Twenty Ways to Optimize Energy Efficiency in the Use of Induction Motors

Course No: M06-021
Credit: 6 PDH

A. Bhatia

CED engineering.com
PDH FOR THE PROFESSIONAL

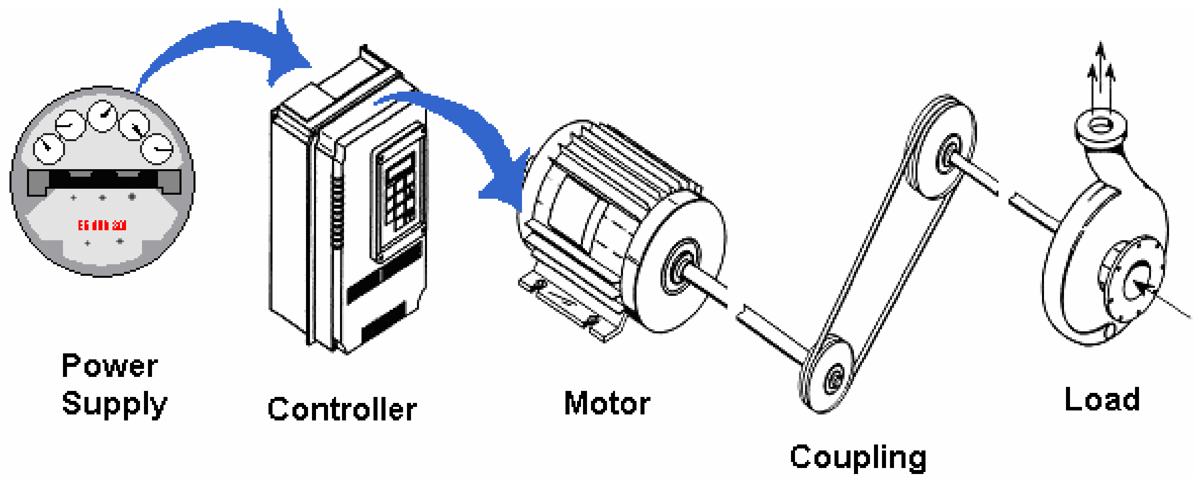
Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.com

Twenty Ways to Optimize Energy Efficiency in the Use of Induction Motors

Electric motors convert electrical energy into mechanical energy. This energy is then used to drive a fan, a compressor, a pump or another rotating or oscillating part.

A motor-driven system consists of several components: the electrical power supply, motor controls, the electric motor, and a mechanical transmission system. For example, the heating, ventilating, and air conditioning (HVAC) systems use single or three-phase electrical motors to supply mechanical energy through shafts or belts to compressors, pumps and fans.



Each component of this system can be optimized for reliability and efficiency.

This course is designed to identify opportunities to improve motor and motor-drive system efficiency. It provides 20 different strategies to guide you into the electric motor evaluation process and highlights common ways you can improve system efficiency and reliability to achieve permanent long-term electric cost reduction. The concepts range from basic power quality issues, transmission efficiencies and monitoring and maintenance. The categories provide a series of steps for checking each of your motors.

Motor Basics Overview

A motor will draw as much power and consume as much energy as it requires moving the load.

$$\text{Motor Energy} = \frac{(\text{Motor Load}) \times (\text{Operating Time})}{(\text{Motor Efficiency})}$$

and

Motor Load (hp) = $\sqrt{3} \times V \times I \times pf \times Eff / 0.746$

Where

- hp = horsepower
- V = voltage
- I = curent (amps)
- pf = power factor
- Eff. = efficiency

Efficiency expresses the energy losses inherent in the construction of the motor, and the ratio of power delivered at the shaft to power input. ‘

Power factor is a form of electrical efficiency due to voltage and current waveforms being out of phase with each other. It is the ratio of real power input (watts) to the product of the actual current and voltage (volt-amperes). Induction motors have a lagging power factor below unity.

Typically motors can be classed into two categories, alternating current (AC) type or direct current (DC) type. The basic motor principles are alike for both the AC and DC motor. Magnetism is the basis for all electric motor operation. It produces the forces necessary for the motor to run.

Not all motors are alike, and the different types have different applications and efficiencies. Because of relatively low-cost, low-maintenance, and straightforward simplicity of the three-phase, alternating-current induction motors, this makes them the preferred choice for most of the applications.

This course will focus on the fundamental principles for operation of these types of motors.

Concepts and Construction

The basic principle of operation for all motors is electromagnetism. When the electric current flows through a conductor such as a copper wire, it produces a magnetic field which causes the motion. The prime link between electricity and magnetism is motion. Insulating materials such as paper and plastics are used to separate the magnetic and electrical circuits.

Three-phase induction motors are built with two basic components: the rotor and the stator. The rotor is made up of the shaft, rotor core (a stack of steel laminations that form slots and aluminum conductors and end rings formed by either a die cast or fabrication process) and sometimes a fan. This is the rotating part of the electromagnetic circuit. A fabricated rotor core with air ducts is shown below.

The other major part is the stator. The stator consists of a laminated iron core in the shape of a hollow cylinder, with internal slots so that insulated conductor windings from each of the three phases may be inserted into them.

Insulation is inserted to line the slots, and then coils wound with many turns of wire are inserted into the slots to form a circuit.

When balanced three-phase voltage is applied to the windings of the stator, the balanced three-phase currents flows in three interconnected phase windings. These currents produce a magnetic field which results in torque to turn the rotor. *In the most common type of electric motor, AC induction, electric power is not conducted to the rotor directly, but* *receives its power inductively. The construction of induction motors are dominated by this principle.*

Three-phase current refers to a typical configuration of power distribution where three wires conduct three separate electrical phases. The current flow in the three-phase wires is offset from each other by 120 degrees of each 360-degree cycle. Since the stator windings connect to these separate phases, the magnetic field they produce rotates by virtue of their common 120-degree displacement, even though the stator itself is stationary. The current flowing in each supply conductor alternates direction along the conductor with a frequency of 60 cycles /sec (Hz), referred to as alternating current (AC).

Each of the three phases of stator winding is arranged in pairs called poles. The number of poles in the stator determines the speed at which the rotor rotates: "the greater the number of poles, the slower the rotation." This is because the circumferential distance between poles is shorter with a greater number of poles. The rotor, therefore, can move slower to "keep up" with the rotating magnetic field. The speed of the motor's magnetic field (referred to as the synchronous speed), in revolutions per minute (RPM) is calculated using the following equation:

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

where:

- N = rotational speed of stator magnetic field in RPM (synchronous speed)
- f = frequency of the stator current flow in Hz
- P = number of motor magnetic poles

Standard RPM's are as follows:

TYPICAL ACTUAL SPEED	SYNCHRONOUS SPEED	NUMBER OF POLES
3530	3600	2
1750	1800	4
1175	1200	6
880	900	8

At no-load the rotor will turn at a speed y equal to N. In order to produce torque, the rotor in an induction motor must rotate slower than the magnetic field. The difference between rotor speed and synchronous speed is called *'Slip'*; usually expressed as a percentage of synchronous speed. Therefore, the actual speed of a motor with a synchronous speed of 1,800 rpm is generally 1,750 rpm. Slip is defined by equation:

%age Slip = (Synchronous Speed – Rotor Speed) x 100 / Synchronous Speed

Thus speed of an AC motor is determined by two factors: the applied frequency and the number of poles. In most cases the number of poles is constant and the only way to vary the speed is to change the applied frequency. Changing the frequency is the primary function of an AC drive.

Types of Motor

There are several major classifications of motors in common use, each with specification characteristics that suit it to a particular application. The motor classification based on power input is either alternating current (AC) motors or the direct current (DC) motors.

Alternating Current (AC) Motor Types

AC motors can be divided into two main types: induction and synchronous.

Induction Motors

Induction Motors (3-phase) are the most widely used motors in industrial and commercial applications. Induction motors are simple because they do not require an electrical rotor connection. An additional starter circuit is required.

Induction motors fall into two sub classifications:

1) Squirrel cage motors

2) Wound rotor motors

The induction motor is generally classified by a NEMA design category.

Single phase Induction motors are used where three-phase power is not available; typically in residential and commercial applications. They are used in applications with power requirements below 1 HP. There are several classifications which describe their starting and running modes.

- Split Phase
- Capacitor Run
- Capacitor start
- Capacitor start-Capacitor run
- Shaded Pole

- Universal Motors

Synchronous Motors

Synchronous motors are special purpose motors that do not require any slip and operate at synchronous speed.

Synchronous Motors are commonly used where exact speed is required. Synchronous motors operate at synchronism with the line frequency and maintain a constant speed regardless of load without sophisticated electronic control. The two most common types of synchronous motors are reluctance and permanent magnet. The synchronous motor typically provides up to a maximum of 140% of rated torque. These designs start like an induction motor but quickly accelerate from approximately 90% sync speed to synchronous speed. When operated from an AC drive they require boost voltage to produce the required torque to synchronize quickly after power application.

Standard designs of Induction Motors based on NEMA

A motor's rotor must turn slower than the rotating magnetic field in the stator to induce an electrical current in the rotor conductor bars and thus produce torque. When the load on the motor increases, the rotor speed decreases. As the rotating magnetic field cuts the conductor bars at a higher rate, the current in the bars increases, which makes it possible for the motor to withstand the higher loading. Induction motors are standardized according to their torque characteristics (Designs A, B, C, and D).

1) *Nominal Torque, Normal Starting Current Motors (Design A)* - Design A motors have a low resistance, low inductance rotor producing low starting torque and high breakdown torque. The low resistance characteristic causes starting current to be high. It is a high efficiency design; therefore the slip is usually 3% or less.

    - Locked rotor current 6 to 10 times full load current
    - Good running efficiency & power factor
    - High pull out torque
    - Low rated slip (~ 200% full load torque)

2) *Nominal Torque, Low Starting Current Motors (Design B) - Design B* motors have a higher impedance rotor producing a slightly higher starting torque and lower current draw. NEMA Design B motors deliver a starting torque that is 150 percent of full-load or rated torque and run with a slip of 3 to 5 percent at rated load.

    - Higher reactance than Design A

- Starting current = 5 times full load current
- Starting torque, slip, efficiency are nearly the same as Design A
- Power factor & pull out torque are some what less

3) *High Torque, Low Starting Current Motors (Design C)* - Design C motors use a two-cage rotor design, and have high resistance for starting low resistance for running. This creates a high starting torque with a normal starting current and low slip. During starting, most of the current flows in the low inductance outer bars. As the rotor slip decreases, current flows more in the inner low resistance bars.

The Design C motor is usually used where breakaway loads are high at starting, but are normally run at rated full load, and are not subject to high overload demands after running speed has been reached. The slip of the Design C motor is 5% or less.

- High starting torque than either Designs A & B
- Break down torque lower than Designs A & B
- Full load torque same as Designs A & B

4) *High Slip Motors (Design D)* - Design D motors have the highest resistance rotor creating high slip, high starting torque and low starting current. Because of the high amount of slip, the speed varies dramatically with load. The slip of this type motor is approximately 5 to 8%. Motors with slip greater than 5 percent are specified for high inertia and high torque applications.

- High starting torque (=275% full load torque)
- Low starting current
- High slip
- Low efficiency

5) *High-Efficiency Motors (Design E)* - With the passage of the Energy Policy Act of 1992 (EPACT), motors were mandated to meet minimum efficiencies based on their hp and speed ratings.

Although Design B motors have become more energy efficient as a result, NEMA also added the category of Design E motors in 1994. This category allows higher inrush currents than the Design B requirements; this generally enables greater efficiencies as well. However, circuit breakers protecting the motor circuit need to be sized to take that inrush into account.

Another important detail to consider is that Design E motors may have less slip, and therefore would drive a fan or pump impeller at a slightly higher speed. This results in a flow slightly higher than the design flow, as well as a correspondingly higher torque requirement for the motor. This has the effect of overloading the motor, which shortens its life.

Direct Current (DC) Motors

DC motors are used in applications where precise speed control is required. The manner in which their windings are connected sub classifies them into three groups-

- Series
- Shunt
- Compound
- Permanent Magnet

1) Shunt Wound

A shunt motor has the field windings connected in parallel (separately) to the armature coil. The speed varies based on the mechanical load. The shunt-wound motor offers simplified control for reversing, especially for regenerative drives.

2) Series Wound

A series motor has field windings connected in series with the armature coil. Although the series wound motor offers high starting torque, it has poor speed regulation. Series-wound motors are generally used on low speed, very heavy loads.

3. Compound Wound

A compound motor has one set of field windings connected in series with the armature. Another set of field windings in connected in parallel. The compound motor will have some characteristics of both the series and shunt motors. The compound-wound motor offers a combination of good starting torque and speed stability.

4) Permanent Magnet

The permanent magnet motor has a conventional wound armature with commutator and brushes.

Permanent magnets replace the field windings. This type of motor has excellent starting torque, with speed regulation slightly less than that of the compound motor. Peak starting torque is commonly limited to 150% of rated torque to avoid demagnetizing the field poles. Typically these are low horsepower.

Armature voltage controlled DC drives are capable of providing rated current and torque at any speed between zero and the base (rated) speed of the motor. These drives use a fixed field supply and give motor characteristics as seen in Figure 1.2. The motor output horsepower is directly proportional to speed (50% horsepower at 50% speed).

Anatomy of a Speed Torque Curve

The term constant torque describes a load type where the torque requirement is constant over the speed range.

Horsepower at any given operating point can be calculated with the following equation:

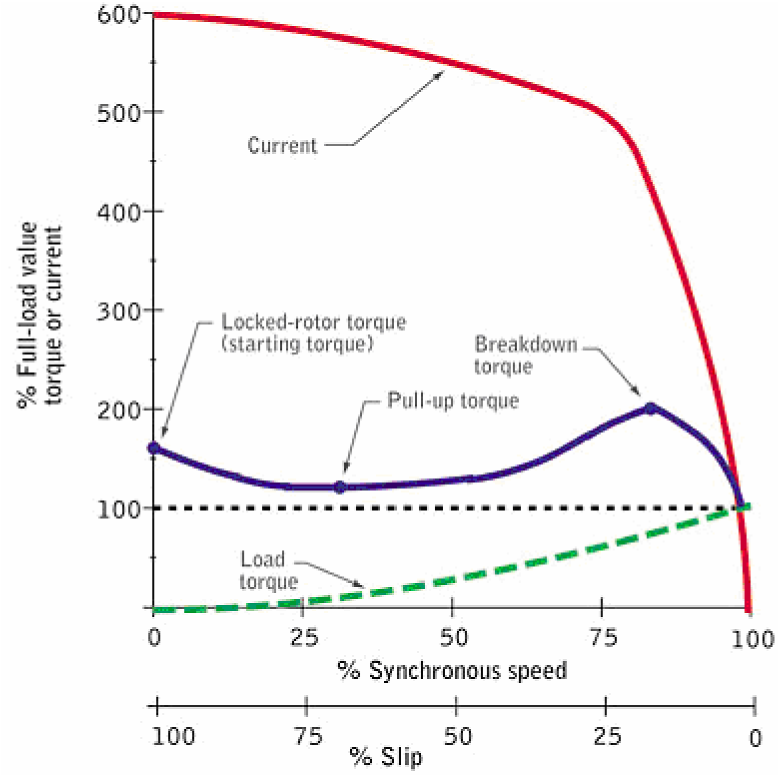
HP = Torque x Speed / 5250

where:

- Torque is measured in Lb-Ft
- Speed is measured in RPM.

As stated earlier, induction motors are standardized according to their torque characteristics (Designs A, B, C, and D). Torque is in turn characterized by **starting or locked-rotor torque**, which is the minimum torque produced by the motor at rated voltage and frequency at all angular positions of the rotor; **pull-up torque**, which is the minimum torque developed by the motor during acceleration; and **breakdown torque**, which is the maximum torque that the motor can supply before stalling.

Below is the characteristic curve in most generic form for Design-B motor at standstill (locked rotor).



As the motor begins to accelerate, the torque drops off reaching a minimum value, called Pull-up Torque, between 25-40% of synchronous speed. As acceleration continues, rotor frequency and inductive reactance decrease. The rotor flux moves more in phase with the stator flux as torque increases. Maximum Torque (or Breakdown Torque) is developed where inductive reactance becomes equal to the rotor resistance. Beyond this point the inductive reactance continues to drop off but rotor current also decreases at the same rate, reducing torque. It reaches synchronous speed and proves that if rotor and stator are at the same speed, rotor current and torque are zero. This type of curve is appropriate for starting a load such as a fan or pump, whose torque increases with speed.

Performance characteristics of motor; torque, current, and power factor all vary with the percentage of the motor's full-load speed. Generally speaking, the following can be said about a speed-torque curve when starting across the line. Starting torque is usually around 200% even though current is at 600%. This is when slip is the greatest. *(Starting torque is also called Blocked Rotor Torque, Locked Rotor Torque or Breakaway Torque.)*

Most induction motors are Design B, with Design A being the second most common. While NEMA limits for locked rotor torque for Designs A and B motors are the same, some manufacturers design their motors for different criteria. Frequently, Design A motors have higher starting current and start-up torque characteristics. In contrast to Design B motor, a Design-D motor produces a high starting torque that steadily decreases to its full-load value. This design is appropriate for a conveyor belt or other loads with a high starting torque.

The locked rotor torque and current, breakdown torque, pull-up torque and the percent slip determine the classifications for NEMA design motors.

Overloads

It is important to remember that during the starting process, a motor will draw large amount of current to satisfy torque requirements of the load. Current then steadily decreases as the motor reaches its rated speed.

If the torque required is greater than the motor's ability, it will result in a locked rotor, and the current draw will increase to the locked rotor value.

If this torque requirement is greater than the rated torque of the motor at its rated speed, but is still less than the breakdown torque, the motor must increase its slip; that is, it must slow down in order to provide it. The current will exceed the rated value, creating an overload condition.

Such a large inrush of current may cause the supply voltage to dip momentarily, affecting other equipment connected to the same lines. The stator and rotor windings could incur thermal damage if this condition persists. To prevent this, large motors will connect extra resistors to inductors in series with the stator during starting.

Extra protective devices are also required to remove the motor from the supply lines if an excessive load causes a stalled condition. For this reason, the NEC requires overload protection to interrupt current flow, typically at approximately 125% of the motor's rated full-load current. This overload protection is usually provided within the motor control device upstream of the motor, either a motor starter or variable-speed drive (VSD).

Motor Current Components

An induction motor requires both active and reactive power to operate. The active or true power, measured in kW, is consumed and produces work or heat. ‘The reactive power, expressed in kVARs, is stored and discharged in the inductive or capacitive elements of the circuit, and establishes the magnetic field within the motor that causes it to rotate. The total power or apparent power is the product of the total voltage and total current in an AC circuit and is expressed in KVA. The total power is also the vector sum of the active and reactive power components and the power factor is the ratio of the active to the total power.

Power factors are usually stated as "leading" or "lagging" to show the sign of the phase angle.

- With a purely resistive load, current and voltage changes polarity in step and the power factor will be 1. Electrical energy flows in a single direction across the network in each cycle.
- Inductive loads - transformers, motors and wound coils - consume reactive power with current waveform lagging the voltage.
- Capacitive loads - capacitor banks or buried cables - generate reactive power with current phase leading the voltage.

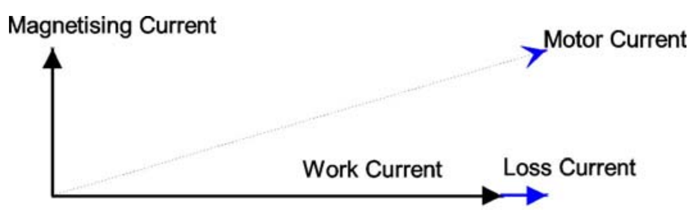
An induction motor draws current from the supply that is made up of resistive components and inductive components.

The resistive components are:

1. Load current
2. Loss current

The inductive components are:

1. Leakage reactance
2. Magnetizing current



Motor Current Components

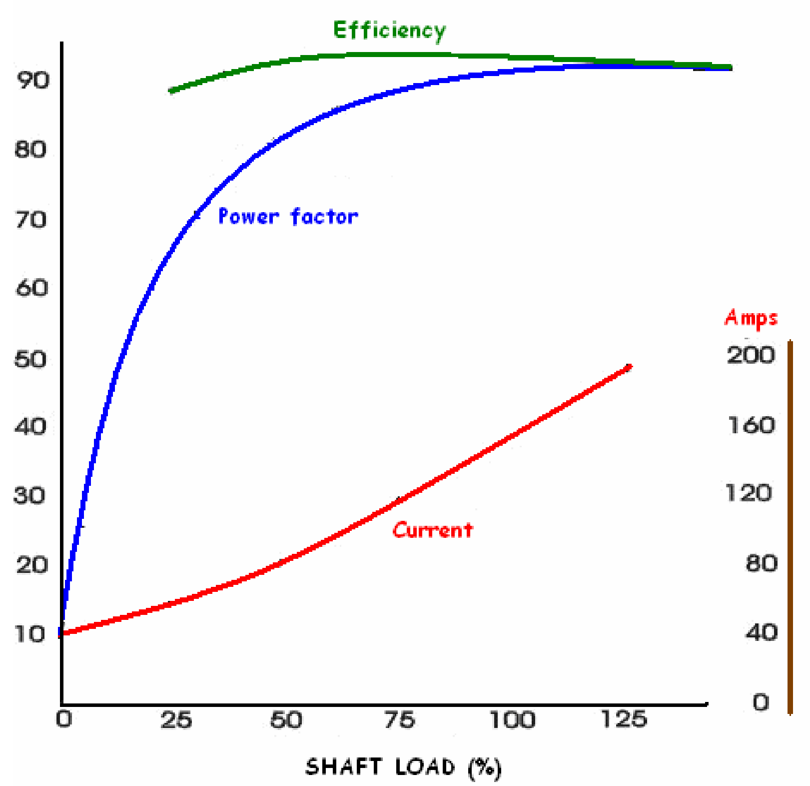
The current due to the leakage reactance is dependant on the total current drawn by the motor, but the magnetizing current is independent of the load on the motor. The magnetizing current is typically between 20% and 60% of the rated full load current of the motor. The magnetizing current is the current that establishes the flux in the iron and is very necessary if the motor is going to operate. The magnetizing current does not actually contribute to the actual work output of the motor. It is the catalyst that allows the motor to work property. The magnetizing current and the leakage reactance can be considered passenger components of current that will not affect the power drawn by the motor, but will contribute to the power dissipated in the supply and distribution system.

Take for example a motor with a current draw of 100 Amps and a Power Factor of 0.75. The resistive component of the current is 75 Amps and this is what the KWh meter measures.

The higher current will result in an increase in the distribution losses of (100 x 100) / (75 x 75) = 1.777 or a 78% increase in the supply losses.

In the interest of reducing the losses in the distribution system, power factor correction is added to neutralize a portion of the magnetizing current of the motor. Typically, the corrected power factor will be 0.92 - 0.95. Power factor correction is achieved by the addition of capacitors in parallel with the connected motor circuits and can be applied at the starter, or applied at the switchboard or distribution panel.

Figure below shows the relationship of motor efficiency, power factor, and current drawn in relation to the shaft loading. Clearly the drop in power factor is significant with low motor loading.



PART 2 MOTOR LOSSES

Motor losses may be categorized as those which are fixed, occurring whenever the motor is energized, and remaining constant for a given voltage and speed; and those which are variable and increase with motor load.

Fixed losses are assumed to be constant at all conditions of motor loading from no load to full rated load. This is not exactly true, but it is nearly so, and little significant error is created by this approximation. Fixed losses include magnetic core losses (hysteresis and eddy current) and mechanical friction losses (bearing friction, brush friction, and air friction or windage).

Variable Losses are those that vary with the load on the motor and thus with the motor current. These losses increase as the load on the motor, and therefore as the current drawn by the motor, increase. They are primarily the power lost in the resistance of the motor windings and are often called copper losses, or I^2R losses.

Variable losses also include stray load losses such as minor variations in fixed losses with load and speed and other small miscellaneous losses. Variable losses are approximately proportional to the square of the motor load current.

Internal Losses and Method of Reducing Them

Motor energy losses can be segregated into five major areas, each of which is influenced by design and construction decisions. One design consideration, for example, is the size of the air gap between the rotor and the stator. Large air gaps tend to maximize efficiency at the expense of power factor, whereas small air gaps slightly compromise efficiency while significantly improving power factor. These losses are described below.

1. Stator power Losses (Iron & Copper loss)
2. Rotor power Losses (Iron & Copper loss)
3. Magnetic core Loss (Hysteresis & Eddy current)
4. Friction and windage
5. Stray load losses

All these losses add up to the total loss of the induction motor. Frictional loss and windage loss are constant, independent of shaft load, and are typically very small. The major losses are iron loss and copper loss. The iron loss is essentially constant and independent of shaft load, while the copper loss is an I^2R loss which is shaft load dependent. The iron loss is voltage dependent and will reduce with reducing voltage.

1) Stator Power Losses

Stator losses appear as heating due to current flow (I) through the resistance (R) of the stator winding. This is commonly referred to as an I^2R loss.

Stator Losses = $I^2 R$

Where

- I = Stator Current
- R = Stator Resistance

Stator current, I = Output hp * .746 / (√3 * Voltage * Power factor * Efficiency)

I^2R losses can be reduced by modifying the stator slot design or by decreasing insulation thickness to increase the volume of wire in the stator. For a given motor, the winding resistance is inversely proportional to the weight of copper conductors used in the stator winding. Therefore, stator losses could also be reduced by using additional conductor material in the stator winding.

2) Rotor Losses

Rotor losses consist of copper and iron losses. During normal operation of induction motors, since the slip is very small, the magnetic reversals in the rotor core are only in the order of one or two per second. The iron losses caused by this are very small and hence can be neglected.

Rotor Losses = Copper losses = input power to rotor – output power of rotor

= Tw1 – Tw2 = T (w1 – w2)

Where

- T = Torque on motor
- w1 = Angular velocity of stator field
- w2 = Angular velocity of rotor

But Slip (S) is given by:

S = (w1 – w2) / w1 = T (w1 – w2)/ Tw1

Thus,

Rotor Losses [T (w1 –w2)] = S x Tw1

Or

Rotor losses = Slip x input power to rotor

The rotor loss is a function of slip. Rotor losses can be reduced by increasing the size of the conductive bars and end rings to produce a lower resistance, or by reducing the electrical current.

3) Magnetic Core Losses

Core loss represents energy required to magnetize the core material (hysteresis) and includes losses due to creation of eddy currents that flow in the core. Core loss is a crucial parameter used to determine the performance of a material in an electromagnetic device. Core losses could be reduced by:

1) Increasing the length of magnetic structure and thus decreasing flux density
2) Using thinner laminations in the magnetic structure and thus reducing eddy current losses
3) Using silicon grades of electrical steel (in general higher the silicon content (up to 4%), the lesser is the magnetic losses).

The table below shows the magnetic losses for various grades.

		Magnetic Loss (w/lb at 15 kg)		
Steel Grade	**Thickness**	**Hysteresis**	**Eddy Current Loss**	**Total**
Non-silicon	0.018	1.33	1.42	2.75
	0.024	1.33	2.30	3.63
M-45	0.0185	1.32	0.72	2.02
	0.025	1.32	1.11	2.43
M-36	0.0185	1.19	0.64	1.83
	0.025	1.19	0.87	2.06

Source: US Steel Corporation, Pittsburg

4) Friction and Windage Losses

Windage and friction losses occur due to bearing friction and air resistance. Improved bearing selection, air-flow, and fan design are employed to reduce these losses. In an energy-efficient motor, loss minimization results in reduced cooling requirements so a smaller fan can be used. Both core losses and windage/friction losses are independent of motor load.

5) Stray Load Losses

Stray load losses are the result of leakage fluxes induced by load currents. Both stray load losses and stator and rotor I^2R losses increase with motor load. Some of the influencing factors are winding design ratio of air gap length to rotor slot openings, air gap flux density, etc. By careful design, some of the elements contributing to stray losses can be minimized.

In a very general sense, the average loss distribution for NEMA – Design B Motors is tabulated below:

Motor Loss Categories

No Load Losses	Typical Losses %	Factors Affecting these Losses
Magnetic Core Loss	15 - 20%	Type and quantity of magnetic material
Friction and Windage	5 - 15%	Selection /design of fans and bearings
Motor Operating under Load	**Typical Losses %**	**Factors Affecting these Losses**
Stator Power Loss, I^2R	25 - 40%	Stator conductor size
Rotor Power Loss, I^2R	15 - 25%	Rotor conductor size
Stray load loss	10 – 20%	Manufacturing and design methods

The loss distribution table indicates that major losses are confined to the stator and rotor. This loss can be reduced by increasing the conductor material in both stator and rotor windings.

For a motor with 90% full load efficiency, the copper loss and iron loss are of the same order of magnitude, with the iron loss typically amounting to 25% to 40% of the total losses in the motor at full load. For an induction motor with a full load efficiency of 90%, we could expect the iron loss to be between 2.5% and 4% of the motor rating. If by reducing the voltage, we are able to halve the iron loss, then this would equate to an iron loss saving of 1-2% of the rated motor load. If the motor is operating under open shaft condition, then the power consumed is primarily iron loss and we could expect to achieve a saving of 30% to 60% of the energy consumed under open shaft conditions. It must be reiterated however, that this is only about 1% to 2% of the rated motor load.

Motor Efficiency is the output of the motor divided by the electrical input to the motor; usually expressed as a percentage power or work output which is input less losses.

Efficiency (%) = Watts output x 100 / Watts input

= 746 x HP x 100 / (V x I x PF)

= (Input – Losses) x 100 / Input

= Output x 100 / (Output + losses)

Energy Conservation in Motors

The following formulas can be used to find out % Loading, Motor Losses and Efficiency of the motor:

Load Factor

Load factor is defined as the ratio expressed as a percentage of the average load to the actual maximum load during a selected interval of time.

Load Factor = Average Demand X 100/ Maximum Demand

In context of motors, the % Loading of Motor = Actual KW Consumption x 100 / Rating of Motor (KW)

The following method has been used to find out motor losses and efficiency

1) Take Designed Efficiency at full load and at 75 % to calculate losses at full load and at 75% load. This data can be obtained from the manufacturer.
   a) Losses at Full Load (L100) = KW of motor x [(1/full load efficiency) - 1]
   b) Losses at 75 % Load (L75)= KW of motor x [(1/75% load efficiency) - 1]
2) Determine variable losses and fixed losses in present % loading of the motor by solving below two equations:
   a) L100 = (%Load) x (%Load) x A + B
   b) L75 = (%Load) x (%Load) x A + B

Where:

- A = Variable Losses (KW)
- B = Fixed Losses (KW)

Total Losses (neglecting windage and frictional losses) = A + B

External Energy Loss in the Usage of Induction Motors

Besides internal losses inherent to the motors, there are external losses that occur at the utilizing end. Generally motors are used for driving fans, blowers, pumps, conveyers etc. There are numerous opportunities to reduce energy consumption by proper selection of the driven equipment. The major energy reduction possibilities lie in the analysis of driven equipment and process conditions. This analysis should focus on getting answers to the following questions:

1) What are the losses in the process connected to the driven equipment?
2) Is there any energy efficient technology available to replace the present system?
3) What are the current developments pertaining to the process? What are the benefits? Can they be tried?

PART 3 OPTIMIZING YOUR MOTOR DRIVE SYSTEM

This section highlights the energy conservation measures you can adopt to improve induction motor system efficiency and reliability.

Some of these steps require the one-time involvement of an electrical engineer or technician. Others are implemented when motors fail or major capital changes are made in the facility.

QUALITY OF ELECTRIC SUPPLY

Quality plays a vital role in utility. Motors are designed to operate using power with a frequency of 60 hertz (in US) and a sinusoidal wave form. Using power with distorted wave forms will degrade motor efficiency. The parameters like voltage and frequency must be maintained to the best possible values, which may ultimately contribute to the efficient running of electrical equipment and to keep losses to minimum.

Let us take one parameter for example, the voltage, and its influence on an Induction Motor.

Overvoltage

As the voltage is increased, the magnetizing current increases by an exponential function. At about 10 to 15 percent over voltage both efficiency and power factor significantly decrease while the full-load slip decreases. The starting current, starting torque, and breakdown torque all significantly increase with over voltage conditions.

Under Voltage

If a motor is operated at reduced voltage, even within the allowable 10 percent limit, the motor will draw increased current to produce the torque requirements imposed by the load. This causes an increase in both stator and rotor I^2R losses. Low voltages can also prevent the motor from developing an adequate starting torque.

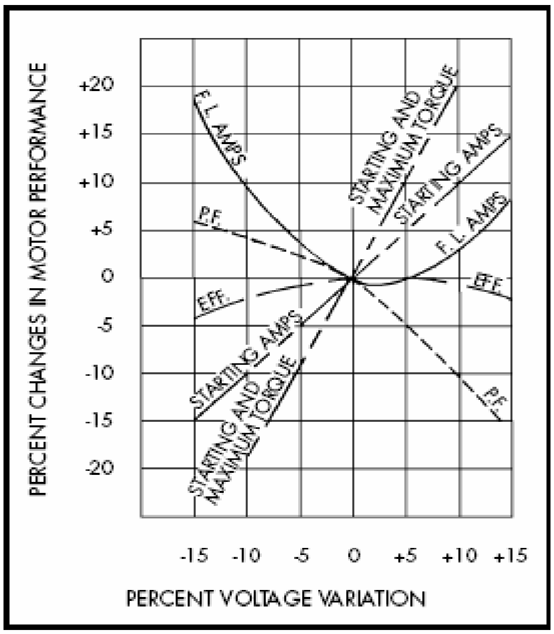
The table below provides the fact that low voltages entail in energy loss because of low torque, less speed, more current, and finally low-efficiency.

Induction Motor Performance Variations w/ Supply Voltage

Motor Characteristics	Supply Voltage as % of Normal Voltage		
	90%	100%	110%
Starting Torque	81%	100%	121%

Motor Characteristics	**Supply Voltage as % of Normal Voltage**		
	90%	**100%**	**110%**
Total Current	111%	100%	93%
Speed	98.5%	100%	101%
Efficiency	Decrease	100%	Decrease

The voltage unbalance has significant impact on other motor characteristics, which is depicted in the figure below:



Voltage Variation Effect on Motor Performance

1) MAINTAIN VOLTAGE LEVELS

As a rule of thumb, the voltage unbalance of 2.5% will result in 1.5% loss in motor efficiency. Therefore, on a 100-hp motor rated at 93% efficiency and operating for 8,000 hours per year, a voltage unbalance of 2.5% will result in 100 hp x 0.746 kW/hp x 8,000 hrs/yr x (100/93 - 100/94.5) = 10,145 kWh of extra energy. This amounts to $608 per annum on energy pricing of $0.06 per kWh. Overall consumption may be much higher because of numerous motors in a facility.

Voltage at the motor should be kept as close to the nameplate value as possible, with a maximum deviation of 5%. Although motors are designed to operate within 10% of nameplate voltage, large variations significantly reduce efficiency, power factor, and service life. When operating at less than 95% of design voltage, motors typically lose 2 to 4 points of efficiency, and service temperatures increase up to 20°F, greatly reducing insulation life. Running a motor above its design voltage also reduces power factor and efficiency. Because voltage decreases with distance from the step-down transformer, all voltage measurements should be taken at the motor terminal box.

The system voltage can also be modified by:

- Adjusting the transformer tap settings;
- Installing automatic tap-changing equipment if system loads vary considerably over the course of a day;
- Installing power factor correction capacitors that raise the system voltage while correcting for power factor;

Since motor efficiency and operating life are degraded by voltage variations, only motors with compatible voltage nameplate ratings should be specified for a system.

---

2) ELIMINATE PHASE UNBALANCE

A voltage imbalance occurs when there are unequal voltages on the lines to a polyphase induction motor. This imbalance in phase voltages also causes the line currents to be out of balance. The magnitude of current unbalance may be 6 to 10 times as large as the voltage unbalance. An energy audit data on an extrusion machine of manufacturing facility indicates that a 100-hp motor operating at full load with 2.5% voltage unbalance, the line currents were unbalanced by 27.7%. The unbalanced currents cause torque pulsations, vibrations, increased mechanical stress on the motor, and overheating of one, and possibly two phase windings. This results in a dramatic increase in motor losses and heat generation, which will decrease the efficiency of the motor and shorten its life. As a rule of thumb, percent additional temperature rise due to voltage imbalance is estimated by:

Percent additional temperature rise = 2 x (% voltage unbalance)^2.

For example, a motor with a 100°C temperature rise would experience a temperature increase of 8°C when operated under conditions of 2% voltage unbalance. Winding insulation life is reduced by one-half for each 10°C increase in operating temperature.

Voltage imbalance is defined by NEMA as 100 times the maximum deviation of the line voltage from the average voltage on a three-phase system divided by the average voltage. For example, if the measured line voltages are 462, 463, and 455 volts, the average is 460 volts. The voltage imbalance is:

Imbalance = [largest voltage difference from average] x 100 / [Average Voltage]

$$\left[\frac{460 - 455}{460}\right] \times 100\% = 1.1\%.$$

A voltage unbalance of only 3.5 percent can increase motor losses by approximately 20 percent. Imbalances over 5 percent indicate a serious problem. Imbalances over 1 percent require derating of the motor, and will void most manufacturers' warranties. Per NEMA MG1-14.35, a voltage imbalance of 2.5 percent would require a derate factor of 0.925 to be applied to the motor rating.

Several factors that can affect voltage balance include:

1) Loose or dirty connections, bad splices, unbalanced loads, transformer taps
2) Unevenly distributed single-phase loads on the same power system
3) Faulty operation of power factor correction equipment
4) Unbalanced or unstable utility supply
5) Unbalanced transformer bank supplying a three-phase load that is too large for the bank
6) Different cable sizing
7) Unidentified single-phase to ground faults
8) Faulty circuits (an open circuit on the distribution system primary)

The following steps will ensure proper system balancing:

- Check your electrical system single-line diagram to verify that single-phase loads are uniformly distributed;
- Regularly monitor voltages on all phases to verify that a minimum variation exists;
- Install required ground fault indicators; and
- Perform annual thermographic inspections

---

3) MAINTAIN HIGH POWER FACTOR

Power factor is a measure of how effectively electrical power is being used. A high power factor (approaching unity) indicates efficient use of the electrical distribution system while a low power factor indicates poor use of the system.

Induction motors typically have a lagging power factor. The inductive portion creates no use of electrical energy, but the inductance requires a current flow. The current flow causes additional loading on the electrical generating equipment. The electrical distribution system must carry the extra current, which results in more loss in wires carrying the energy to the load, thereby reducing the energy available to the load.

Three main detrimental effects of a low, lagging power factor are:

Direct costs of low power factor

A majority of power companies have penalties in their rates for low, lagging power factor and incentives for high power factor. Power factor may be billed as one of or combination of, the following:

1) A penalty for power factor below and a credit for power factor above a predetermined value,
2) An increasing penalty for decreasing power factor,
3) A charge on monthly KVAR Hours,
4) KVA demand: A straight charge is made for the maximum value of KVA used during the month. Included in this charge is a charge for KVAR since KVAR increase the amount of KVA.

Indirect Costs

5) Low power factor cuts down system loadability. That is, it reduces the capacity of the power system to carry kilowatts. The capacity of all apparatus is determined by the KVA it can carry. Hence, larger generators, transmission lines, transformers, feeders and switches must be provided for each kilowatt of load when power factor is low than when it is high. Thus, capital investment per kilowatt of load is higher.
6) Low power factor means more current per kilowatt. Hence, each kilowatt must carry a higher burden of line losses, making it cost more to transport each kilowatt of power.
7) Low power factor may depress the voltage, reducing the output of practically all electrical apparatus.
8) Low power factor reduces the efficiency of the electrical distribution network both within and outside of your facility. The low power factor:
    - Reduces generator capacity and efficiency;
    - Increases the voltage drop across transformers so that voltage regulation of the transformer is impaired; and
    - Makes larger distribution lines necessary and causes a greater voltage drop in these lines.

Power factor is adversely affected by low loading of motors. There are frequent industrial and batch production facilities, wherein the motor load varies significantly during operation. For example, rolling mills or crushers have varying and fluctuating loads. For such applications, it is advantageous to employ automatic power factor demand controllers, which auto-switch the capacitors to maintain a preset power factor value.

Power factor correction can be made in two ways:

1) Reduce the amount of reactive energy

   a. Avoid supplying equipment with voltage in excess of the rated voltage;

   b. Use the highest-speed motor that an application can accommodate. Two-pole (nominal 3,600 rpm) motors have the highest power factors (power factor decreases as the number of poles increases);

   c. Low power factor results when motors are operated at less than full load. This often occurs in cyclic processes (such as circular saws, ball mills, conveyors, compressors, grinders, extruders, or punch presses) where motors are sized for the heaviest load. In these applications, power factor varies from moment to moment. Examples of situations include a surface grinder performing a light cut, an unloaded air compressor, and a circular saw spinning without cutting.

2) Compensate artificially for the consumption of reactive energy with power factor capacitors. Power capacitors serve as leading reactive current generators and counter the lagging reactive current in the system. By providing reactive current, they reduce the total amount of current your system must draw from the utility. In practice, two type of equipment are available for power factor correction:

   a. *Capacitors:* Power factor correction is achieved by the addition of capacitors in parallel with the connected motor circuits and can be applied at the starter, or applied at the switchboard or distribution panel. Connecting capacitors at each starter and being controlled by each starter is known as "Static Power Factor Correction" while connecting capacitors at a distribution board and being controlled independently by the individual starters is known as "Bulk Correction".

   b. *Rotary Equipment:* Phase advancers, synchronous motors and synchronous condensers. A synchronous motor usually runs at unity or leading power factor. A synchronous motor with over-excited field (synchronous condenser) will act as a capacitor. If a synchronous motor is run with a leading power factor, it can perform useful work and correct power factor at the same time. What this means is that the exciting current, instead of flowing back and forth from induction motor to power utility company, flows back and forth between the induction and synchronous motors.

One should aim to establish and target a power factor of around 0.95 to 0.98.

Note that when the power factor is unity, the current is in phase with the voltage and the circuit is resistive.

Other Suggested Actions to Improve Power Factor

1) Regularly monitor voltages at the motor terminals to verify that voltage unbalance is maintained below 1%.

2) Check your electrical system single line diagrams to verify that single-phase loads are uniformly distributed.

3) Install ground fault indicators as required and perform annual thermographic inspections. Another indicator that voltage unbalances may be a problem is 120 Hz vibration. A finding of 120 Hz vibration should prompt an immediate check of voltage balance.

4) Provide rightly sized motors: With over sizing, the motor shall be operated at part load all the time. This shall result in low power factors entailing the higher capital expenditure not only on the motor itself but also the increased capital cost of matching switchgear and wiring. The operating costs and the cost of providing power factor correction equipment will be higher.

5) Provide power factor controllers to improve the overall power factor.

6) Select Efficient Transformers: Install efficient and properly sized step-down transformers. Older, underloaded, or overloaded transformers are often inefficient.

7) Identify and Eliminate Distribution System Losses: Regularly check for bad connections, poor grounding, and shorts to ground. Such problems are common sources of energy losses, cause for potential hazards as well as reduce system reliability. A number of specialized firms can search for such problems in your facility using electrical monitoring equipment and infrared cameras.

8) Minimize Distribution System Resistance: Power cables that supply motors running near full load for many hours should be oversized in new construction or during rewiring. This practice minimizes line losses and voltage drops.

4) USE ENERGY EFFICIENT MOTORS

The only way to improve motor efficiency is to reduce motor losses. Even though standard motors operate efficiently, with typical efficiencies ranging between 83 and 92 percent, energy-efficient motors perform significantly better. An efficiency gain from only 92 to 94 percent results in a 25 percent reduction in losses. Since motor losses result in heat rejected into the atmosphere, reducing losses can significantly reduce cooling loads on an industrial facility's air conditioning system.

What is an energy-efficient motor?

There is often some confusion in the definition of energy-efficient motors. Efficiency descriptions such as "extra," "high," "plus," "premium," "super," and "ultra," are manufacturers' descriptions that do not have uniform meanings. However, "energy-efficient" is the only term that has an established definition. This definition was set by the National Electrical Manufacturers Association (NEMA) and is used in the Energy Policy Act of 1992 (EPACT). To be considered energy efficient, a motor's performance must equal or exceed the nominal full-load efficiency values provided by NEMA, Table 12-10 of NEMA MG-1-1993, Rev1. [NEMA Premium™ motors meet other NEMA standards and have even higher average efficiencies than average energy-efficient motors.]

The Energy Policy Act of 1992 (EPACT) requires that most general purpose induction motors manufactured for sale in the United States after October 24, 1997, meet new minimum efficiency standards. The Act applies to 1- through 200-hp general-purpose, T-frame, single-speed, foot-mounted, continuous-rated, polyphase, squirrel-cage, induction motors conforming to NEMA Designs A and B. Covered motors are designed to operate with 230 or 460 volt power supplies, have open or “closed” (totally enclosed) enclosures, and operate at speeds of 1200, 1800, or 3600 rpm.

Many manufacturers currently offer products that exceed the EPACT minimum efficiency levels. A non-profit coalition of utilities, public interest groups and government officials, known as the Consortium of Energy Efficiency (CEE), has developed a new set of efficiency levels for these motors exceeding the EPACT criteria.

Efficiency Levels for Open Drip-Proof (ODP) Motors

Motor hp	EPAct Energy-Efficient	CEE Premium Efficiency	EPAct Energy-Efficient	CEE Premium Efficiency	EPAct Energy-Efficient	CEE Premium Efficiency
	1200 RPM		1800 RPM		3600 RPM	
1	80.0	82.5	82.5	85.5	N/A	80.0
1.5	84.0	86.5	84.0	86.5	82.5	85.5
2	85.5	87.5	84.0	86.5	84.0	86.5
3	86.5	89.5	86.5	89.5	84.0	86.5
5	87.5	89.5	87.5	89.5	85.5	89.5
7.5	88.5	91.7	88.5	91.0	87.5	89.5
10	90.2	91.7	89.5	91.7	88.5	90.2
15	90.2	92.4	91.0	93.0	89.5	91.0
20	91.0	92.4	91.0	93.0	90.2	92.4
25	91.7	93.0	91.7	93.6	91.0	93.0
30	92.4	93.6	92.4	94.1	91.0	93.0
40	93.0	94.1	93.0	94.1	91.7	93.6
50	93.0	94.1	93.0	94.5	92.4	93.6
60	93.6	95.0	93.6	95.0	93.0	94.1
75	93.6	95.0	94.1	95.0	93.0	94.5
100	94.1	95.0	94.1	95.4	93.0	94.5
125	94.1	95.4	94.5	95.4	93.6	95.0
150	94.5	95.8	95.0	95.8	93.6	95.4
200	94.5	95.4	95.0	95.8	94.5	95.4

Efficiency Levels for Totally Enclosed Fan-Cooled (TEFC) Motors

Motor hp	EPAct Energy-Efficient	CEE Premium Efficiency	EPAct Energy-Efficient	CEE Premium Efficiency	EPAct Energy-Efficient	CEE Premium Efficiency
	1200 RPM		1800 RPM		3600 RPM	
1	80.0	82.5	82.5	85.5	75.5	78.5
1.5	85.5	87.5	84.0	86.5	82.5	85.5
2	86.5	88.5	84.0	86.5	84.0	86.5
3	87.5	89.5	87.5	89.5	85.5	88.5

Motor hp	**EPAct Energy-Efficient**	**CEE Premium Efficiency**	**EPAct Energy-Efficient**	**CEE Premium Efficiency**	**EPAct Energy-Efficient**	**CEE Premium Efficiency**
	1200 RPM		1800 RPM		3600 RPM	
5	87.5	89.5	87.5	89.5	87.5	89.5
7.5	89.5	91.7	89.5	91.7	88.5	91.0
10	89.5	91.7	89.5	91.7	89.5	91.7
15	90.2	92.4	91.0	92.4	90.2	91.7
20	90.2	92.4	91.0	93.0	90.2	92.4
25	91.7	93.0	92.4	93.6	91.0	93.0
30	91.7	93.6	92.4	93.6	91.0	93.0
40	93.0	94.1	93.0	94.1	91.7	93.6
50	93.0	94.1	93.0	94.5	92.4	94.1
60	93.6	94.5	93.6	95.0	93.0	94.1
75	93.6	95.0	94.1	95.4	93.0	94.5
100	94.1	95.4	94.5	95.4	93.6	95.0
125	94.1	95.4	94.5	95.4	94.5	95.4
150	95.0	95.8	95.0	95.8	94.5	95.4
200	95.0	95.8	95.0	96.2	95.0	95.8

When comparing motor efficiencies, be sure to use a consistent measure of efficiency. In the United States, the recognized motor efficiency testing protocol is the Institute of Electrical and Electronics Engineers (IEEE) 112 Method B, which uses a dynamometer to measure motor output under load.

Different testing methods yield significantly different results as used in other countries. The NEMA nameplate labeling system for Design A and B motors in the 1- to 500-hp range uses bands of efficiency values based on IEEE 112 testing.

Energy-Efficient Motors v/s Conventional Standard Motors

Considerable variation exists between the performance of standard and energy-efficient motors. Improved design, materials, and manufacturing techniques enable energy-efficient motors to accomplish more work per unit of electricity consumed. Some of the noted measures are:

1) Using steel with superior magnetic properties

2) Reducing the air gaps between rotors and stators

3) Higher quality and thinner laminations in the stators

4) Increasing the thickness of the conductors

5) Reducing fan losses and using efficient cooling systems

6) Using better insulation materials

As a result of these measures, energy-efficient motors use considerably less electrical power than old standard-efficiency motors to produce the same shaft power.

Why Choose Energy-Efficient Motors?

In comparison to standard motors, high efficiency motors are approximately 20% more expensive; however the increased costs are justified with an attractive payback period in most of the cases.

The following table provides a comparison of the operating costs for a 50 HP motor over an average lifespan of 20 years.

Incentives for purchasing high efficiency motors

Basis for Comparison	Standard Motor	High Efficiency Motor	Difference	Remarks
Purchase Price ($)	28,540	34,248	5,708	20% greater
Efficiency Level (%)	89.5	93.6	4.1	4.5% greater
Wasted Energy Consumption (%)	10.5	6.4	4.1	39% less
Annual energy costs ($)	95,785	91,586	4,199	3.3 and 2.7 times the initial costs of the motors
Annual losses attributed to waste ($)	10,061	5,862	4,199	41.7 % less
Energy costs over a 20 year span ($)	1,915,700	1,831,720	83,980	4.3 % less
Losses due to waste over a 20 year span ($)	201,220	117,240	83,980	15 times greater than the purchase price difference

When should you consider buying an energy-efficient motor?

Energy-efficient motors should be considered in the following circumstances:

1) For all new installations
2) When purchasing equipment packages, such as compressors, HVAC systems, and pumps
3) When major modifications are made to facilities or processes
4) Instead of rewinding older, standard efficiency units
5) To replace oversized and under-loaded motors
6) As part of a preventive maintenance or energy conservation program

The cost effectiveness of an energy-efficient motor in a specific situation depends on several factors, including motor price, efficiency rating, annual hours of use, energy rates, costs of installation & downtime, your firm's payback criteria, and the availability of utility rebates.

Replacing your Existing Standard Motor with Energy Efficient Motor

The decision of replacing your existing motors with energy efficient motors depends on the analysis of "how the existing installed motor compares at the average load with the energy efficient motor." The conditions which increase viability of installing energy efficient motors are as follows:

1) The average loading on the motor - motors operating at low load factors, low power factors and having fluctuating load characteristics require first attention.
2) Operational hours are high (nearly continuous)
3) Electricity tariffs-including KWh rates and maximum demand charges are high
4) Standard motor is old; number of rewinding are more and frequent
5) Existing motor is considerably oversized
6) Payback periods occur within 4 years

As a rule of thumb, an energy-efficient motor that costs up to 20% more than a standard model is typically cost effective, if used more than the number of annual hours listed in table below. Table below lists the selection criteria in terms of the minimum annual hours your motor should operate, depending on the cost of electricity (¢/kWh)

	Average Electricity Price per kWh		
Minimum Payback Criteria	**4 cents**	**6 cents**	**8 cents**
2-year	5250	3500	2600
3-year	3500	2300	1750
4-year	2600	1750	1300

For example, if electricity costs 4¢/kWh and you are replacing a motor that runs as few as 3500 annual hours, an energy-efficient model would be cost effective with a 3-year payback.

The efficiency of standard motor at less loading is low; its operating performance get reduces considerably. If the delta to star change over option is not suitable for improving the efficiency, replacement of existing standard motor with energy efficient motor could be very viable subject to meeting the above cost criteria.

The efficiency of the Energy efficient motor is almost constant at all percentage loadings. Due to its flat efficiency characteristics, it maintains efficiency almost constant at all loads. Normally, this option is suitable for the motors with rated capacity below 50 HP. The efficiencies of standard motors above 50 HP rating are almost similar to that of energy efficient motors. In many cases, though the initial cost of energy efficient motor is 15 to 20% higher than the standard motor, the simple payback period is less due to the savings.

Typical cases of motor replacement by Energy Efficient Motors have shown payback periods of between 6 months and 2.5 years, depending on whether the motor is being run continuously over the year or in shingle shift.

In addition to higher efficiencies, other advantages of buying energy-efficiency motors include:

- Longer motor life expectancy than standard or conventional motors.
- Lower operating cost
- Lower demand charge
- Lesser power factor correction
- Lower branch-circuit losses
- Lower operating temperature and reduced heat load
- Reduced HVAC demand

- Savings increase with time
- Interchangeability
- Confirmation with NEMA standards
- Cooler and quieter operation
- Longer insulation life
- Improved bearing life
- Less starting thermal stress
- Greater stall capacity
- Less susceptible to impaired ventilation
- Better buy than the old U frame motors
- Higher service factors
- Better suited for energy management systems
- Thermal margin for speed control

A word of caution with High Efficiency Motors (Inrush Current)

The use of high efficient motors can cause undesirable side effects particularly in small establishment and residential network. Because of superior materials and technology used in production of high efficient motor design, the starting current to the motor is increased due to reduced resistance in the stator and rotor circuits. In fact, energy-efficient motors may draw almost 50% more inrush current than standard-efficiency motors. The voltage drop during motor starting can cause dimming of lights or even shutdown of sensitive electronic equipment. Residential customers in particular, who are rarely knowledgeable about the higher inrush current of their efficient HVAC units, call the utilities to fix the problem because they perceive the utility-supplied power as the cause. In many cases, utilities have to significantly oversize their transformers to reduce the voltage drop.

---

5) USE INVERTER DUTY MOTORS

Motor manufacturers have responded to the ever present rising cost of electricity by offering a line of high efficiency motor designs in addition to their standard motors. Some manufacturers have gone further to offer a higher or premium efficiency design motors. The main advantage of the efficiency design motors is to reduce the losses by better design and construction techniques thus improving the overall performance and efficiency of the motor.

The term “inverter duty motor” has a slightly different meaning today than did 5 years ago. When inverter duty motors were first introduced, it meant in certain application where the load demand was constant (i.e. conveyors, compressors, positive displacement pumps, etc.), the motor had the ability to run at low speed under the same torque requirements as top speed by the addition of sufficient cooling (typically a second AC blower motor running continuously at top speed). Today’s inverter duty motors not only have the added cooling capacity (if required for constant torque applications) but also have a robust insulation system. The major ingredient is a new spike resistant or inverter duty magnetic wire capable of handling the voltage peaks and with a high reliability class of insulation. This will inherently decrease the internal heat build-up to a safe and acceptable level and offer the high efficiency.

OPTIMIZE TRASMISSION EFFICIENCY

Transmission equipment including shafts, belts, chains, and gears should be properly installed and maintained. About one-third of the electric motors in the industrial and commercial sectors use belt drives. Belt drives provide flexibility in the positioning of the motor relative to the load, and the pulleys (sheaves) of varying diameters allow the speed of the driven equipment to be increased or decreased.

V-belts: The majority of belt drives use *V-belts*. V-belts use a trapezoidal cross section to create a wedging action on the pulleys to increase friction and the belt’s power transfer capability.

With conventional V-belts the efficiency for power transmission is low as high frictional engagement exists between the lateral wedge surfaces of the belts, which cause less power transmission and hence higher power consumption for the same work to be done by the load. However, with Flat-belts, this frictional engagement is on the outer pulley diameter only.

V-belts contain higher bending cross-section and large mass which cause higher bending loss. Also, as each groove of the pulley contains individual V-belt, the tension between the belt and the pulley distributes unevenly which causes unequal wear on the belt. This leads to vibrations and noisy running and hence reduces power transmission further. The consequences could be bearing damage also.

Joined or multiple belts are specified for heavy loads. V-belt drives can have peak efficiency of 95% to 98% at the time of installation. Efficiency is also dependent on pulley size, driven torque, under or over-belting, and V-belt design and construction. Efficiency deteriorates by as much as 5% (to a nominal efficiency of 93%) over time if slippage occurs, because the belt is not periodically re-tensioned.

6) REPLACE V-BELTS WITH EFFICIENT FLAT, COGGED OR SYNCHRONOUS BELT DRIVES

A properly designed belt transmission system provides high efficiency, has low noise, does not require lubrication, and presents low maintenance requirements. However, certain types of belts are more efficient than others, offering potential energy cost savings.

The problem associated with V-belts can be solved by using energy efficient flat, cogged or synchronous belts.

With flat belts drive, the frictional engagement and disengagement is on the outer pulley diameter and not on the lateral wedge surface as in the case of the V-belt. Wear on the belt is less and hence the life of the flat belt drive is higher than V-belt.

Some of the applications where conversion of V-belts with Flat belts is much effective are compressors, milling machines, sliding lathes, rotary printing presses, stone crushers, fans, generators in hydroelectric power plants etc.

Cogged belts have slots that run perpendicular to the belt's length. The slots reduce the belt's bending resistance. Cogged belts can be used with the same pulleys as equivalently rated V-belts.

They run cooler, last longer, and have an efficiency that is about 2% higher than that of standard V-belts.

Synchronous belts (also called timing, positive-drive, or high torque drive belts) are toothed and require the installation of mating toothed-drive sprockets. Synchronous belts offer an efficiency of about 98% and maintain that efficiency over a wide load range. In contrast, V-belts have a sharp reduction in efficiency at high torque due to increasing slippage. Synchronous belts require less maintenance and re-tensioning, operate in wet and oily environments, and run slip-free. However, synchronous belts are noisy, unsuitable for shock loads, and transfer vibrations.

Replacement of V-belts with "synchronous" belts which have teeth that engage sprocket lugs on the pulley can typically save 5 to 15% of the transmitted energy.

Example

A continuously operating, 100-hp, supply-air fan motor (93% efficient) operates at an average load of 75% while consuming 527,000 kWh annually. What are the annual energy and dollar savings if a

93% efficient (E1) V-belt is replaced with a 98% efficient (E2) synchronous belt? Electricity is priced at $0.05/kWh.

Energy Savings = Annual Energy Use x (1 - E1/E2) = 527,000 kWh/year x (1 – 93/98) = 26,888 kWh/year

Annual Dollar Savings = 26,888 kWh x $0.05/kWh = $1,345

Suggested Actions

1) Consider synchronous belts for all new installations as the price premium is small due to the avoidance of conventional pulley costs. Install cogged belts where the retrofit of a synchronous belt is not cost effective.
2) Synchronous belts are the most efficient choice. However, cogged belts may be a better choice when vibration damping is needed or shock loads cause abrupt torque changes that could shear a synchronous belt's teeth. Synchronous belts also make a whirring noise that might be objectionable in some applications.
3) For centrifugal fans and pumps, which exhibit a strong relationship between operating speed and power, synchronous belt sprockets must be selected that take into account the absence of slippage. Operating costs could actually increase if slippage is reduced and a centrifugal load is driven at a slightly higher speed.
4) *For the equipment operating on gear system, helical gears are more efficient than worm gears. Use worm gears only with motors under 10 hp.*

OPTIMIZE STARTING SYSTEMS OF INDUCTION MOTORS

The common practice of starting induction motors is by direct-on-line switching for small and medium rated motors. As per the characteristics, the induction motor takes large starting current i.e. 6 times more than its full load current. The direct-on-line starting, though inexpensive to implement, brings about instability in the supply system and induces sudden mechanical forces on the drive couplings and driven members.

Star/delta starting is provided for large motors where the starting applied voltage and current are reduced by one-third. For wound rotor motor (not a cage rotor), the starting system employs resistance in the winding to improve power factor and torque. After start up, the resistance is cut out and the wound rotor motor runs as Induction Motor. Besides, we have the Auto–Transformer starting method by which initial current and voltage are reduced. These all are established starting systems.

The various energy conservation aspects on motor starting and running are as follows:

7) APPLY DELTA TO STAR CONVERSION FOR MOTORS WITH LESS THAN 50% LOADING

The induction motor with a constant percentage loading below 50% would operate at lower efficiency in delta mode. This efficiency at low loading can be improved by converting delta connection into star connection. The reported savings due to this conversion varies from around 3% to 10% because the rated output of motor drops to one-third of delta configuration without affecting performance and the percent loading increases as compared to delta mode. This option does not require any capital investment and is one of the least cost options available for the energy conservation in induction motors.

Though the margin of saving due to this option is low, but as the plant installations normally have hundreds of motors, converting most of the under-loaded motors in the plant would result into considerable savings.

A word of caution:

1) While implementing permanent Delta to Star conversion, care should be taken to decrease the setting of over load protection relay to two-thirds of the delta setting.
2) Some motors operate on step loading and some on continuously variable load. For example, a machine with an induction motor performs three operations in its operating cycle resulting into motor loading of 25%, 40% & 80%. In such cases permanent Delta to Star conversion is not possible. An automatic Delta-Star change-over controller could be installed there. It will connect the motor in Star mode in 25% & 40% motor load operations; and in Delta mode in 80% load operation.
3) The option of permanent Delta to Star conversion can not be implemented for the loads where starting torque requirement is very high. For the applications where starting torque requirement is high but otherwise the load is low, automatic Delta to Star converter should be installed.

4) The motors which operate on continuously variable load, feasibility of installing Soft-Starter/Energy Saver is to be worked out instead of automatic Delta-Star controller.

---

8) APPLY SOFT STARTERS WITH ENERGY SAVERS

Soft starters are motor controllers applied for a smooth start. Starting current and torque are directly related to the voltage applied when starting the motor. By reducing the line voltage when the motor is started, soft starter reduces the starting inrush current and eliminates the high impact or jerk starts that causes mechanical wear and damage.

Soft starters, which have solid state electronic components, are used to control the input voltage according to the torque required by the driven equipment. Thus at almost all the load, the motor operates at the same efficiency and power factor.

This results in smooth starting of the motors by drawing lower current and thus avoiding the high instantaneous current normally encountered.

Studies have shown that the energy savings obtained by soft starters are dependent on the loading of the motor. Savings are pronounced for motor loading between 10-50%. However if the load is higher then 50% of the rated, savings are generally small and simple payback periods are long.

Soft starters are useful in cases where motors operate with high impact loads. Some of the applications are cranes, conveyors, hoists, compressors, machine tools, textile machinery, food processing machinery etc.

A word of caution:

1) It should be noted that energy saving properties of soft starters may adversely affect the stability of certain drive system due to reduction of the developed torque.
2) Soft starters also distort current drawn from the utility grid, so the decision for installation of soft starters has to be taken after serious consideration of these issues.

---

9) SELECT MOTORS FOR VARYING LOAD APPLICATIONS

There are few industrial applications where the motor load fluctuates, varying from no load to peak load. This fluctuation causes variation in motor temperature. When there is definite repeated load cycle the motor, selection can be based on the root mean square (RMS) value of motor losses for the load cycle. Since the load losses at different loads are generally not available, a good approximation for motor selection can be based on the RMS horsepower for the load cycle. This is based on the assumption that when the motor is running and 100% heat dissipation is effective. When the motor is stopped, since there is no forced cooling, the effective cooling can be taken at one-fifth. The above method of motor selection is illustrated below:

Consider the duty cycle of a rod twist mill in a steel plant as given below:

Load	Duration
50 hp	30 minutes
20 hp	10 minutes
10 hp	10 minutes
Stop	10 minutes
Total Duration	60 minutes

Now $hp^2 \times t$ $= 50^2 \times 30$ $= 75{,}000$

$= 20^2 \times 10$ $= 4{,}000$

$= 10^2 \times 10$ $= 1{,}000$

= stop x 30 = 0

Total (hp^2 x time) = 80,000

Effective cooling time, T = 30 + 10 + 10 + 10/5

= 52 minutes

$$Hp = \sqrt{\sum (hp^2 \times time) / T} = \sqrt{80000/52} = 39.22 \text{ hp}$$

Thus, from the thermal standpoint, a 40 hp motor will be suitable for this application. However, the peak load observed in the duty cycle should be within the peak load rating of the motor, otherwise a suitable correction should be given and a slightly higher rating motor should be selected to satisfy peak load rating of the selected motor. Another point to be remembered is that such a method of selecting motors is not suitable for applications requiring frequent starting and loads with high inertia.

---

10) INSTALL VARIABLE SPEED DRIVE (VSD)

AC (Alternating Current) induction motors are essentially constant speed machines, with a variation of speed from no load to full load of about 2% to 5%, representing the “slip” of the motor. The speed of the machine is determined by the frequency of the power supply and the number of magnetic poles in the design of the stator.

Fixed speed motors serve the majority of applications. In these applications or systems, some processes operate with variable loads, depending on temperature, flow or pressure factors, as well as hours of operation. In these cases, substantial energy savings can be achieved by varying the speed of the motors and the driven load using a commercially available variable frequency drive.

The following table gives typical examples of loads and their energy savings potential.

Type Of Load	Applications	Energy Consideration
Variable Torque Load - HP varies as the cube of the speed - Torque varies as the square speed	- Centrifugal Fans - Centrifugal Pumps - Blowers - HVAC Systems	Lower speed operation results in significant energy savings as power to the motor drops with the cube of the speed.
Constant Torque Load - Torque remains the same at all speeds - HP varies directly with the speed.	- Mixers - Conveyors - Compressors - Printing Presses	Lower speed operation saves energy in direct proportion to the speed reduction.
Constant Horsepower Load - Develops the same horsepower at all speeds. - Torque varies inversely with the speed.	- Machine tools - Lathes - Milling machines - Punch presses	No energy savings at reduced speeds; however, energy savings can be realized by attaining the optimized cutting and machining speeds for the part being produced.

What is VFD?

A Variable-Frequency Drive (VFD) is a device that controls the voltage and frequency that is being supplied to a motor and therefore controls the speed of the motor and the system it is driving. By meeting the required process demands, the system efficiency is improved.

A VFD is capable of adjusting both the speed and torque of an induction motor.

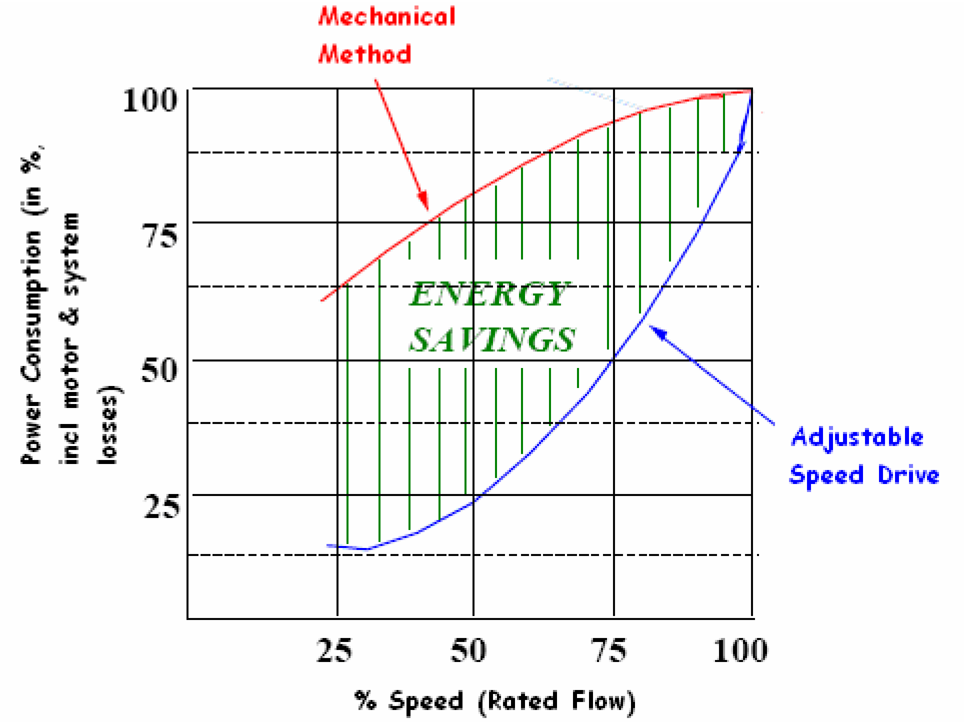
The potential area where installation of VSD would lead to substantial energy savings is centrifugal loads namely pumps, fans and compressors. For centrifugal equipment, even a minor change in the motor's operating speed translates into a significant change in imposed load and annual energy consumption. Fan and pump "affinity" laws indicate that the horsepower loading placed upon a motor by centrifugal loads varies as the third power or cube of its rotational speed. A seemingly minor 20 rpm increase in a motor's rotational speed (from 1740 to 1760 rpm) can result in a 3.5% increase in the load placed upon a motor driving a pump or fan. In contrast, the quantity of air or water delivered varies linearly with speed. Electronic adjustable speed drives can typically save 14% to 50% of energy for motors driving pumps, fans or compressors.

Although pumps and fans provide the best applications for VSD retrofits, speed controls are not necessarily cost-effective for all pumps and fans. The best way to determine the cost-effectiveness of a proposed VSD installation is to look at the power needed at each operating condition with and without a VSD. The energy savings can then be calculated by taking the reduction in power at each condition and estimating the savings based on the actual (or expected) operating time at that condition. In general, good applications for variable-speed flow control or VSD control are those:

1) systems which are designed for higher flow than actually required by the load;
2) where mechanical throttling (by valves or dampers) provides the variation and where the majority of the operation is below the design flow;
3) systems which use flow diversion or bypassing (typically via a pressure-reducing valve);
4) system which are greatly oversized for the flow required.

This situation can occur where successive safety factors were added to the design and where a process changed so that the equipment now serves a load less than the original design, and where a system was over designed for possible future expansion.

The figure below shows the energy savings potential of a centrifugal pump, when the flow control is made with VSD instead of mechanical throttling.



A word of caution:

Selecting the proper VFD for your application is best achieved by understanding the technology, your specific load requirements and asking the right question up front. This question might be: "Does my load profile vary sufficiently to justify a VFD?"

The process systems requiring constant pressure regardless of flow should not be retrofitted with VSD drive. The VSD drive shall reduce the pressure at the outlet of the fan or pump at lower flow.

The other disadvantages and the features that need careful attention are:

a) The VSD application may need inverter-grade motors as the standard high-efficiency motors may overheat

b) The VSD use mainly class B motors

c) The VSD may need TEBC or TEAO motors for applications that require extended use at lower speeds

d) The VSD are not available for higher voltage systems

e) Expensive or unavailable for systems over 480-volt

f) The VSD motors need heavy insulation

g) The VSD application may result in harmonic distortion, reflective wave, shaft currents, temperature rise and have RFI issues (use RFI filters or shielded cable)

VSD – Choice of Motors

Application	Services	VSD Choice
Maintaining Constant Pressure	Domestic Water Supply Chilled Water Systems Boiler Feed Service Hot Water Systems Municipal Water Booster Systems Water Seal Systems Irrigation Systems Differential Chilled and Hot Water Systems	VSD with Standard Motor
Maintaining Constant level	Sewage Lift Stations Industrial Waste Services Sewage Treatment Plants Condensate Return Systems Container Filling Systems	VSD with Efficiency Motor
Maintaining Constant Temperatures	Incinerator and Furnace Cooling Cooling and Heating Systems Heat Exchanger Supply Bearing Frame Cooling Differential Temperature System Condenser Water Circulation	VSD with premium efficiency motors
Maintaining Constant Flow	Sludge return Systems Process Recirculation Services	VSD with inverter duty motor

Practical Case Study of Hotel Air-conditioning Chilled Water Pump Motor

This is a case study involving the installation of a 25 HP variable speed drive in a chilled water pump that is a part of the air-conditioning system at a hotel. The chilled water pumping system consisted of 2 centrifugal pumps driven by 3,550 rpm motors with a parallel discharge system connected. The number of hours in operation before installing the variable speed drives was 38 hours a day with one pump running 24 hours a day and the other running 14 hours. The second pump was needed for the warmer room temperatures in the afternoon. The pump that ran on a start-stop basis was manually controlled. In the hotel public access areas, such as restaurants, lobbies, meeting rooms, as well as the guest rooms, temperatures were regulated through the use of thermostats and the flow of cold water into the air handler units or ventilators, which were controlled by valves that would open and close, adjusting to the appropriate temperature settings. This created a situation during specific times of the day where room temperatures became cold. For example, early in the morning or when hotel occupancy was low and the pump or pumps in the facility were operating unnecessarily. It is estimated that significant savings can be achieved if variable speed drives are installed in one pump while leaving the second pump as a backup. Variable speed pumps can vary from 75% to 100% of nominal speed. The average number of hours of operation for the second pump drops from 14 to 5 hours per day.

It is good to have a single large pump or fan with standby depending on the criticality of process rather than a series of staged pumps or fans that come on sequentially as the process needs increase.

Note that the variable speed drive (VSD) could be any of the following:

1) Variable-frequency drive
2) Variable-pitched sheave
3) Magnetic-coupled clutch
4) Eddy-current (electromagnetic) clutch

There are also other options for speed variation such as DC motors, gearboxes, friction discs, hydraulic couplings; however, variable-frequency drive is the most common of all.

---

11) INSTALL TWO-SPEED MOTORS

Two-speed induction motors can be the ideal solution for the applications where the load fluctuates by the hours of the day or where multiple equipment is installed to perform the work. Take cooling towers for instance; when the load is reduced during favorable ambient conditions during night time, an opportunity exists to step down the speed of the cooling tower fan to achieve energy savings.

With a two-speed motor, frequent cycling of one-speed motors at full power could be replaced with long periods of operation at half speed.

Two-speed motors improve efficiency for refrigerators, air conditioners, heat pumps, and distribution fans. Residential central air conditioners (and some furnace blower motors, clothes washers, and ceiling fans) currently use two speed compressors (with 1-5 hp motors).

---

12) IMPLEMENT MOTOR CONTROLS

To reduce electrical consumption, use controls to adjust motor speeds or turn off motors when appropriate. Often equipment can run at less than full speed or be turned off completely during part of a process cycle. When correctly used, motor controls save significant amounts of energy, reduce wear on the mechanical system, and improve performance.

Motor Idling

Motor idling is a very common feature of industrial usage. In general, compressors, lathes and machines tools as well as production lines themselves are all culprits since motors are left on when there is no actual productivity work being done. Depending on the circumstances, up to 50% full load current may be consumed by idling motors particularly when still connected to gear trains and belt drivers.

Switch Off When Not Required

One of the simplest means to achieve energy conservation is to switch off when not needed. The auto controls can be used for this purpose. NEMA Publication MG 10, Energy Management Guide for Selection and Use of Polyphase Motors, includes a comprehensive load shedding guidelines. The maximum number of on/off cycles per hour and the maximum amount of time off between cycles is affected by motor size, type of load (variable or fixed), and motor speed.

---

13) MATCH MOTOR OPERATING SPEEDS

Remember, induction motors have an operating speed that is slightly lower than their rated synchronous speed. For example, a motor with a synchronous speed of 1800 rpm will typically operate under full load at about 1,750 rpm. Operating speed (full-load rpm) is stamped on motor nameplates.

The energy consumption of centrifugal pumps and fans is extremely sensitive to operating speed. An increase of just 5 rpm can significantly affect the pump or fan operation leading to increased flow, reduced efficiency and increased energy consumption. As a rule of thumb, increasing operating speed by 2% can increase the power required to drive the system by 8%. To maintain system efficiency, it is critical to match full-load speeds when replacing pump and fan motors.

Select replacement energy-efficient motors with a comparable full-load speed for centrifugal load applications (pumps and fans). Look for motor manufacturers stamp "full-load rpm" ratings on motor nameplates and often publish this data in catalogs. This operating speed rating varies by as much as 50 rpm. In general, try to select a replacement fan or pump motor with a full-load rpm rating equal to or less than that of the motor being replaced.

---

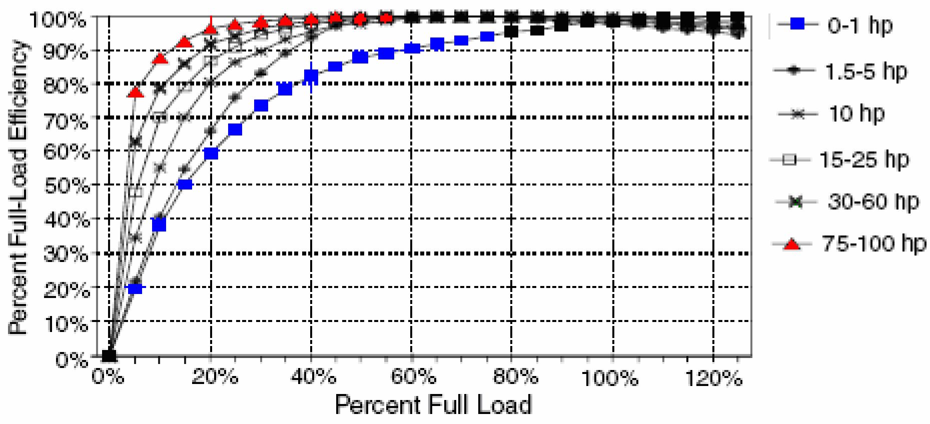
14) SIZE MOTORS FOR EFFICIENCY

Most electric motors are designed to run at 50% to 100% of rated load. Maximum efficiency is usually near 75% of rated load. Thus, a 10-horsepower (hp) motor has an acceptable load range of 5 to 10 hp; with peak efficiency at 7.5 hp. A motor's efficiency tends to decrease dramatically below about 50% load. If your operation uses equipment with motors that operate for extended periods under 50% load, consider making modifications. Sometimes motors are oversized because they must accommodate peak conditions, such as when a pumping system must satisfy occasionally high demands. Options available to meet variable loads include two-speed motors, adjustable speed drives, reservoirs for fluids, fly wheels for mechanical equipment and other load management strategies that maintain loads within an acceptable range.

Efficiency versus Motor Load Relationships

The efficiency of both standard and energy-efficient motors typically peaks near 75% of full load and is relatively flat down to the 50% load point. Motors in the larger size ranges can operate with reasonably high efficiency at loads down to 25% of rated load.

The figure below shows the efficiency curves for the different sizes of motors at different loadings. In general the efficiency drops with low loadings.



MOTOR PART-LOAD EFFICIENCY RANGE
(as percent of Full-Load Efficiency)

Efficiency values at partial load points are also tabulated below for energy-efficient and standard motor models of various sizes.

Efficiency at Full and Partial Loads for 1800 RPM, ODP Motors

	Full Load	75% Load	50% Load	25% Load
100 hp				
U.S. Motors - Premium	95.8	96.1	96.1	94.3
Reliance XE	95.4	95.7	95.4	93.2
Magnetek Standard	93.0	94.0	94.0	89.3
U.S. Motors - Standard	92.4	93.8	93.9	91.6
40 hp				
U.S. Motors - Premium	94.5	94.9	94.6	92.0
Reliance XE	94.1	94.1	94.0	91.4
Magnetek Standard	91.0	89.5	92.4	86.5
U.S. Motors - Standard	90.2	88.0	90.8	86.9
20 hp				
U.S. Motors - Premium	93.0	92.7	92.5	89.5
Reliance XE	92.0	93.0	92.0	84.8
Magnetek Standard	88.5	89.5	89.5	84.0
U.S. Motors - Standard	88.0	88.0	86.3	79.9
10 hp				
U.S. Motors - Premium	91.7	90.4	89.8	85.3
Reliance XE	91.7	92.2	91.8	87.8
Magnetek Standard	87.7	89.5	88.5	82.5
U.S. Motors - Standard	86.0	88.0	86.0	80.6
5 hp				
U.S. Motors - Premium	89.5	90.4	89.5	84.3
Reliance XE	89.5	89.7	87.5	82.6
Magnetek Standard	85.5	86.5	85.5	75.0
U.S. Motors - Standard	84.0	84.0	82.0	74.0

The interpretation of the table above reveals two distinct trends:

1) Larger motors exhibit both higher full- and partial-load efficiency values, and
2) The efficiency decline below the 50% load point occurs more rapidly for the smaller size motors.

Thus, a 100-hp standard motor operating at 40% of rated load may operate as efficiently as energy efficient 40-hp motor operating at its rated load point.

On the other hand, an energy-efficient 5-hp replacement motor could operate with efficiency as much as five points above that of a standard 10-hp motor operating at its 40% load point.

Determining if your motors are properly loaded enables you to make informed decisions about when to replace motors and which replacements to choose. Note that the overloaded motors can overheat and lose efficiency. Many motors are designed with a service factor that allows occasional overloading. Service factor is a multiplier that indicates how much a motor can be overloaded under ideal ambient conditions. For example, a 10-hp motor with a 1.15 service factor can handle an 11.5-hp load for short periods of time without incurring significant damage. Although many motors have service factors of 1.15, running the motor continuously above rated load reduces efficiency and motor life. Never operate overloaded when voltage is below nominal or when cooling is impaired by altitude, high ambient temperature, or dirty motor surfaces.

---

15) CHOOSE RIGHT OPERATING VOLTAGE

Generally, high-voltage motors have lower efficiencies than equivalent medium-voltage motors because increased winding insulation is required for the higher voltage machines. This increase in insulation results in a proportional decrease in available space for copper in the motor slot. Consequently, I^2R losses increase.

Losses are also incurred when a motor designed to operate on a variety of voltage combinations (for example, 208 - 230/460 volts) is operated with a reduced voltage power supply. Under this condition, the motor will exhibit a lower full-load efficiency, run hotter slip more, produce less torque, and have a shorter life. Efficiency can be improved by simply switching to a higher voltage transformer tap. When choosing motors for a 208 volt electrical system, use a motor specifically designed for that voltage rather than a “Tri-Voltage” motor rated at 208-230/460. Tri-Voltage motors are a compromise design that run hotter and are less efficient and reliable than a 200 volt motor operating at 200 or 208 volts.

If operation at 208 Volts is required, an efficiency gain can be procured by installing an energy-efficient NEMA Design A motor.

---

16) SELECT THREE-PHASE MOTORS

Generally for small load applications single-phase motors are used. It is preferable to use 3-phase motors wherever possible for the following reasons:

1) Power factor for single-phase motor is lower than that of a three-phase motor of the same rating
2) A three-phase motor has higher efficiency than that of single-phase motor
3) The rating of the given machine increases with increase in number of phases. For example output of three-phase motor is 1.5 times the output of single phase-motor of same size.
4) Select the right size of motor

---

17) MINIMIZE REWIND LOSSES

Rewinding can reduce motor efficiency and reliability. As a rule of thumb, with rewound motors, deduct one efficiency point for motors exceeding 40 hp and two points for smaller motors.

Although failed motors can usually be rewound, the repair-versus-replace decision is quite complicated and depends on such variables as the rewind cost, expected rewind loss, energy-efficient motor purchase price, motor size and original efficiency, load factor, annual operating hours, electricity price, availability of a utility rebate, and simple payback criteria.

A quality rewind can maintain the original motor efficiency. Here are several rewind "rules of thumb":

1) Always use a qualified rewind shop. Have motors rewound only at reliable repair shops that use low temperature (under 700°F) bakeout ovens, high quality materials, and a quality assurance program based on EASA-Q or ISO-9000.
2) If a motor core has been damaged or the rewind shop is careless, significant losses can occur.
3) 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.
4) 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.

It is often worthwhile to replace a damaged motor with a new energy-efficient model to save energy and improve reliability.

18) REPLACE OVERSIZED & UNDERLOADED MOTORS BY APPROPRIATE SIZE

Avoid over sizing of motors and choose right type and size of motors to suit load and operating conditions.

Motors rarely operate at their full-load point. Electrical energy audit surveys of 60 motors at four industrial plants indicate that, on average, they operate at 60% of their rated load. Motors that drive HVAC system supply and return fans generally operate at 70% to 75% of rated load.

By knowing the percent loading and power factor of motor during full load and off load, it is possible to estimate operating efficiency from motor characteristic curves. If the efficiency is low, the motor may be replaced by a higher efficiency motor after calculating the payback period.

Consider a pump requiring 30 hp load running for 8,000 hrs per annum, being driven by three alternatives i) 30 hp , ii) 40 hp and iii) 60 hp. The table below shows the effect of energy loss due to use of oversized motors.

Energy Consumption Due To Oversized Motors

	Rating of Motor Used		
	30 hp	**40 hp**	**60 hp**
Motor Load	30 hp	30 hp	30 hp
Operating Load	1	0.75	0.5
Motor Efficiency	0.88	0.87	0.82
Motor Input	34.08 kW	34.48 kW	36.58 kW
Electric Units consumed for 8000 hrs	2,03,449	2,05,776	2,18,309
Extra Energy Consumed	-	2327 kWh	14860 kWh
Cost of Energy Loss @ 6 cents per kWh	-	~ $140	~ $ 890

* Motor Efficiency/ratings refer to GEC performance chart of KOPAK range of motors, 415 V, 3-phase, 60 Hz, 3,000 rpm.

Replacing a standard induction motor with a high-efficiency model has many other advantages. In addition to cutting down electricity costs, the replacement will probably have a longer life because it runs cooler and has better bearings. Also, it will need fewer capacitors to boost the motor's power factor.

However before taking a decision on replacement, it is important to ascertain the application and the characteristics of motor particularly efficiency v/s load and motor load v/s speed.

Motor Load and Speed Relationships

The actual operating speed of an induction motor is somewhat less than its synchronous speed. This difference between the synchronous and actual speed is referred to as slip. Many energy-efficient motors tend to operate with a reduced full-load slip or at a slightly higher speed than their standard efficiency counterparts. This small difference can be significant.

For centrifugal equipment such as fans and pumps, even a minor change in the motor's operating speed translates into a significant change in imposed load and annual energy consumption. *Fan and pump "affinity" laws indicate that the horsepower loading placed upon a motor by centrifugal loads varies as the third power or cube of its rotational speed.* A seemingly minor 20 rpm increase in a motor's rotational speed (from 1740 to 1760 rpm) can result in a 3.5% increase in the load placed upon a motor driving a pump or fan. In contrast, the quantity of air or water delivered varies linearly with speed.

Slip and operating speed are dependent upon applied load, and the loading imposed upon a motor is in turn dependent upon its size. For example,

a) A 25% loaded 100-hp motor could be replaced by a 50-hp motor loaded to approximately 50%;

b) A 62.5% loaded 40-hp motor could be replaced by an 83% loaded 30-hp motor; or a fully loaded 25-hp motor.

As loads on a motor are progressively increased, it begins to rotate slower until, at the full-load point, operation occurs at the full-load speed. Thus, oversized and lightly loaded motors tend to operate at speeds which approach synchronous. An appropriately sized fully loaded energy-efficient motor, with a higher full-load rpm than the motor to be replaced, may actually operate at a slower speed than the original oversized motor. This speed and load shift can be significant and must be taken into account when computing both energy and demand savings. For example, consider a 40% loaded, four-pole, 10-hp standard efficiency motor (Siemens) which is to be replaced by a 5-hp, energy-efficient. The standard efficiency motor has a full-load efficiency of 84.0% at a full-load speed of 1,720 rpm. The energy efficient U.S. Motors exhibit full-load efficiencies of 89.5% with full-load speeds of 1,760 and 1,740 rpm, respectively.

The standard motor would actually operate at 1,768 rpm and so shall be the energy-efficient U.S. motor. Energy savings, assuming 2,500 hours per year of operation, are 849 kilowatt-hours (kWh) for the energy efficient motor. Energy savings and load points for the efficient motors are tabulated below, assuming that the full-load speed for the oversized 10-hp motor ranges from 1,715 to 1,760 rpm. The data assumes replacement of a standard efficiency 10 hp, 40% loaded motor with an energy efficient 1,800 rpm 5-hp unit with 2,500 hours per year of operation.

Energy Savings Due to Replacement of an Oversized Motor as a Function of Full-Load Speed

Full-Load rpm of Oversized Motor	Load Imposed on 5-hp 1780 rpm Motor, % of Rated	Annual Energy Savings, kWh
1715	80.26	823
1720	80.00	849
1730	79.49	902
1740	78.98	955
1750	78.47	1007
1760	77.97	1059
No speed correction: 849 kWh		

---

19) REPAIR OR REPLACE?

The best opportunity to install an energy-efficient motor is usually when a motor fails and must be repaired or replaced. Many times when a motor fails, a decision must be made immediately in order to get production going again. If an energy-efficient motor is not readily available, the failed motor will be either repaired or replaced with a standard model.

It is therefore important to plan for this type of event in advance.

Consider the following:

a) Develop a set of criteria for all repair/replace decisions.

b) Decide on repair and/or replace events in advance for critical motor applications.

c) Create a motor inventory and list all available spare motor alternatives for each application.

Remember, the cost to replace a working motor includes the full price of the motor plus electrical and mechanical costs (removal and disposal of the old motor, rigging in the new motor, alignment, wiring, etc.). The most opportune times to upgrade to energy-efficient motors are during new construction and during replacement of failed units when all of the costs except for the efficiency premiums are unavoidable anyway.

If the motor can be repaired or rewound, follow these rules of thumb:

1) If the motor is less than 200 hp, it's usually more cost-effective to replace it. Evaluate the payback for the repair versus the replacement.

2) If the repair will cost more than 60 percent of the cost of a new energy-efficient motor, buy the new motor instead.

3) If the cost of downtime during the repair is more than twice the purchase price of a new energy-efficient motor, buy the new motor instead.

4) If the motor is oversized, poorly rewound before or is part of inefficient drive system that warrant changes anyway, buy the new motor instead.

---

20) MONITORING & MAINTENANCE

Good housekeeping of electrical installations in a plant is easily achieved when all the tenets of preventive maintenance methods are followed. Preventive maintenance maximizes motor reliability and efficiency. Develop a monitoring and maintenance program for all three-phase motors based on manufacturers' recommendations and standard industrial practices.

Improved maintenance practice ranges from the simplest task of using clean hands during lubrication to the more complex task of replacing windings in a manner which results in no loss in efficiency. The following must be noted:

Cleanliness of Motors

- Blowing off dust, greasing as per manufacturers instructions, cleaning the surface of grit, foreign deposits, cleaning of end cover rills and fan ducts, and painting (if needed) should be performed. Cable ducts should be inspected regularly and cleaned.
- Loose & dirty connections and temporary wiring should be avoided.
- Electrical Panels should not be cluttered-up with odd positions of switch gears. Surroundings and lower portions are to be maintained clean. Panel knockout holes, if unused, should be plugged. Panel covers should be inspected at regular intervals.
- Portable measuring instrument are to be maintained well and periodically calibrated. Their accuracy must be verified now and then.
- Panel instruments are to be kept clean and marked red at the value not to be exceeded. Instruments are vital to record readings; the abnormality of which is sure sign of fault and energy waste in installations.
- Electrical accidents are unforeseen, sudden and at times fatal. Electrical safety is a statutory requirement. Safety apparatus rubber mats, gloves, ear thing rods and

caution boards must be exhibited and kept neatly. Ear thing strips and wires are to be inspected for electrical conductivity and mechanical strength.

Perform Periodic Checks

- Check motors often to identify potential problems
- Distribute loads evenly throughout the facility
- Inspections should include daily or weekly noise, vibration, and temperature checks
- Approximately twice a year, test winding and winding-to-ground resistance to identify insulation problems
- Periodically check bearing lubrication, shaft alignment, and belts. A variety of specialized instruments is available for monitoring purposes

Control Temperatures

- Keep motors cool because high temperatures reduce insulation life and motor reliability
- Where possible ensure motors are shaded from the sun and located in well ventilated areas
- Keep motor terminals clean, since dirt acts as an insulator

Lubricate Correctly

- Lubricate motors according to manufacturers' specifications.
- Apply high-quality greases or oils carefully to prevent contamination by dirt or water.

Maintain Motor Records

- Maintain a separate file on each motor to keep technical specifications, repair, testing, and maintenance data.
- Maintain time-series records of test results, such as winding resistance. This information will help you identify motors that are likely to develop mechanical or electrical problems. In addition, these records may be necessary for the proper repair of a failed motor.
- The stock of motors should be maintained and reviewed to see if there is a possibility of switching motors so that the large motors which are under-loaded (or oversized) can be replaced by smaller capacity motors available in the factory. While in ideal circumstances, the moving of motors should mean that only few small motors need be bought to fill arising vacancies, in some cases motors cannot be replaced by

smaller units because of mounting problems and short peak loads. In these cases, replacement by improved efficiency motors should be considered taking advantage of the development of energy-efficient motors.

PART 3 MOTOR LOAD ESTIMATION TECHNIQUES

Field Measurements

To establish the energy saved in a given installation, it is important to ensure that the measurement techniques are appropriate and correct.

Three-phase induction motors are a three-wire circuit and ideally, three-phase power measurement techniques must be employed in order to achieve meaningful results. Comparisons are best made under controlled conditions with a true kW or kWh metering system. The rotating disk kWh meter is what the power bill is based on and so it is a good instrument to use.

Measurements made on one-phase and multiplied by three can be extremely erroneous, especially under light load conditions. The kilowatt loading on the three phases at light loads can be severely unbalanced even though the currents may not be unbalanced to the same degree. When using the two watt meter method, care with phasing is very important as this can totally alter the results.

Measurements made by multiplying voltage, current and power factor on each phase can work with a continuous sinusoidal current provided that each phase is individually measured, and the power consumption from each phase is then summed to give the three-phase power consumption.

Measurements on non-sinusoidal currents and or voltage must be made with true integrating watt meters. The formula of $P = \sqrt{3} \times V \times I \times pf$ applies only with a continuous sine wave current and voltage. When solid state electronic devices such as SCR or triac switching elements are present in the circuit to control the voltage, it results in non-sinusoidal current and voltage. Under these conditions, current, voltage and power factor measurements are meaningless in determining the power consumed. By definition, power is the integral of instantaneous volts x amps of the period of one or more cycles. At the instance that current is flowing, the SCR or triac is turned ON resulting in full line voltage at that instance in time. Therefore, there is no difference between measurements made on the input of the energy saver or the output of the energy saver with the exception that there is some loss in the energy saver which will appear on input measurements but not output measurements.

Equipment to read Motor Parameters

The following are the various instruments used for measuring the motor parameters:

- Power analyzer for monitoring KW, KVA, KVAR, P.F.
- Digital Ammeter, Voltmeter

- Tachometer to measure speed (contact/non contact type)
- Frequency meter
- Tong tester.
- Analog/Digital Multimeter (AC/DC)
- Temperature Indicator & Thermocouples
- Digital Wattmeter

Load Estimation Methodology

Operating efficiency and motor load values must be assumed or based on field measurements and motor nameplate information. The motor load is typically derived from a motor's part-load input kW measurements as compared to its full-load value (when kW or voltage, amperage, and power factor readings are available), from a voltage compensated amperage ratio, or from an operating speed to full-load slip relationship.

The *kilowatt technique* should be used whenever input kilowatt measurements are available.

Use *slip technique* only when strobe tachometer readings are at hand and kilowatt values are not available.

The full-load or synchronous speed for the existing motor may be extracted from the nameplate, whereas speed characteristics for new motors are obtained from manufacturers' catalogs.

Motor Load Estimation Techniques

Kilowatt Ratio Technique

Motor Load = [$\sqrt{3}$ * V (avg.) * A (avg.) * (power factor/100) / 1000] / [hp rated * 0.746/ full load eff.]

Voltage Compensated Slip Technique

Motor Load = [RPM, synch – RPM, measured] / [(RPM, synch – RPM, full load nameplate) * (rated voltage / measured voltage)^2]

Few energy offices recommend against using the slip technique as an indicator of load and suggest that loads be estimated by comparing a motor's true root-mean-square (RMS) amperage draw against its full-load or nameplate value. Thus, the load on a motor is defined as:

Amperage ratio technique

$$Motor\ load = \frac{amps_{\ measured}}{amps_{\ full\ load,\ nameplate}} \times \left[\frac{volts_{\ measured}}{volts_{\ nameplate}}\right]$$

While the amperage of a motor is approximately linear down to 50% load, the relationship is not directly proportional (i.e., at 50% load, current is higher than 50% of full-load current). An improved version of the amperage ratio load estimation technique makes use of a linear interpolation between a motor's full- and half-load current values. The modified equation, useful for estimating loads in the 50% to full-load range, is:

$$Motor\ Load = 0.5 + 0.5 \times \left[\frac{amps_{measured} \times \left[\frac{volts_{\ measured}}{volts_{\ nameplate}}\right] - amps_{50\%\ load}}{amps_{full\ load} - amps_{50\%\ load}}\right]$$

The current at 50% load (amps 50%) can be found from manufacturer data.

The accuracy of the amperage ratio methodology is best for motors with outputs exceeding 10-shaft hp. Below 50% load the amperage curve becomes increasingly nonlinear and is therefore not a good indicator of load.

PART 4 **COST EVALUATING METHODS**

Simple Payback Evaluation

The simple payback method is frequently used to determine how long it would take for a piece of equipment to "pay for itself" through saved costs. The payback time is calculated as follows:

Number of Years = Total Initial Capital Cost ÷ Total Annual Savings

Simple Motor Payback Calculation		
Cost of Energy-Efficiency Motor	[A] = $ __________	
Horsepower	[B] = __________	hp
Cost of Electricity	[C] = $ __________	/kWh
Hours of Operation per Year	[D] = __________	hrs/yr
Efficiency of Standard Motor	[E] = __________	%
Efficiency of Energy-Efficiency Motor	[F] = __________	%
Annual Electricity Cost Reduction:		
0.746 *B * C* [(100/E) - (100/F)] =	[G] = $ __________	/kWh
Simple Motor Payback Calculation:		
A/G =	[H] = __________	yrs

Methodology:

1) Obtain actual price quotes from motor distributors. Note that the motors rarely sell at full list price. You can typically obtain a 20% to 60% discount from vendors. The following three techniques can help you determine whether an energy efficient motor is cost effective:

2) Use the following formulas to calculate the annual energy savings:

   Savings = hp * L * 0.746 * hr * C * [(100/ Estd) – (100/ Eee)]

   Where:

   - hp = Motor horsepower

- L = Load factor (%age of full load)
- 0.746 = conversion of horsepower to kW units
- hr = Annual operating hours
- C = Average energy costs ($ per kWh)
- Estd = Standard motor efficiency (%)
- Eee = Energy efficient motor efficiency (%)

3) Use the following formulas to calculate the simple payback. Simple payback is defined as the time required for the savings from an investment to equal the initial or incremental cost.

   For new motor purchase, the simple payback is the price premium minus any utility rebate for energy efficient motors, divided by the annual dollar savings:

   Payback (years) = (Price Premium – Utility rebate, if any) / Annual dollar savings

   When calculating the simple payback for replacing an operating motor, you must include the full purchase price of the motor plus any installation costs:

   Payback (years) = (Motor Price + Installation charge – Utility rebate) / Annual dollar savings

   In typical industrial applications, energy-efficient motors are cost effective when they operate more than 4,000 hours a year, given a 2-year simple payback criterion. For example, with an energy cost of $0.04/kWh, a single point of efficiency gain for a continuously operating 50-hp motor with a 75% load factor saves 4,079 kWh or $163 annually. Thus, an energy-efficient motor that offers four points of efficiency gain can cost up to $1,304 more than a standard model and still meet a 2-year simple payback criterion.

Note that simple payback analysis should only be used as a risk indicator. Simple payback neglects the impact of a number of important variables, such as tax incentives, inflation, etc.

Net Present Value Evaluation

Calculating the net present value (NPV) is a better technique for appraising the profitability of an investment. By using the discounted cash flow technique, the NPV takes into account the time value of money. A summary of this approach appears in the following steps:

1. Evaluate the cost/savings of the factors in the above table for each option that is being considered (for example, purchasing a VFD or purchasing a mechanical drive system

instead). Capital costs will be expressed in total dollars; operating expenses will be expressed in terms of time.

2. Determine the real discount rate that should be used for each time dependent and future-valued factor. For example, for energy savings calculations:
    - x% per annum = nominal discount rate
    - y% per annum = rate at which electricity rates will rise
    - i% = {x/y – 1}%

   As another example, salvage value in years from the present should be discounted using the rate at which the interest rate is expected to rise between now and 'n' years.

3. The factors for each option should be discounted to their present values, using the appropriate discount rate. The number of years used for time dependent factors should be chosen as a reasonable payback period. Present value tables and annuity tables are useful for the discounting process.

4. The net present value (NPV) of each option is found by summing the costs and savings that have been calculated in present value terms for each factor.

5. For any option, if:
    - NPV > 0, there is a net gain
    - NPV < 0, there is a net loss
    - NPV = 0, breakeven occurs at the time under consideration.

6. The option with the greatest positive value of NPV is the most profitable.

7. The procedure could be repeated assuming different total time periods.

8. A comparison between two options could also be made by using the relative difference between the options for each factor and finding one NPV.

Refer to another course: "Six Ways to Perform Economic Evaluation of Projects" (CED Course No. B03-003) for more details on the subject.

PART 5 CONCLUSIONS – MYTH & REALITY

Various opportunities exist that can reduce operational costs associated with motors. Standard motors, for example, can be replaced with high efficiency motors as they wear out. High efficiency motors can also be purchased for new installations, particularly for cases where units must operate more than 12 hours a day. Another savings opportunity is the installation of variable speed drives on motors that run with variable loads. Electrical energy conservation in motors can be effected both in initial design as well as in a running plant. The methodology is shown below:

Electrical Energy Conservation in Motors		
Sno.	**Plant Design Stage**	**Running Plant**
1	Choose right type and size of motor to suit the load and operating parameters.	Identify under-loaded motors and replace them with the right size when replacement motors are available in-house.
2	Consider high efficiency motors	In case in-house replacement motors are not available, consider connecting the motors to "Star" when the motor runs under-loaded always
3	Consider the running cost in addition to the first cost in purchase of motors	Study the process application and modify with suitable energy efficient equipment and systems.
4	Select suitable variable frequency drives and power factor controllers	Consider variable speed drives in such applications as pumps, fans etc.
5	Consider energy efficient operating system (such as belt conveyor or bucket elevators in place of pneumatic conveyors)	Improve power factor by installing capacitors or power factor controllers

A word of Caution

A common myth is that "Voltage Reduction Leads to Energy Savings".

There is no doubt that the basic technology of using SCRs to reduce the voltage applied to a partially loaded induction motor will reduce the iron loss. But this shall also increase the currents, which will increase copper loss by the current squared, offsetting and often exceeding the reduction in iron loss. This often results in a net increase in motor losses. Therefore application is commercially viable only if the iron losses are considerable.

Energy audit result of textile spinning facility demonstrates that energy savings per kW motor rating are much higher for small motors than large, and the potential market for this technology is really confined to the small single-phase applications.

The energy audit data below carried using calibrated rotating disk kWh meters illustrates that the large induction motors are still efficient at low loads so the maximum achievable savings are small relative to the motor rating. Large motors have a very low iron loss, often 2% to 6% of the motor rating.

Energy Audit Data on Large Motor								
kW	0.37	0.75	2.2	5.5	11	30	110	355
Efficiency	66.2	74	82.5	86.4	89.2	91.6	93.2	94.9
Power factor	0.69	0.83	0.84	0.85	0.86	0.88	0.91	0.88

But the case is different for small motors as the efficiency drop is much more alarming at low loads. Very small motors, (particularly single-phase motors) have a much higher iron loss and so the potential to save energy is considerably higher.

Energy Audit Data on Small Motor							
kW	0.25	0.37	0.55	0.75	1.1	1.5	2.2
Efficiency	63	68	69	70	72	76	78
Power factor	0.6	0.63	0.66	0.7	0.74	0.84	0.86

The analyses show that the large induction motors are inherently very efficient. The iron losses for large motor are relatively low and their efficiency falls by a very small margin between full load and half load. This basic fact must need to be considered while applying any potential energy saving conclusion.

Worthwhile power savings on the account of reducing voltage are thus going to be achievable on induction motors with a very high iron loss. Typically, these will be small motors or inefficient and predominantly single phase motors, operating above their design voltage, or below their design frequency.

In conclusion, it is worth noting that a lack of knowledge about basic motor characteristics and a poor understanding of power metering on three-phase systems could result in extrapolations and estimations which totally misrepresent the achievable results. The motor efficiency can only be improved when it has dropped considerably below the maximum efficiency for that motor.

Summary

Due to the increasing need to lower operational costs and rising cost of electricity, various opportunities to save energy are available in the use of induction motors.

In many situations, greater energy savings can just be achieved by soft measures such as altering the operation of the machine to minimize the idle operating time, or preventive measures such as maintaining a consistent power quality, minimizing phase imbalance, maintaining optimum power factor, etc. These relatively low cost measures can yield an improved payback period relative to the use of an energy saving device.

Yet other measures involve installing energy efficiency motors. The energy efficient motors, in addition to the savings associated with a cut in energy use, are more durable than standard motors, requiring fewer repairs and maintenance expenses. The Energy Policy Act of 1992 (EPACT) requires that general purpose, polyphase, single-speed, squirrel-cage induction motors manufactured for sale in the U.S. and rated from 1 to 200 hp meet minimum efficiency standards. The standard also requires standardized testing and labeling procedures.

An improvement in motor efficiency is just one aspect. The majority of energy savings opportunities accrue when the motor and the driven equipment is seen together. Use of efficient transmission system, soft starters, synchronous belts, variable speed drives can result in enormous savings.

It is a good idea to have an electrical engineer review the electrical system periodically, especially before installing a new motor or after making changes to the system and its loads. For faster realization of energy savings, seeking the help of qualified energy consultants will be of immense help.

Not the least, a change of thought is a must at all levels of plant engineering personnel as well as corporate management. The top executives should be alive to the need of conserving energy and provide support to the downstream personnel to go head; as without the active nod from top, it is difficult to achieve anything at the lower levels.
