ELECTRIC MOTORS

1. INTRODUCTION

This section describes the main features of the electric motors.

1.1 Where motors are used

An electric motor is an electromechanical device that converts electrical energy to mechanical energy. This mechanical energy is used for, for example, rotating a pump impeller, fan or blower, driving a compressor, lifting materials etc. Electric motors are used at home (mixer, drill, fan) and in industry. Electric motors are sometimes called the "work horses" of industry because it is estimated that motors use about 70% of the total electrical load in industry.

1.2 How a motor works

The general working mechanism is the same for all motors (Figure 1):

- An electric current in a magnetic field will experience a force.
- If the current carrying wire is bent into a loop, then the two sides of the loop, which are at right angle to the magnetic field, will experience forces in opposite directions.
- The pair of forces creates a turning torque to rotate the coil.
- Practical motors have several loops on an armature to provide a more uniform torque and the magnetic field is produced by electromagnet arrangement called the field coils.

In understanding a motor it is important to understand what a motor load means. Load refers to the torque output and corresponding speed required. Loads can generally be categorized into three groups (BEE India, 2004):

- ***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.

Components of electric motors vary between different types of motors and are therefore described in section 2 for each motor separately.

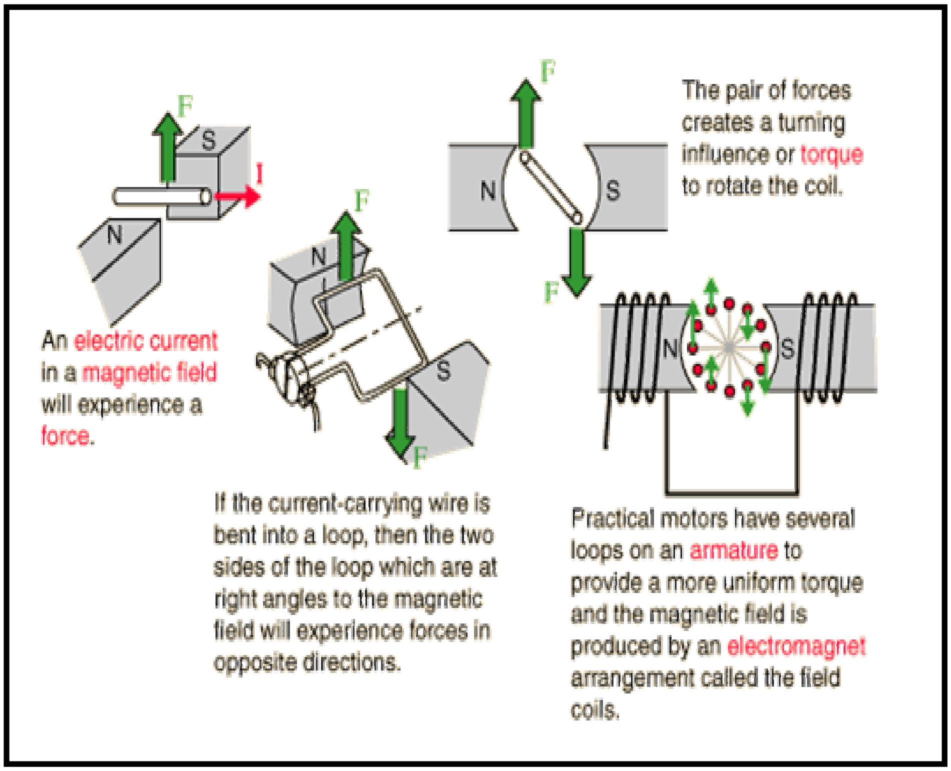

Figure 1. Basic Principle of how Electric Motors Work (Nave, 2005)

2. TYPES OF ELECTRIC MOTORS

This section describes the two main types of electric motors: DC and motors. A list of suppliers of electric motors is available on www.directindustry.com/find/electric-motor.html.

Figure 3 shows the most common electric motors. These are categorized based on the input supply, construction, and operation mechanism, and are further explained below.

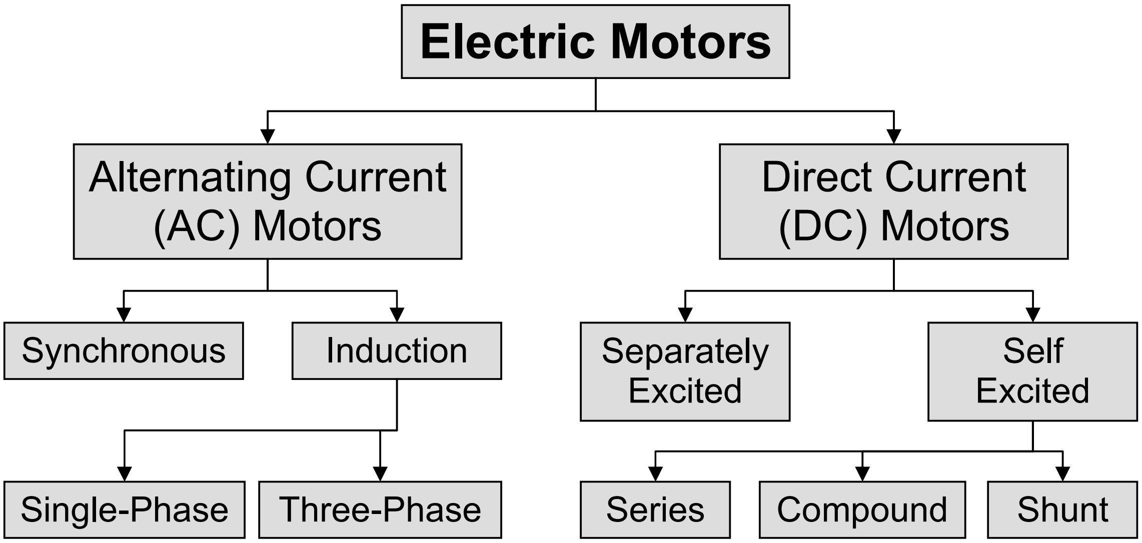

Figure 2. Classification of the Main Types of Electric Motors

2.1 DC motors

Direct-current motors, as the name implies, use direct-unidirectional current. DC motors are used in special applications where high torque starting or smooth acceleration over a broad speed range is required.

A DC motor is shown in Figure 3 and has three main components:[1]

- ***Field pole.*** Simply put, the interaction of two magnetic fields causes the rotation in a DC motor. The DC motor has field poles that are stationary and an armature that turns on bearings in the space between the field poles. A simple DC motor has two field poles: a north pole and a south pole. The magnetic lines of force extend across the opening between the poles from north to south. For larger or more complex motors there are one or more electromagnets. These electromagnets receive electricity from an outside power source and serve as the field structure.
- ***Armature.*** When current goes through the armature, it becomes an electromagnet. The armature, cylindrical in shape, is linked to a drive shaft in order to drive the load. For the case of a small DC motor, the armature rotates in the magnetic field established by the poles, until the north and south poles of the magnets change location with respect to the armature. Once this happens, the current is reversed to switch the south and north poles of the armature.
- ***Commutator.*** This component is found mainly in DC motors. Its purpose is to overturn the direction of the electric current in the armature. The commutator also aids in the transmission of current between the armature and the power source.

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[1] Taken from *Components of an Electric Motor* with the permission from Bureau of Energy Efficiency India, 2005.

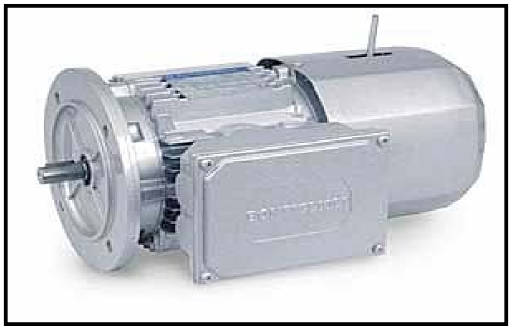

Figure 3. A DC Motor
(Direct Industry, 2005)

The main advantage of DC motors is speed control, which does not affect the quality of power supply. It can be controlled by adjusting:

- the armature voltage – increasing the armature voltage will increase the speed
- the field current – reducing the field current will increase the speed.

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.

The relationship between speed, field flux and armature voltage is shown in the following equation:

Back electromagnetic force: $E = K\Phi N$
Torque: $T = K\Phi I_a$

Where:
E = electromagnetic force developed at armature terminal (volt)
Φ = field flux which is directly proportional to field current
N = speed in RPM (revolutions per minute)
T = electromagnetic torque
I_a = armature current
K = an equation constant

2.1.1 Separately excited DC motor

If the field current is supplied from a separate source it is a separately excited DC motor.

2.1.2 Self excited DC motor: shunt motor

In a shunt motor, the field winding (shunt field) is connected in parallel with the armature winding (A) as shown in figure 4. The total line current is therefore the sum of field current and armature current.

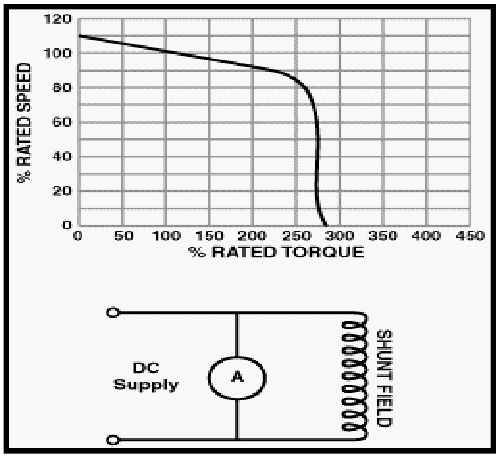

Figure 4: Characteristics of a DC Shunt Motor
(Rodwell International Corporation, 1999)

The following can be said about the speed of shunt motors (E.T.E., 1997):

- The speed is practically constant independent of the load (up to a certain torque after which speed decreases, see Figure 4) and therefore suitable for commercial applications with a low starting load, such as machine tools
- Speed can be controlled by either inserting a resistance in series with the armature (decreasing speed) or by inserting resistance in the field current (increasing speed)

2.1.3 Self excited DC motor: series motor

In a series motor, the field winding (shunt field) is connected in series with the armature winding (A) as shown in figure 5. The field current is therefore equal to the armature current. The following can be said about the speed of a series motor (Rodwell International Corporation, 1997; L.M. Photonics Ltd, 2002):

- Speed is restricted to 5000 RPM
- It must be avoided to run a series motor with no load because the motor will accelerate uncontrollably

Series motors are suited for applications requiring a high starting torque, such as cranes and hoists (see Figure 5).

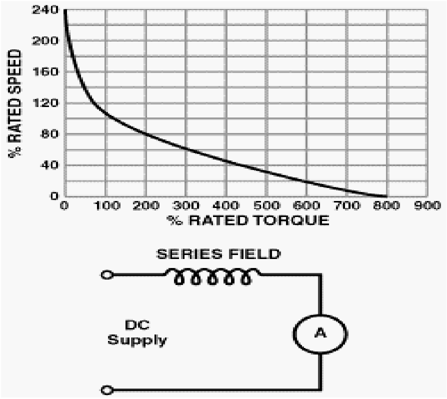

Figure 5: Characteristics of a DC Series Motor
(Rodwell International Corporation, 1999)

2.1.4 DC Compound Motor

A DC compound motor is a combination of shunt and series motor. In a compound motor, the field winding (shunt field) is connected in parallel and in series with the armature winding (A) as shown in figure 6. For this reason this motor has a good starting torque and a stable speed. The higher the percentage of compounding (i.e. percentage of field winding connected in series), the higher the starting torque this motor can handle. For example, compounding of 40-50% makes the motor suitable for hoists and cranes, but standard compound motors (12%) are not (myElectrical, 2005).

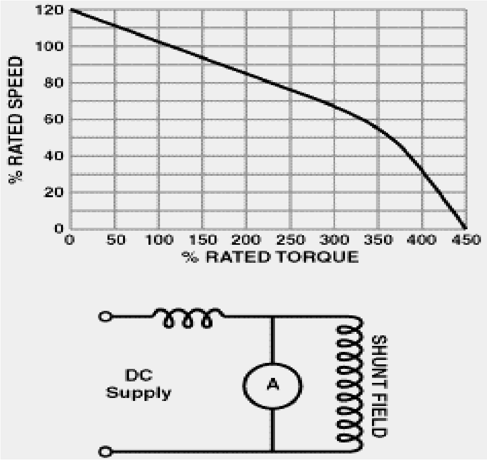

Figure 6: Characteristics of a DC Compound Motor
(Rodwell International Corporation, 1999)

2.2 AC Motors

Alternating current (AC) motors use an electrical current, which reverses its direction at regular intervals. An AC motor has two basic electrical parts: a "stator" and a "rotor" as shown in Figure 7. The stator is in the stationary electrical component. The rotor is the rotating electrical component, which in turn rotates the motor shaft.

The main advantage of DC motors over AC motors is that speed is more difficult to control for AC motors. To compensate for this, AC motors can be equipped with variable frequency drives but the improved speed control comes together with a reduced power quality. Induction motors are the most popular motors in industry 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).

2.2.1 Synchronous motor

A synchronous motor is an AC motor, which runs at constant speed fixed by frequency of the system. It requires direct current (DC) for excitation and has low starting torque, and synchronous motors are therefore suited for applications that start with a low load, such as air compressors, frequency changes and motor generators. Synchronous motors are able to improve the power factor of a system, which is why they are often used in systems that use a lot of electricity.

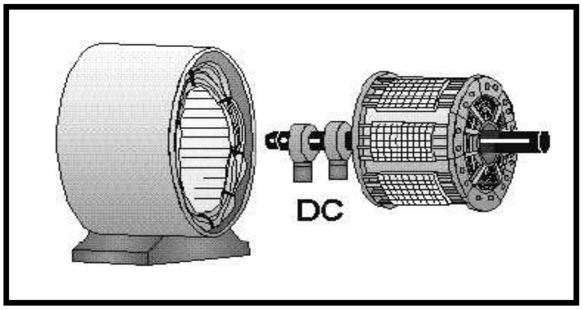

Figure 7. A Synchronous Motor
(Integrated Publishing, 2003)

The main components of a synchronous motor are (Figure 7):[2]

- ***Rotor.*** The main difference between the synchronous motor and the induction motor is that the rotor of the synchronous motor travels at the same speed as the rotating magnetic field. This is possible because the magnetic field of the rotor is no longer induced. The rotor either has permanent magnets or DC-excited currents, which are forced to lock into a certain position when confronted with another magnetic field.
- ***Stator***. The stator produces a rotating magnetic field that is proportional to the frequency supplied.

This motor rotates at a synchronous speed, which is given by the following equation (Parekh, 2003):

$$N_s = 120\, f / P$$

Where:

f = frequency of the supply frequency
P= number of poles

2.2.2 Induction motor

Induction motors are the most common motors used for various equipments in industry. Their popularity is due to their simple design, they are inexpensive and easy to maintain, and can be directly connected to an AC power source.[3]

a. Components

An induction motor has two main electrical components (Figure 8):[4]

- Rotor. Induction motors use two types of rotors:
  - A squirrel-cage rotor consists of thick conducting bars embedded in parallel slots. These bars are short-circuited at both ends by means of short-circuiting rings.
  - A wound rotor has a three-phase, double-layer, distributed winding. It is wound for as many poles as the stator. The three phases are wired internally and the other ends are connected to slip-rings mounted on a shaft with brushes resting on them.

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[2] Taken from *Components of an Electric Motor* with the permission from Bureau of Energy Efficiency India, 2005.

[3] For more detailed information on induction motors it is recommended to read *AC Induction Motor Fundamentals* by Parekh (2003)

[4] Taken from *Components of an Electric Motor* with the permission from Bureau of Energy Efficiency India, 2005.

- Stator. The stator is made up of a number of stampings with slots to carry three-phase windings. It is wound for a definite number of poles. The windings are geometrically spaced 120 degrees apart.

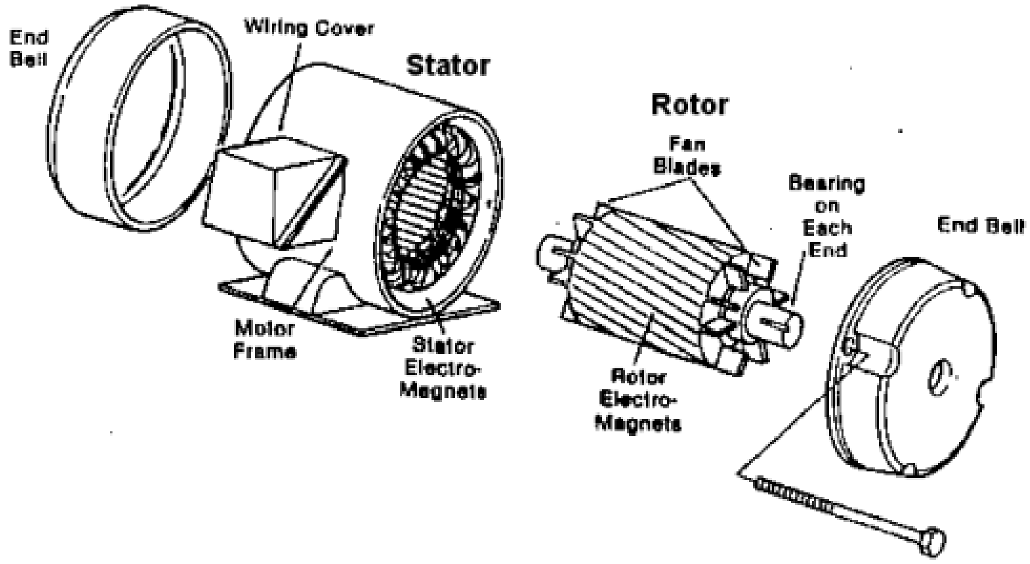

Figure 8. An Induction Motor (Automated Buildings)

c. Classification of induction motors

Induction motors can be classified into two main groups (Parekh, 2003):

- Single-phase induction motors. These only have one stator winding, operate with a single-phase power supply, have a squirrel cage rotor, and require a device to get the motor started. This is by far the most common type of motor used in household appliances, such as fans, washing machines and clothes dryers, and for applications for up to 3 to 4 horsepower.
- Three-phase induction motors. The rotating magnetic field is produced by the balanced three-phase supply. These motors have high power capabilities, can have squirrel cage or wound rotors (although 90% have a squirrel cage rotor), and are self-starting. It is estimated that about 70% of motors in industry are of this type, are used in, for example, pumps, compressors, conveyor belts, heavy-duty electrical networks, and grinders. They are available in 1/3 to hundreds of horsepower ratings.

d. Speed of induction motor

Induction motors work as follows. Electricity is supplied to the stator, which generates a magnetic field. This magnetic field moves at synchronous speed around the rotor, which in turn induces a current in the rotor. The rotor current produces a second magnetic field, which tries to oppose the stator magnetic field, and this causes the rotor to rotate.

In practice however, the motor never runs at synchronous speed but at a lower “base speed”. The difference between these two speeds is the “slip”, which increases with higher loads. Slip only occurs in all induction motors. To avoid slip, a slip ring can be installed, and these motors are called “slip ring motors”. The following equation can be used to calculate the percentage slip (Parekh, 2003):

$$\% \text{ Slip} = \frac{N_s - N_b}{N_s} \times 100$$

Where:

N_s = synchronous speed in RPM
N_b = base speed in RPM

e. Relationship between load, speed and torque

Figure 9 shows the typical torque-speed curve of a three-phase AC induction motor with a fixed current. When the motor (Parekh, 2003):

- Starts there is a high starting current and low torque ("pull-up torque").
- Reaches 80% of the full speed, the torque is at its highest level ("pull-out torque") and the current begins to drop.
- Is at full speed, or synchronous speed, the torque and stator current drop to zero.

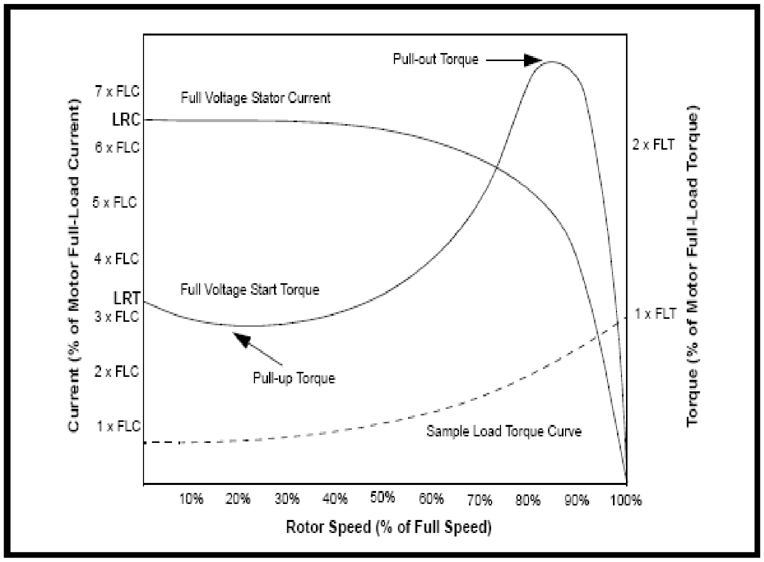

Figure 9. Typical Torque-Speed Curve of 3-Phase AC Induction Motors (Parekh, 2003)

3. ASSESSMENT OF ELECTRIC MOTORS

This section describes how to assess the performance of electric motors.[5]

3.1 Efficiency of electric motors

Motors convert electrical energy to mechanical energy to serve a certain load. In this process, energy is lost as shown in Figure 11.

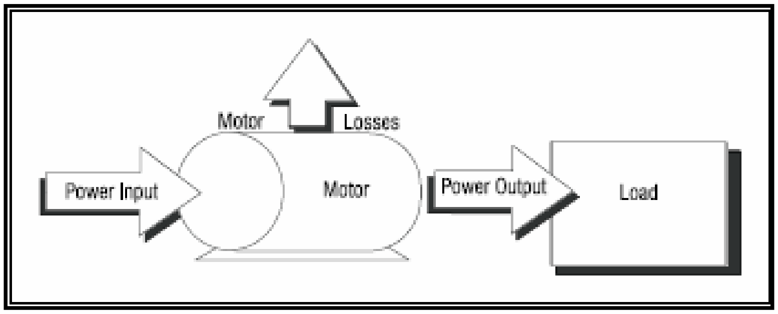

Figure 10 . Motor Losses (US DOE)

The efficiency of a motor is determined by intrinsic losses that can be reduced only by changes in motor design and operating condition. Losses can vary from approximately two percent to 20 percent. Table 1 shows the types of losses for an induction motor.

Table 1. Types of Losses in an Induction Motor (BEE India, 2004)

Type of loss	Percentage of total loss (100%)
Fixed loss or core loss	25
Variable loss: stator I^2R loss	34
Variable loss: rotor I^2R loss	21
Friction & rewinding loss	15
Stray load loss	5

The efficiency of a motor can be defined as "the ratio of a motor's useful power output to its total power output."

Factors that influence motor efficiency include:
- Age. New motors are more efficient
- Capacity. As with most equipment, motor efficiency increases with the rated capacity
- Speed. Higher speed motors are usually more efficient
- Type. For example, squirrel cage motors are normally more efficient than slip-ring motors
- Temperature. Totally-enclosed fan-cooled (TEFC) motors are more efficient than screen-protected drip-proof (SPDP) motors
- Rewinding of motors can result in reduced efficiency
- Load, as described below

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[5] This section is based on the 16-page fact sheet "Determining Electric Motor Load and Efficiency" developed by the US DOE under the Motor Challenge program. It is recommended to consult this fact sheet for more detailed information.

There is a clear link between the motor’s efficiency and the load. Manufacturers design motors to operate at a 50-100% load and to be most efficient at a 75% load. But once the load drops below 50% the efficiency decreases rapidly as shown in Figure 11. Operating motors below 50% of rated loads has a similar, but less significant, impact on the power factor. High motor efficiencies and power factor close to 1 are desirable for an efficient operation and for keeping costs down of the entire plant and not just the motor.

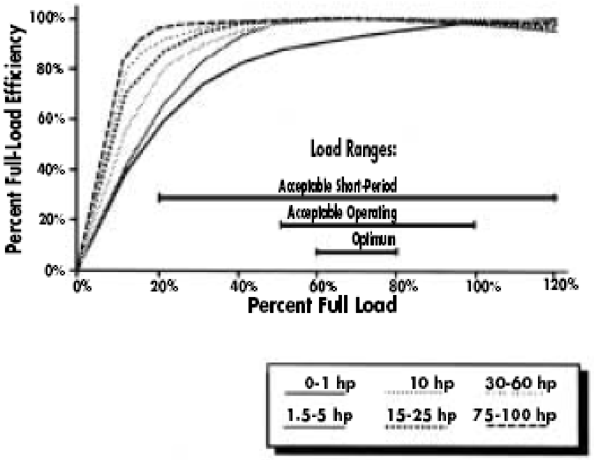

Figure 11. Motor Part-load Efficiency (as function of % full-load efficiency) (US DOE)

For this reason, it is useful to determine both the load and efficiency when assessing a motor’s performance. In most countries it is a requirement for manufacturers to display the full-load efficiency on the motor’s nameplate. However, when a motor has been in operation for a long time, it is often not possible to determine its efficiency because nameplates of motors are often lost or painted over.

To measure the motor’s efficiency, it must be disconnected from the load and taken to a test bench for a series of tests. The results of these tests are then compared with the standard motor performance curves which are provided by the manufacturer.

In case it is not possible to disconnect the motor from the load, an approximate efficiency value can be obtained from tables with typical motor efficiency values. The US DOE fact sheet (www1.eere.energy.gov/industry/bestpractices/pdfs/10097517.pdf) provides tables with typical motor efficiency values for standard motors that can be used if the manufacturer is unable to give these. Efficiency values are provided for:

- 900, 1200, 1800 and 3600 rpm standard efficiency motors
- Motors sized between 10 to 300 HP
- Two types of motors: open drip-proof motors (ODP) and totally enclosed fan-cooled motors (TEFC)
- Load levels of 25%, 50%, 75% and 100%.

The fact sheet also explains three categories of more sophisticated methods to assess a motor's efficiency: special devices, software methods, and analytical methods.

Alternatively, a motor survey can be carried out to determine the load, which also gives an indication of the performance of the motor. This is explained in the next section.

3.2 Motor load

3.2.1 Why assess motor load

Because the efficiency of a motor is difficult to assess under normal operating conditions, the motor load can be measured as an indicator of the motor's efficiency. As loading increases, the power factor and the motor efficiency increase to an optimum value at around full load.

3.2.2 How to assess the motor load

The following equation is used to determine the load:

$$\text{Load} = \frac{P_i \times \eta}{HP \times 0.7457}$$

Where,

η = Motor operating efficiency in %
HP = Nameplate rated horse power
Load = Output power as a % of rated power
P_i = Three phase power in kW

A motor load survey is carried out to measure the operating load of different motors across the plant. The results are used to identify motors that are undersized (causing motor burn out) or oversized (resulting in inefficiency). The US DOE recommends conducting a motor load survey of all motors operating over 1000 hours per year.

There are three methods to determine the motor load for motors operating individually:

- ***Input power measurement***. This method calculates the load as the ratio between the input power (measured with a power analyzer) and the rated power at 100 % loading.
- ***Line current measurement.*** The load is determined by comparing the measured amperage (measured with a power analyzer) with the rated amperage. This method is used when the power factor is not known and only the amperage value is available. It is also recommended to use this method when the percentage loading is less than 50%
- ***Slip method.*** The load is determined by comparing the slip measured when the motor is operating with the slip for the motor at full load. The accuracy of this method is limited but it can be used with the use of a tachometer only (no power analyzer is needed).

Because the input power measurement is the most common method used, only this method is described for three-phase motors.

3.2.3 Input power measurement

The load is measured in three steps.

Step 1. Determine the input power using the following equation:

$$Pi = \frac{V\ x\ I\ x\ PF\ x\ \sqrt{3}}{1000}$$

Where,

Pi = Three phase power in kW
V = RMS (root mean square) voltage, mean line to line of 3 phases
I = RMS current, mean of 3 phases
PF = Power factor as a decimal

It is noted that power analyzers give the power value directly. Industries that do not have a power analyzer can use multi-meters or tong-testers to measure voltage, current and power factor separately to calculate the input power.

Step 2. Determine the rated power by taking the nameplate value or by using the following equation:

$$P_r = hp\ x\ \frac{0.7457}{\eta_r}$$

Where,

P_r = Input power at full-rated load in kW
HP = Nameplate rated horse power
η_r = Efficiency at full-rated load (nameplate value or from motor efficiency tables)

Step 3. Determine the percentage load using the following equation:

$$Load = \frac{Pi}{P_r}\ x\ 100\%$$

Where,

Load = Output power as a % of rated power
Pi = Measured three phase power in kW
P_r = Input power at full-rated load in kW

3.2.4 Example

Question:

The following power measurement observations were made for a 45 kW three phase induction motor with 88% full load efficiency.

- V = 418 Volt
- I = 37 Amp

- PF = 0.81

Calculate the load.

Answer:

- Input Power = (1.732 x 418 x 37 x 0.81)/1000 = 21.70 kW
- % Loading = [21.70 /(45/0.88)] x 100 = 42.44 %

4. ENERGY EFFICIENCY OPPORTUNITIES

This section includes factors affecting electric motor performance.[6]

4.1 Replace standard motors with energy efficient motors

High efficiency motors have been designed specifically to increase operating efficiency compared to standard motors. Design improvements focus on reducing intrinsic motor losses and include the use of lower-loss silicon steel, a longer core (to increase active material), thicker wires (to reduce resistance), thinner laminations, smaller air gap between stator and rotor, copper instead of aluminum bars in the rotor, superior bearings and a smaller fan, etc.

Energy efficient motors cover a wide range of ratings and the full load. Efficiencies are 3% to 7% higher compared with standard motors as shown in Figure 12. Table 2 describes the improvement opportunities that are often used in the design of energy efficient motors.

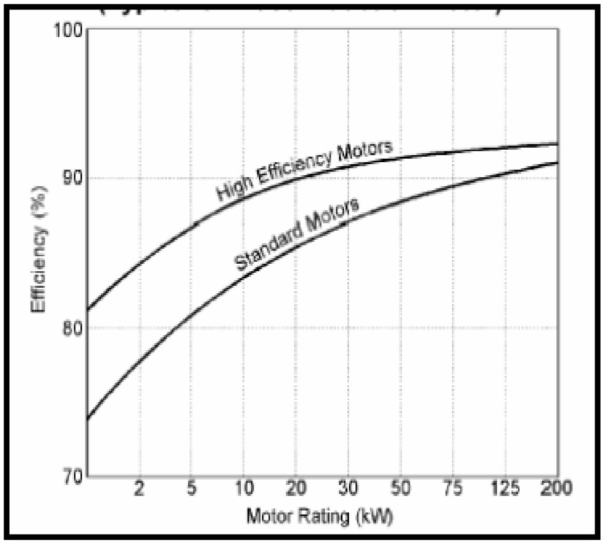

Figure 12. Comparison between high efficiency and standard motor
(Bureau of Indian Standards)

As a result of the modifications to improve performance, the costs of energy efficient motors are higher than those of standard motors. The higher cost will often be paid back rapidly through reduced operating costs, particularly in new applications or end-of-life motor replacements. But replacing existing motors that have not reached the end of their useful life

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[6] Section 4 is taken (with edits) from *Energy Efficiency in Electrical Utilities*, 2004, with permission from the Bureau of Energy Efficiency, India

with energy efficient motors may not always be financially feasible, and therefore it is recommended to only replace these with energy efficiency motors when they fail.

Table 2. Efficiency Improvement Areas used in Energy Efficient Motors
(BEE India, 2004)

Power Loss Area	Efficiency Improvement
1. Iron	▪ Use of a thinner gauge because 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 the resistance (R) of the windings and reduces losses due to current flow (I)
3 Rotor I2R	▪ Use of a larger rotor conductor bars increases the cross section, thereby lowering the conductor resistance (R) and losses due to current flow (I)
4 Friction & Winding	▪ Use of a 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

4.2 Reduce under-loading (and avoid over-sized motors)

As explained in section 3, under-loading increases motor losses and reduces motor efficiency and the power factor. Under-loading is probably the most common cause of inefficiencies for several reasons:

- Equipment manufacturers tend to use a large safety factor when selecting the motor.
- Equipment is often under-utilized. For example, machine tool equipment manufacturers provide for a motor rated for the full capacity load of the equipment. In practice, the user may rarely need this full capacity, resulting in under-loaded operation most of the time.
- Large motors are selected to enable the output to be maintained at the desired level even when input voltages are abnormally low.
- Large motor are selected for applications requiring a high starting torque but where a smaller motor that is designed for high torque would have been more suitable.

The motor size should be selected based on a careful evaluation of the load. But when replacing an oversized motor with a smaller motor, it is also important to consider the potential efficiency gain. Larger motors namely have inherently higher rated efficiencies than smaller motors. Therefore, the replacement of motors operating at 60 – 70% of capacity or higher is generally not recommended. On the other hand there are no rigid rules governing motor selection and the savings potential needs to be evaluated on a case-by-case basis. For example, if a smaller motor is an energy efficient motor and the existing motor not, then the efficiency could improve.

For motors that consistently operate at loads below 40% of the rated capacity, an inexpensive and effective measure could be to operate in star mode. A change from the standard delta operation to a star operation involves re-configuring the wiring of the three phases of power input at the terminal box.

Operating in the star mode leads to a voltage reduction by factor '√3'. The motor is electrically downsized by star mode operation, but performance characteristics as a function of load remain unchanged. Thus, motors in star mode have a higher efficiency and power factor when in full-load operation than partial load operation in the delta mode.

However, motor operation in the star mode is possible only for applications where the torque-to-speed requirement is lower at reduced load. In addition, conversion to star mode should be avoided if the motor is connected to a production facility with an output that is related to the motor speed (as the motor speed reduces in star mode). For applications with high initial torque and low running torque requirements, Delta-Star starters are also available, which help to overcome high initial torque.

4.3 Sizing to variable load

Industrial motors frequently operate under varying load conditions due to process requirements. A common practice in this situation is to select a motor based on the highest anticipated load. But this makes the motor more expensive as the motor would operate at full capacity for short periods only, and it carries the risk of motor under-loading.

An alternative is to select the motor rating based on the load duration curve of a particular application. This means that the selected motor rating is slightly lower than the highest anticipated load and would occasionally overload for a short period of time. This is possible as manufacturers design motors with a service factor (usually 15% above the rated load) to ensure that running motors above the rated load once in a while will not cause significant damage.

The biggest risk is overheating of the motor, which adversely affects the motor life and efficiency and increases operating costs. A criteria in selecting the motor rating is therefore that the weighted average temperature rise over the actual operating cycle should not be greater than the temperature rise under continuous full-load operation (100%). Overheating can occur with:

- Extreme load changes, such as frequent starts / stops, or high initial loads
- Frequent and/or long periods of overloading
- Limited ability for the motor to cool down, for example at high altitudes, in hot environments or when motors are enclosed or dirty

Where loads vary substantially with time, speed control methods can be applied in addition to proper motor sizing (see section 4.8).

4.4 Improving power quality

Motor performance is affected considerably by the quality of input power, which is determined by the actual volts and frequency compared to rated values. Fluctuation in voltage and frequency much larger than the accepted values has detrimental impacts on motor performance. Table 6 presents the general effects of voltage and frequency variation on motor performance.

Voltage unbalance can be even more detrimental to motor performance and occurs when the voltages in the three phases of a three-phase motor are not equal. This is usually caused by the supply different voltages to each of the three phases. It can also result from the use of different cable sizes in the distribution system. An example of the effect of voltage unbalance on motor performance is shown in Table 7.

- The voltage of each phase in a three-phase system should be of equal magnitude, symmetrical, and separated by 120°. Phase balance should be within 1% to avoid derating of the motor and voiding of manufacturers' warranties. Several factors can affect voltage balance: single-phase loads on any one phase, different cable sizing, or faulty circuits. An unbalanced system increases distribution system losses and reduces motor efficiency.

Table 7. Effect of Voltage Unbalance in Induction Motors (BEE India, 2004)

	Example 1	Example 2	Example 3
Percentage unbalance in voltage*	0.30	2.30	5.40
Unbalance in current (%)	0.4	17.7	40.0
Increase in temperature (oC)	0	30	40

* Percent unbalance in voltage = (maximum deviation from mean voltage / mean voltage) x 100

Voltage unbalance can be minimized by:
- Balancing any single phase loads equally among all the three phases
- Segregating any single phase loads which disturb the load balance and feed them from a separate line / transformer

4.5 Rewinding

It is common practice in industry to rewind burnt-out motors. The number of rewound motors in some industries exceeds 50% of the total number of motors. Careful rewinding can sometimes maintain motor efficiency at previous levels, but in most cases results in efficiency losses. Rewinding can affect a number of factors that contribute to deteriorated motor efficiency: winding and slot design, winding material, insulation performance, and operating temperature. For example, when heat is applied to strip old windings the insulation between laminations can be damaged, thereby increasing eddy current losses. A change in the air gap may affect power factor and output torque.

However, if proper measures are taken, the motor efficiency can be maintained after rewinding, and in some cases efficiency can even be improved by changing the winding design. Using wires of greater cross section, slot size permitting, would reduce stator losses and thereby increasing efficiency. However, it is recommended to maintain the original design of the motor during the rewind, unless there are specific load-related reasons for redesign.

The impact of rewinding on motor efficiency and power factor can be easily assessed if the no-load losses of a motor are known before and after rewinding. Information of no-load losses and no-load speed can be found in documentation of motors obtained at the time of purchase. An indicator of the success of rewinding is the comparison of no load current and stator resistance per phase of a rewound motor with the original no-load current and stator resistance at the same voltage.

When rewinding motors it is important to consider the following:
- Use a firm that ISO 9000 certified or is member of an Electrical Apparatus Service Association.

- Motors less than 40 HP in size and more than 15 years old (especially previously rewound motors) often have efficiencies significantly lower than currently available energy-efficient models. It is usually best to replace them. It is almost always best to replace non-specialty motors under 15 HP.
- If the rewind cost exceeds 50% to 65% of a new energy-efficient motor price, buy the new motor. Increased reliability and efficiency should quickly recover the price premium.

4.6 Power factor correction by installing capacitors

As noted earlier, induction motors are characterized by power factors less than one, 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 often used to improve the power factor. The capacitor will not improve the power factor of the motor itself but of the starter terminals where power is generated or distributed. The benefits of power factor correction include reduced kVA demand (and hence reduced utility demand charges), reduced I^2R 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 size of capacitor depends upon the no-load reactive kVA (kVAR) drawn by the motor. This size should not exceed 90% of the no-load kVAR of the motor, because higher capacitors could result in too high voltages and motor burn-outs. The kVAR of the motor can only be determined by no-load testing of the motor. An alternative is to use typical power factors of standard motors to determine the capacitor size.

More information on the power factor and capacitors is given in the chapter *Electricity*.

4.7 Improving maintenance

Most motor cores 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 can cause deterioration in motor efficiency over time 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.

Ambient conditions can also have a detrimental effect on motor performance. For example, extreme temperatures, high dust loading, corrosive atmosphere, and humidity can impair insulation properties; mechanical stresses due to load cycling can lead to misalignment.

Appropriate maintenance is needed to maintain motor performance. A checklist of good maintenance practices would include:
- Inspect 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)
- Check 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

- Lubricate 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
- Check 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
- Ensure 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
- Provide adequate ventilation and keep motor cooling ducts clean to help dissipate heat to reduce excessive losses. The life of the insulation in the motor would also be longer: for every $10^{o}C$ increase in motor operating temperature over the recommended peak, the time before rewinding would be needed is estimated to be halved

4.8 Speed control of induction motor

Traditionally, DC motors were used when variable speed capability was desired. But because of the limitations of DC motors (as explained in section 2), AC motors are increasingly the focus for variable speed applications. Both AC synchronous and induction motors are suitable for variable speed control.

Because an induction motor is an asynchronous motor, changing the supply frequency can vary the speed. The control strategy for a particular motor will depend on a number of factors including investment cost, load reliability and any special control requirements. This requires a detailed review of the load characteristics, historical data on process flows, features required of the speed control system, the electricity tariffs and the investment costs.

The characteristics of the load (explained in section 1) are particularly important in deciding whether speed control is an option. 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.

4.8.1 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 two operating speeds and thus 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 that require limited speed control (two or four fixed speeds instead of continuously variable speed). These motors tend to be very economical as their efficiency is lower compared to single-speed motors.

4.8.2 Variable speed drives (VSDs)

Variable speed drives (VSDs) are also called inverters and can change the speed of a motor. They are available in a range several kW to 750 kW. They are designed to operate standard induction motors and can therefore be easily installed in an existing system. Inverters are often sold separately because the motor may already be in place, but can also be purchased together with a motor.

When loads vary, VSDs or two-speed motors can often reduce electrical energy consumption in centrifugal pumping and fan applications by 50% or more.

The basic drive consists of the inverter itself which converts the 50 Hz incoming power to a variable frequency and variable voltage. The variable frequency 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).

4.8.3 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 an armature and field windings. The field windings require a DC excitation for motor operation, usually with a constant level voltage from the controller. 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-generator would be mounted onto the motor to produce a speed feedback signal that is used inside the controller.

4.8.4 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 that are lifted 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.

5. OPTION CHECKLIST

This section lists the most important energy efficiency options for electric motors.

- Maintain supply voltage level with a maximum deviation of 5% from the nameplate value.
- Minimize phase unbalance within 1% to avoid derating of the motor
- Maintain high power factor by installing capacitors as close to the motor as possible
- Select proper motor size to avoid inefficiencies and poor power factor
- Ensure that the motor is loaded more than 60%
- Adopt a proper maintenance strategy for motors
- Use variable speed drives (VSD) or two-speed systems wherever applicable.
- Replace oversized, undersized and failed motors with energy efficiency motors
- Get burnt out motors rewound by a qualified expert
- Optimize transmission efficiency by proper installation and maintenance of shafts, belts, chains, and gears
- Control the ambient temperature to maximize insulation life and motor reliability, e.g. by avoiding exposure to the sun, locating them in well-ventilated areas, and keeping them clean
- Lubricate the motor according to manufacturers’ specifications and apply high-quality greases or oils to prevent contamination with dirt or water

6. WORKSHEETS

This section includes the following worksheets:

- Motor Data collection
- Motor Load Analysis

Worksheet 1. MOTOR DATA COLLECTION

No.	Motor Reference	Motor Tag No.	HT/LT	kW	Voltage	FLA (Amp)	Power Factor	Speed(RPM)	Insulation Class	Service Factor	Frame Size	Manufacturer

Worksheet 2. MOTOR LOAD ANALYSIS

No.	Motor Reference	Motor ID	Rated Power (KW)	Rated Efficiency	Actual Measured Values				% Motor Loading
					Voltage (KV)	Current (Amp)	Power Factor	Input Power (KW)	

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