motor is energized from 3 phase AC source whereas the rotor is excited from a separate DC source to produce magnetic flux in air gap.

The synchronous motor runs at synchronous speed to develop torque. This motor operates at fixed frequency which keeps the motor speed constant irrespective of the load or 3-phase voltage supply. The most advantage of the use of such kind of motor is that it can operate over a wide range of power factors by adjusting its field excitation. It is not self starting machine for which auxiliary measures has to be taken.

**2.1.2 Motor characteristics**

**Motor speed:**

The speed of a motor is defined as the number of revolutions created by a magnetic field in a given time and specified as revolutions per minute (RPM). In case of an AC motor the speed depends upon the frequency of the input power and the number of poles wound in the motor. The synchronous speed refers to the speed at which the rotating magnetic field revolves which follows the given equation

**Synchronous Speed (RPM) = (120 ×Frequency)/ No. of Poles**

Where the frequency is the number of cycles per second, in Hertz

Most of Indian motors operate at synchronous speeds such as 3000 / 1500 / 1000 / 750 / 600 / 500 / 375 RPM corresponding no. of poles 2, 4, 6, 8, 10, 12, 16 (always even) with the supply frequency of 50 Hz.

**Slip**

The actual speed of motor is less than the synchronous speed. Slip is defined as the difference between synchronous and full load speed and usually is expressed in terms of percentage of synchronous speed i.e.,

**Slip (%) × 100**

From the above equation, it is clear that the speed of an AC motor can be determined by the number of motor poles and input frequency. So by varying the frequency the motor speed can be varied infinitely. In most of the cases, Variable Frequency Drive (VFD) has been added to change the motor speed.

**Power Factor**

The power factor of a motor is the ratio between the real power to the apparent power which is given by:

Power Factor = Cos Φ

where P is in kW and S in kVA.

**2.1.3 Motor Efficiency**

The efficiency (η) of the motor is defined as the ratio of the mechanical energy delivered at the rotating shaft (output power) to the electrical energy applied at its terminals (input power), and given by,

η =

and input = output + losses.

As per above relations, it is found that the efficiency of motor is directly related to the losses occurred in the motors. Intrinsic losses are classified as **fixed losses** and **variable losses** and which can be reduced by modifying the motor designs. Fixed losses remain constant at all loads i.e. independent of loads whereas variable losses vary with load.

**Fixed losses** are of three types *viz.* (i) **Iron losses** or **magnetic core losses** (ii) **Friction losses** (iii) **windage losses**.

Iron losses or magnetic core losses include eddy current and hysteresis losses in the stator. Friction and windage losses are also known as mechanical losses. Friction losses are occurred due to friction in the bearings and brush etc. whereas windage losses of the motor caused by air friction of rotating parts.

**Variable losses** are classified as resistance losses occurred in both stator and rotor and various stray losses. These losses generate heat and thus increase the temperature of the motor which lower the efficiency of the motor. Resistance losses is proportional to the resistance of the material and square of the current i.e. I2R. Stray loss is proportional to the square of the rotor current and may result from variety of sources which are difficult to assess or compute.

The overall performance of a motor can be upgraded by improving its efficiency and power factor. The value of power factor close to unity is desirable for efficient operation of a motor. The motor which drives inductive loads is considered as power factors less than one. In that case higher current should be drawn to supply same real power than for a load having higher power factor. As the resistance losses of the motor is proportional to the square of the current, so it increases when the motor draws more current.

Squirrel cage motors have higher efficiency than slip-ring motors, and the same way the higher-speed motors are found more efficient than lower-speed motors. It is also found that the motor efficiency is highly affected by the motor temperature. Totally-enclosed, fan-cooled (TEFC) motors are more efficient than screen-protected, drip-proof (SPDP) motors.

**2.2 Energy- Efficient Motors**

Energy-efficient motors (EEM) are built by improving the designs in such a way that operating efficiency could be made more than the standard design motors as indicated in fig 2.1.

Design improvements deal with the reduction of intrinsic motor losses. Improvements could be made by using lower-loss silicon steel, a longer core (to increase the surface area of material), thicker wires (to reduce resistance), thinner laminations (to minimize cost), smaller air gap between stator and rotor, copper bars in the rotor, advanced bearing systems and a smaller fan, etc.

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**Figure 2.1 Standard vs. High Efficiency Motors**

Applications of Energy-efficient motors are now initiated in India which performs at higher efficiencies about 3 to 4 % than standard motors. Energy-efficient motors are designed to operate without loss in efficiency at loads between 75 % and 100 % of rated capacity. This may result in major benefits in varying load applications. The power factor is about the same or may be higher than for standard motors. Furthermore, energy- efficient motors have lower operating temperatures and noise levels, greater ability to accelerate higher-inertia loads, and are less affected by supply voltage fluctuations.

Energy efficiency improvements in EEMs can be done as given in Table 2.1 below

|  |  |
| --- | --- |
| TABLE 2.1 ENERGY EFFICIENT MOTORS | |
| **Power Loss Area** | **Efficiency Improvement** |
| 1. Iron | Use of thinner gauge, lower loss core steel reduces eddy current losses. Longer core adds more steel to the design, which reduces losses due to lower operating flux densities. |
| 2. Stator I2R | Use of more copper and larger conductors increases cross sectional area of stator windings. This lowers resistance (R) of the windings and reduces losses due to current flow (I). |
| 3. Rotor I2R | Use of larger rotor conductor bars increases size of cross section, lowering conductor resistance (R) and losses due to current flow (I). |
| 4. Friction & Windage | Use of low loss fan design reduces losses due to air movement. |
| 5. Stray Load Loss | Use of optimized design and strict quality control procedures minimizes stray load losses |

**2.3 Factors affecting Energy efficiency of a motor**

**Power Supply Quality**

Motor performance is affected considerably by the quality of input power that is the actual volts and frequency available at motor terminals vis a vis rated values as well as voltage and frequency

variations and voltage unbalance across the three phases. The Bureau of Indian Standards (BIS) standards specify that a motor should be capable of delivering its rated output with a voltage variation of +/- 6 % and frequency variation of +/- 3 %. Fluctuations much larger than these are quite common in utility-supplied electricity in India. Voltage fluctuations can have detrimental impacts on motor performance.

Voltage unbalance, the condition where the voltages in the three phases are not equal, can be still more detrimental to motor performance and motor life. Unbalance typically occurs as a result of supplying single-phase loads disproportionately from one of the phases. It can also result from the use of different sizes of cables in the distribution system.

The options available for an energy manager to ensure near to rated voltage at motor terminals include

1. Load end power factor improvement by providing matching PF factors.
2. Minimizing line/cable voltage drops from sub-station to motor terminals.
3. Transformer tap changing as required in case of consistent and continuous low voltage situations.

The options that can be exercised to minimize voltage unbalance include:

1. Balancing any single phase loads equally among all the three phases.
2. Segregrating any single phase loads which disturb the load balance and feed them from a separate line/ transformer.

**Power Factor Correction**

Induction motors are characterized by power factors less than unity, leading to lower overall efficiency (and higher overall operating cost) associated with a plant's electrical system. Capacitors connected in parallel (shunted) with the motor are typically used to improve the power factor. The impacts of PF correction include reduced kVA demand (and hence reduced utility demand charges), reduced I2R losses in cables upstream of the capacitor (and hence reduced energy charges), reduced voltage drop in the cables (leading to improved voltage regulation), and an increase in the overall efficiency of the plant electrical system.

The maximum improvement in overall system efficiency is achieved when the capacitor is connected across the motor terminals, as compared to somewhere further upstream in the plant's electrical system.

**Maintenance**

Inadequate maintenance of motors can significantly increase losses and lead to unreliable operation.For example, improper lubrication can cause increased friction in both the motor and associated drive transmission equipment. Resistance losses in the motor, which rise with temperature, would increase.

Therefore, to insure proper motor operation, the following maintenance practices should be followed:

• Inspecting motors regularly for wear in bearings and housings (to reduce frictional losses) and for dirt/dust in motor ventilating ducts (to ensure proper heat dissipation).

• Checking load conditions to ensure that the motor is not over or under loaded. A change in motor load from the last test indicates a change in the driven load, the cause of which should be understood.

• Lubricating appropriately. Manufacturers generally give recommendations for how and when to lubricate their motors. Inadequate lubrication can cause problems, as noted above. Over lubrication can also create problems, e.g. excess oil or grease from the motor bearings can enter the motor and saturate the motor insulation, causing premature failure or creating a fire risk.

• Checking periodically for proper alignment of the motor and the driven equipment. Improper alignment can cause shafts and bearings to wear quickly, resulting in damage to both the motor and the driven equipment.

• Ensuring that supply wiring and terminal box are properly sized and installed. Inspect regularly the connections at the motor and starter to be sure that they are clean and tight.

**Age**

Most motor cores in India are manufactured from silicon steel or de-carbonized cold-rolled steel,

the electrical properties of which do not change measurably with age. However, poor maintenance (inadequate lubrication of bearings, insufficient cleaning of air cooling passages, etc.) can cause a deterioration in motor efficiency over time. Ambient conditions can also have a detrimental effect on motor performance. For example, excessively high temperatures, high dust loading, corrosive atmosphere, and humidity can impair insulation properties; mechanical stresses due to load cycling can lead to misalignment. However, with adequate care, motor performance can be maintained.

**2.4 Soft starters, Variable speed drives**

**Speed control of AC induction motors**

Traditionally, DC motors have been employed when variable speed capability was desired. By controlling the armature (rotor) voltage and field current of a separately excited DC motor, a wide range of output speeds can be obtained. DC motors are available in a wide range of sizes, but their use is generally restricted to a few low speed, low-to-medium power applications like machine tools and rolling mills because of problems with mechanical commutation at large sizes. Also, they are restricted for use only in clean, non-hazardous areas because of the risk of sparking at the brushes. DC motors are also expensive relative to AC motors.

Because of the limitations of DC systems, AC motors are increasingly the focus for variable speed applications. Both AC synchronous and induction motors are suitable for variable speed control. Induction motors are generally more popular, however, because of their ruggedness and lower maintenance requirements. AC induction motors are inexpensive (half or less of the cost of a DC motor) and also provide a high power to weight ratio (about twice that of a DC motor).

An induction motor is an asynchronous motor, the speed of which can be varied by changing the supply frequency. The control strategy to be adopted in any particular case will depend on a number of factors including investment cost, load reliability and any special control requirements. Thus, for any particular application, a detailed review of the load characteristics, historical data on process flows, the features required of the speed control system, the electricity tariffs and the investment costs would be a prerequisite to the selection of a speed control system.

The characteristics of the load are particularly important. Load refers essentially to the torque output and corresponding speed required. Loads can be broadly classified as either constant power or Constant torque. Constant torque loads are those for which the output power requirement may vary with the speed of operation but the torque does not vary. Conveyors, rotary kilns, and constant-displacement pumps are typical examples of constant torque loads. Variable torque loads are those for which the torque required varies with the speed of operation. Centrifugal pumps and fans are typical examples of variable torque loads (torque varies as the square of the speed). Constant power loads are those for which the torque requirements typically

change inversely with speed. Machine tools are a typical example of a constant power load.

The largest potential for electricity savings with variable speed drives is generally in variable torque applications, for example centrifugal pumps and fans, where the power requirement changes as the cube of speed. Constant torque loads are also suitable for VSD application.

**Motor Speed Control Systems**

**Multi-speed motors**

Motors can be wound such that two speeds, in the ratio of 2:1, can be obtained. Motors can also be wound with two separate windings, each giving 2 operating speeds, for a total of four speeds. Multi-speed motors can be designed for applications involving constant torque, variable torque, or for constant output power. Multi-speed motors are suitable for applications, which require limited speed control (two or four fixed speeds instead of continuously variable speed), in which

cases they tend to be very economical. They have lower efficiency than single-speed motors.

**Adjustable Frequency AC Drives**

Adjustable frequency drives are also commonly called inverters. They are available in a range of kW rating from fractional to 750 kW. They are designed to operate standard induction motors. This allows them to be easily added to an existing system. The inverters are often sold separately because the motor may already be in place. If necessary, a motor can be included with the drive or supplied separately. The basic drive consists of the inverter itself which coverts the 50 Hz incoming power to a variable frequency and variable voltage. The variable frequency is the actual requirement, which will control the motor speed. There are three major types of inverters designs available today. These are known as Current Source Inverters (CSI), Variable Voltage Inverters (VVI), and Pulse Width Modulated Inverters (PWM).

**Direct Current Drives (DC)**

The DC drive technology is the oldest form of electrical speed control. The drive system consists of a DC motor and a controller. The motor is constructed with armature and field windings. Both of these windings require a DC excitation for motor operation. Usually the field winding is excited with a constant level voltage from the controller. Then, applying a DC voltage from the controller to the armature of the motor will operate the motor. The armature connections are made through a brush and commutator assembly. The speed of the motor is directly proportional to the applied voltage. The controller is a phase controlled bridge rectifier with logic circuits to control the DC voltage delivered to the motor armature. Speed control is achieved by regulating the armature voltage to the motor. Often a tacho generator is included to achieve good speed regulation. The tacho would be mounted on the motor and produces a speed feedback signal that is used within the controller.

**Wound Rotor AC Motor Drives (Slip Ring Induction Motors)**

Wound rotor motor drives use a specially constructed motor to accomplish speed control. The motor rotor is constructed with windings which are brought out of the motor through slip rings on the motor shaft. These windings are connected to a controller which places variable resistors in series with the windings. The torque performance of the motor can be controlled using these variable resistors. Wound rotor motors are most common in the range of 300 HP and above.

**Example 1.** A 440 V, 20 HP 3-ph motor operates at full load, 88% efficiency and 0.65 power factor lagging:

**A**. Find the current drawn by the motor

**B**. Find the real and reactive power absorbed by the motor

**Solution:**

**A**. Pin (Input power) = 20 x 746 / 0.88 = 16955 W

IL (Input current) = 16955 / (√3 x 440 x 0.65) = 34.2 A

**B**. PF = 0.65 ∴ = cos-1(0.65) = 49.5o (also sin 49.5 °C = 0.76)

P (kW) = √3 x VL x IL x cos 49.5o = √3 x 440 x 34.2 x 0.65 = 16.95 kW

Q (kVAr) = √3 x VL x IL x sin 49.5o = √3 x 440 x 34.2 x 0.76 = 19.8 kVAr

S (kVA) = √3 x VL x IL = √3 x 440 x 34.2 = 26.1 kVA

{Note : S2 = √(P2+Q2)}

**Example 2**. A 4-pole 415 V 3-phase, 50 Hz induction motor runs at 1440 RPM at .88 pf lagging and delivers 10.817 kW. The stator loss is 1060 W, and friction & windage losses are 375 W.

Calculate

**A**. Slip

**B**. Rotor Copper loss

**C**. Line current

**D**. Efficiency

**Solution:**

Supply frequency (f) =50Hz

No. of poles (P) =4 Synchronous speed (Ns) =120f/P=1500 RPM

Actual speed (Nm) =1440 RPM

**A**. Slip(s) = (Ns – Nm)/ Ns = **0.04pu**

**B**. Motor output =10817W

Stator Cu loss =1060W

Friction & windage =375W

Motor Output= Rotor Input – Rotor Copper loss – Friction & windage loss **Eq. (1)**

We know that, Rotor Input = Rotor Copper loss/ slip

Substituting in **Eq. (1)**

Rotor Copper Loss = (Motor output + Friction & windage loss) x slip/ (1- slip)

Therefore, Rotor Copper loss= (10817+375) x 0.04/ (1-0.04)

Rotor Copper loss= **466.33W**

**C**. Motor input = Rotor input + Stator loss

Rotor input = Rotor Copper loss/slip = 466.33/0.04 = 11658W

Motor input = 11658 + 1060 = 12718W V= 415 Volts; Cos φ = 0.88lag;

Line Current =Motor input/ (1.732 x V x Cos φ) = **20.11A**

**D**. Efficiency = (Motor Output/Motor input) x 100%

= (10817/12718) x 100 = **85%**

**Short type questions**

1. Name the three types of commonly used motors.
2. What is the relation between RPM (speed) and frequency of an induction motor?
3. What is an energy efficient motor?
4. Comment on ‘construction aspects’ how an “energy efficient motor” is different from a “standard motor”?
5. What are the types of losses in any motor?
6. What steps should an energy manager take to minimize voltage unbalance?
7. Name the two important parameters that attribute to efficiency of electricity use by AC induction Motors?
8. List methods by which speed control of motor can be achieved.

**Long type questions**

1. What are the losses in the ‘induction motor’ and briefly explain them?
2. Write the checklist of good maintenance practices for proper motor operation?
3. Explain the ways by which efficiencies of energy efficient motors are increased.
4. A 50 kW induction motor with 86 % present full load efficiency is being considered for replacement by a 89 % efficiency motor. What will be the savings in energy if the motor works for 6000 hours per year and cost of energy is Rs. 4.50 per kWh?

**Suggested reading references**

1. Mehta V.K. Mehta R. Principles of Electrical Machines. S. Chand & Company Ltd., 2009

2. Theraja B.L. Theraja A.K. A Textbook of Electrical Technology, Volume II. S. Chand & Company Ltd., 2005