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ENERGY EFFICIENT DRIVEPOWER

AN OVERVIEW

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ABSTRACT

This report examines energy efficiency in drivepower systems. Only systems where the prime movers are electrical motors are discussed. A systems approach is used to examine all major aspects of drivepower, including motors, controls, electrical tune-ups, mechanical efficiency, maintenance, and management. Potential annual savings to the U.S. society of $25 to $50 billion are indicated. The report was written for readers with a semi-technical background.

KEYWORDS: EFFICIENCY, ELECTRIC, ELECTRICAL, DRIVEPOWER, SYSTEM, SYSTEMIC

TABLE OF CONTENTS

Chapter | Page

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

PREFACE

Energy efficiency is a major concern to industry for a variety of reasons. Operating expenses and public relations are just two of these. While a lot of effort has been expended in the area of electrical energy efficiency, the area of concern in this report, most papers use a limited approach when examining the oportunities for efficiency improvement. This paper, however, uses a systems approach - examining the entire power train system from when electrical power first enters a facility to the final output. This type of approach to electrical energy efficiency can improve the overall efficiency by a significant amount.

There are many methods of driving mechanical loads such as waste steam (steam turbine), centralized hydraulic systems, and compressed air. Only electric-drive systems were analyzed. Depending on the application and facilities, these other methods may be a viable alternative to electric drivepower systems.

This document assumes that the reader has an understanding of the basic concepts, practices, and terminology used in electrical and mechanical engineering. The reader should be familiar with terms such as voltage, current, dc power, ac power, power factor, horse power, torque, angular velocity, kilowatt-hours, efficiency, harmonics, and gear ratio.

The authors would like to acknowledge that this report is a condensation of another report titled "The State of the Art: Drivepower" published by the COMPETITEK group of the Rocky Mountain Institute. Paraphrased excerpts are also taken from "Energy Efficient Motor Systems" by S. Nadel, M. Shepard, G. Greenberg, G. Katz, and A. de Almeida, published by the American Council for an Energy-Efficient Economy.

INTRODUCTION

Definition and Purpose

Drivepower is defined as the conversion of electricity into mechanical work in the form of rotary shaftpower. An efficient drivepower system delivers the most appropriate quantity and quality of torque needed to drive a particular machine to perform a particular task, when and where required, at least economic cost.

Full implementation of all efficiency opportunities would save the U.S. society $25 to 50 billion dollars per year in electrical energy and demand charges and an additional long term savings of one hundred to three hundred billion dollars due to delayed construction of power plants. These savings are larger than those identified in previous studies since the previous studies examined only the potential savings from the use of energy efficient motors and adjustable speed drives, rather than a systems approach.

Scope and Limitations

The input boundary of a drivepower system is the electrical wire which supplies power to the motor or its electronic drive. The output system boundary is the shaft of the driven system. A drivepower system includes all components which interconnect the motor shaft and the shaft of the process such as gear drives, belt drives, chain drives. The general areas considered are:

- Motor types.
- Motor selection and maintenance.
- Motor controls.
- Mechanical drivetrain improvements.
- Electrical system tuneups.

Since a broad range of types, sizes, and applications of motors are analyzed, the results are applicable to all sectors of the economy. The main focus of this report will be on large industrial polyphase induction motors since they consume most of the electrical energy. Many results could also be applied to any other area where electric motors are used such as appliances, space heating and cooling, air handling, and water heating systems.

Many new and emerging technologies show promise to improve energy efficiency in the future. Only technologies that are commercially available as of 1988 are analyzed here. New technologies which are not considered here should carefully be analyzed for applicability, feasibility, and energy conservation potential.

There is little reliable data on the number, type, percent loading, and efficiency of motors currently in use in the United States. Of the studies that have been done, there is disagreement on the distribution of the electric motors in use and the functions they perform. A 1977 report to the U.S. Department of Energy appears to contain the best data available despite some short comings. The economic benefits of the ideas presented here are based on the data obtained from this report.

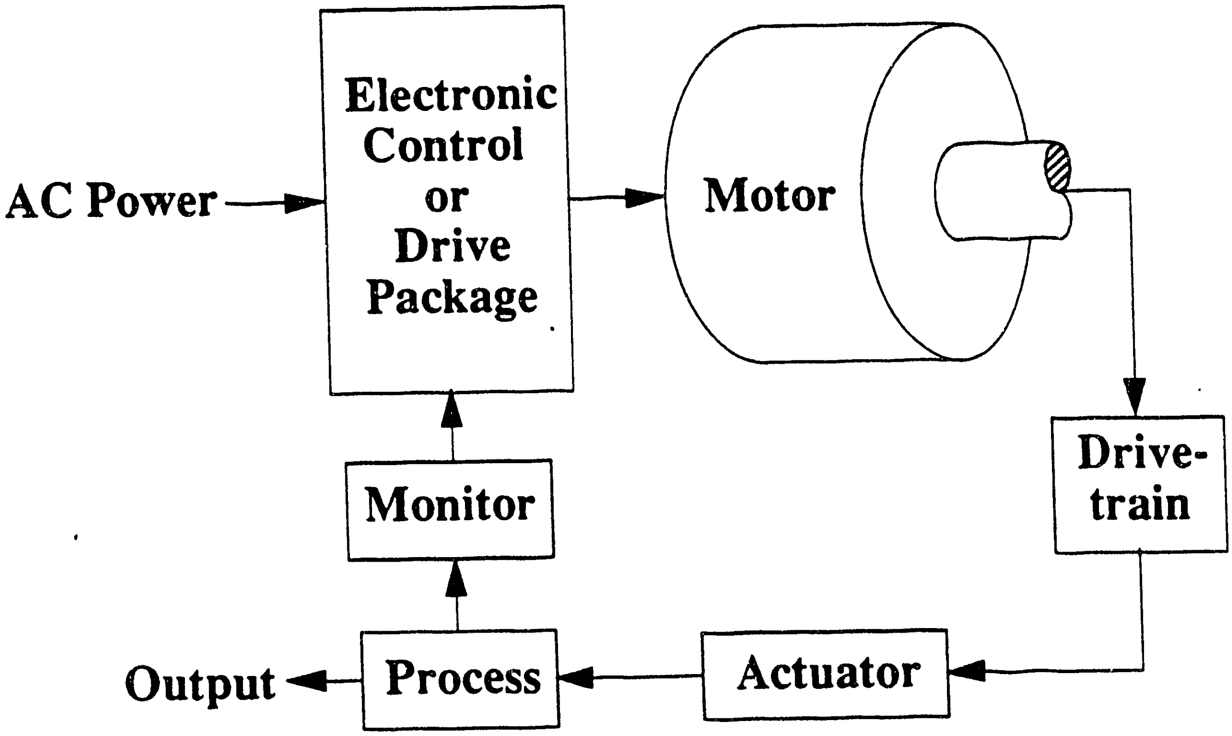

Figure 1.1 • Functional Diagram of a Drivepower System

Figure 1.1 indicates what is meant by a drivepower system. AC power is delivered to the system. The power can be processed by an electronic control or drive package before it is sent to the motor. The motor converts the electrical power into mechanical, or shaft, power. The shaft power is transferred to an actuator via a drivetrain. The drivetrain can be as simple as a directly coupled shaft or it may include gears or belts. The actuator is the device which transfers the shaftpower to the process (load). There are almost as many actuators as there are processes. Some common actuators are compressors, fans, blowers, conveyors, and grinders. Energy efficient drivepower systems often incorporate a monitoring system which observes one or more aspects of the process and uses this information to adjust the operation of the electronic control or drive package, thereby controlling the motor and actuator.

Motor Types

All motors generate torque through the interaction of two magnetic fields which must have a nonzero angle between them. Maximum torque is produced at ±90 (electrical) degrees and minimum torque at zero (electrical) degrees. There are numerous ways to generate these magnetic fields. The following briefly describes the basic operating characteristics of the motors typically used in industrial applications. Speciality motors which may find a niche in industrial applications in the future are briefly examined.

Direct current (dc) motors use either windings (coils) or permanent magnets to generate a magnetic field in the rotor. For the classical dc motor, brushes switch the current in the rotor (armature) coils at exactly the right angle so as to keep the magnetic field effectively stationary in space. The stators' magnetic field is produced by stationary field windings. The brushes maintain the angle between the fields at approximately 90 (electrical) degrees. Thus, maximum torque is always developed.

In **permanent magnet dc motors**, the rotor's magnetic field is produced by a permanent magnet. The stators magnetic field is produced by numerous coils distributed about the periphery of the stator. An electronic drive with a rotor-position sensor or a mechanical switching device mounted on the rotor controls when current is applied to the coils. Maximum torques is produced because the relative angle between the fields is maintained at 90 degrees.

A constant amplitude rotating magnetic field is produced in the polyphase stator coils of a **synchronous motor** by applying polyphase alternating current (ac) to the windings. The field rotates at a speed which is dependent on the spatial configuration of the windings and the frequency of the applied current. The magnetic field in the rotor can be produced by a winding or a permanent magnet. If the field is produced by a winding, dc current is applied to the winding through slip rings mounted on the rotor shaft and a set of stationary brushes or by a shaft-mounted exciter (ac generator) and rectifying diodes. The magnetic field of the rotor chases the magnetic field of the stator. The torque delivered to the load is dependent on the angular displacement between the two fields. Angular displacement increases with increasing load to a maximum at 90 (electrical) degrees. This motor requires special starting methods because it only develops torque at one speed.

Synchronous motors are generally very efficient (96-98%). They are generally used in special applications that require large hp ratings. Synchronous motors are also more expensive because of their complexity and unique starting requirements.

Additional types of synchronous motors are **reluctance motors** and **hysteresis motors**. The hysteresis motor is seldom used in industrial applications because of low efficiency (less than 10%) and the high cost of rotor alloys. The reluctance motor is becoming more popular and shows great promise for future applications.

The stator of the induction motor is identical to the stator of the classical synchronous motor. The differences are in the design of the rotor. The rotor of a **squirrel cage motor** consists of conducting bars and shorting end-rings which are embedded in a laminated steel core. If the steel core is removed, the namesake for this rotor design will be observed. With polyphase ac current applied to the stator windings, a rotating magnetic field of constant amplitude is produced. This field will induce a current into the conducting bars of the rotor. This rotor current will produce a second magnetic field. The interaction of the two magnetic fields will generate a torque which will begin to rotate the rotor. As the speed of the rotor increases, the difference in speed between the rotating stator field and the rotor will decrease. The current in the rotor and the torque produced by the rotor also decreases. Eventually the rotor attains a speed which matches the torque requirements of the load. A change in the torque requirements of the load will result in a change in rotor speed. Because current can only be induced in the rotor by the relative motion between the stator field and the rotor, the rotor **cannot** turn at the same speed as the stator field. The rotor must always turn a little slower than the rotating stator field. This type of induction motor is simple, rugged, reliable, and cheap. For motors greater than 5 hp, it constitutes approximately 93% of the 1980 U.S. installed drivepower capacity.

The **wound rotor induction motor** uses the same principle as in the squirrel cage induction motor to produce torque. The rotor of this motor consists of coils of wire. The coils are connected to shaft mounted slip rings. Current induced into these coils is transferred to external resistances through the slip rings and brushes. Changing the external resistance alters the speed versus torque characteristics of the motor. High resistance provides high torques at low speeds. Resistances near zero produces speed versus torque characteristics similar to those of the squirrel cage induction motor. The wound rotor induction motor is used extensively in overhead cranes and hoisting applications.

In both types of induction motors, a change in the torque requirements of the load results in a small change in rotor speed. For an increase in torque, the rotor must slow down. This increases the relative speed between the rotor and the stator field which increases the rotor current, the intensity of the rotor magnetic field, and the torque produced by the rotor. Large changes in rotor speed can only be accomplished by using multispeed induction motors (usually two-, three-, or four-speed motors) or by varying the frequency of the ac current applied to the stator.

All of these motors are available in a wide variety of frame sizes and bearing configurations with different shaft configurations, insulating systems, overload capabilities, operating voltages, frequencies, shaft speeds, cooling methods, starting methods, and lubricating methods. One major manufacturer estimated that such combinations, for its large motors, resulted in over six million possibilities.

Drivepower Control Systems

There are several different types of controls for drivepower systems. These can usually be classified into two broad different groups:

- Adjustable (or variable) Speed Drives.
- Power Controllers

Adjustable-speed drives (ASDs) are used to regulate the speed of the motor. Since the energy a motor delivers to a load is directly related to its speed, ASDs can closely match the energy that a motor delivers to what a process is demanding from it. This often eliminates the need for throttling systems in the process.

Power controllers regulate flow of power or improve the quality of the power in a system. Some examples of these types of controls are power-factor controllers and load management controllers.

Drivepower Interrelationships

The capital cost of drive systems is trivial when compared to the capital cost of the overall plant. For example, 4 billion dollars worth of electric motors are purchased each year. This amounts to 1% of the total investment in plants and equipment. Over the life-time of the motor, the capital cost is only 1 to 3% of its total cost, including electrical energy, replacement parts, rewinding, and periodic maintenance.

The operating cost of a drive system consists of its energy and maintenance costs. The maintenance costs include monitoring, lubrication, cleaning, belt and chain tensioning, and periodic checking and replacement of the parts which wear. These parts are brushes, sheaves, belts, chains, bearings, and gears. Technical improvements will reduce energy consumption because:

- Energy efficient motors typically run cooler.
- High-efficiency drive systems can reduce vibration.
- Solid-state electronic controls are more reliable.
- "Soft-start" in electronic drives reduces electrical and mechanical stress.
- Mechanical improvements can reduce maintenance costs.

Many drivepower systems are installed inside structures which must be heated or cooled. If the structure is heated, the heat released by the drivepower system will reduce the heating load. If the structure is cooled, the heat released by the drivepower system adds to the cooling load. It has been estimated that, when heating and cooling are considered, a unit of energy released within the thermal envelope of a building causes a net decrease of 0.055 units in electric space conditioning energy demand in households, an net increase of 0.035-0.045 units in commercial buildings, and an net increase of 0.04 units in factories.

Some of the benefits of an efficient drivepower system are dependent on how they interact with humans. Examples of these benefits are:

- Reduced noise due to elimination of mechanical components such as belts drives, chains drives, and speed reducers.
- Reduced maintenance due to cooler operation of the motor and the reduced number of mechanical components.
- Increased production through increased reliability.
- Less downtime.
- Improved quality of end-product due to improved control over the manufacturing process.

There are indirect savings associated with efficient drivepower systems. Here is a brief list of these benefits:

- Electrical distribution cables, buses, transformers, and motor starters can have lower capacities..
- Smaller duct cross-sections are needed for air-conditioning systems due to reduced cooling loads.
- Less sound proofing is required.
- Electronic drives are usually smaller than the mechanical systems they replace.
- Permanent-magnet motors are usually smaller than the induction motors they replace.
- The electronic replacement parts require less storage area then the parts they replace.

The security and reliability of systems can often times be improved by energy-efficient drive systems. For example, more energy-efficient systems can be operated from an emergency power supply than less efficient systems; some types of adjustable-speed electronic drives can be operated directly from emergency dc power supplies; and, with proper design, an adjustable ac drive can be bypassed in an emergency.

Efficient drivepower systems present to the utility smaller, more constant, and more predictable loads with higher power factor (the ratio of the usable power {watts} to the delivered power {volt-amps}), smaller starting inrush current, and more load-management opportunities. On the negative side is the increased harmonics which these systems inject into the power supply. These harmonics can disrupt the operation of other equipment, increase heating in transformers and motors, increase losses in the electrical distribution system, and possibly excite resonance in the power system. There are many other pieces of electrical equipment besides ASDs that inject harmonics into the utilities power system. They are:

- Welders.
- Switching power supplies such as those found in computers and televisions.
- AC to DC power supplies, including battery charges.

With proper design, the harmonics injected into the utilities power supply can be significantly reduced.

Other negative aspects of ADS include their sensitivity to sever sunspot activity and the effect of an electromagnetic-pulse (EMP) resulting from a nuclear explosion. This pulse will permanently destroy electronics in the vicinity of the blast. Motors can also be damaged EMP.

Overview of Drivepower Usage

It is estimated that electric motors use at least half of the world's electricity. In the case of the U.S., Little's report estimated that motors less than one hp make up 90% of the motor population. These motors receive 2% of the total motor input energy but account for only 9% of the losses. Only 2% of the motor population is larger than 5 hp but these motors receive 75% of the total motor input energy and account for 85% of the losses. This clearly indicates that improvements in drivepower efficiency should be aimed at large motors.

Motors in the U.S. receive 68 to 78% of the electricity used in the industrial sector, 45 to 48% of the electricity used in the commercial sector, and 37 to 45% of the electricity used in the residential sector. There are many industries where motors receive more than 80% of the electricity. In the stone, clay, and glass industries, electric motors receive over 90% of the electricity.

There is little current data on the total motor population. The 1977 report estimated that there are 730 million electric motors 1/6 hp and larger operating in the U.S. Each year 35 to 40 million motors in this size range are sold. Ninety percent are fractional-hp (less than one horsepower) motors. The life expectancy of these motors is 10 to 30 years. The diverse nature of the motor market makes precise figures difficult to obtain. Little's report identified hundreds of motor manufacturers, twelve thousand motor distributors, and more than one hundred thousand original-equipment manufacturers.

Approximately six billion dollars worth of motors and generators are purchased each year. Of this total, four billion dollars is for electric motors. Fractional-hp motors account for $3 billion of the motor purchases. The remaining one billion dollars is spent on integral-hp motors of which 90% are ac machines.

Because of the wide variety in motor types and operating characteristics, accurate data on currently available motors was almost impossible to obtain in the past. A database of motors and their efficiencies is currently available (1991) from the Washington State Energy Office. The 1977 report estimated that approximately 50% of the electric drive motor energy went into polyphase ac induction motors of from 5.1 to 125 hp with squirrel-cage rotors and with rotor speeds of approximately 3600, 1800, or 1200 RPM.

Barriers to Implementing Drivepower Efficiency

The market penetration of energy efficient (EEM) motors, adjustable speed drives (ASDs), and other technologies is growing, but at a slow rate despite intense competition among the major manufacturers. The federal government, manufactures, contractors, and end users have implemented barriers which prevents or restricts the introduction of these energy saving devices.

A large percentage of the motors purchased each year are by original equipment manufacturers (OEMs). The equipment they produce with the motor installed is then sold through middlemen to the end user. The middlemen are usually more interested in the price/performance ratio than the efficiency of the over all system. Since, the OEMs and middlemen do not pay the utility bill, they have little incentive to improve the efficiency of their products, especially since it is capital cost that drives sales. For example, almost all motors used in residential space cooling or food refrigeration are in a hermetically sealed package with the compressor. This configuration results in quieter operation, a more compact system, and lower maintenance than separate compressors and motors which are coupled together. Because of this configuration, the OEM controls the type of motor and its efficiency. He has little incentive to use energy efficient motors.

Because the integral-hp-polyphase-motor market is stable and growing quite slowly, manufacturers tend to be more conservative with their engineering and marketing techniques. As a result, they are less likely to introduce a new line of energy-efficient motors when customers are used to the stock already available.

Since the money for utility bills is part of the operating expense, it is easy to obtain and needs little justification. The money for capital expenditures is often difficult to obtain and requires extensive justification. A facility manager with a limited capital budget has little incentive to purchase high-efficiency equipment even though it saves operating expense. Many utilities offer rebates for those who install energy efficient equipment yet this fact is often ignored in the regions of the nation where the utility rates are low.

Some industries operate twenty-four hours a day. Because lost production is expensive, they will not shut down to install high-efficiency systems but even continuously operating industrial facilities must shut down for some maintenance or during equipment failures. However, if energy-efficient systems were available at the time of a shut down, they could be installed with little or no additional delay in the restart.

In order to reduce inventory, plants keep a limited inventory of spare motors. In an emergency, a grossly oversized or a low efficiency motor may be used to drive a load. The damaged motor is repaired and placed in storage and the short time fix provided by the spare motor becomes permanent or is used for an extended period of time.

There is also a tendency to build facilities with a reduced or limited number of motor sizes. This reduces the number and types of spare motors required in inventory. As a result, some loads are driven by grossly oversized motors. Even if energy efficiengt (EEM) motors are used, the efficiency of the system will be lower than would be possible with a properly sized EEM motors.

Motor purchases are typically done by a purchasing agent whose main criteria is the initial cost, reliability, and availability. This person is usually not very concerned with the technical aspects of the motor. The life-cycle cost of the motor is seldom considered in the purchase. Motor distributors and manufactures tend to stress their quality control, excellent service, price, and warranties.

In many areas of the industry, capital spending depends on the perceived market and opportunities to keep or gain market share. Modifying or refining an existing manufacturing process is generally a low priority. Day-to-day operations have the highest priority. Generally, operating funds are easy to obtain because they are required for production. Capital funds are difficult to obtain.

There is no standard for identifying the efficiency or power factor of a motor, just a guideline from the National Electrical Manufacturer's Association (NEMA) for a letter code specifying the motor's efficiency on the nameplate. Manufacturers provide efficiency data for their energy efficient line of motors but it is sometimes unavailable for standard efficiency motors even upon request. Since 1978, there has been an attempt to identify efficiency on the motor nameplate but exact values are not given. It is either identified with a letter code which represents an efficiency range or rounded up to the nearest 0.5 to 2.0%. This is too wide of a range when selecting the best motor for a job. In addition, there is no internationally accepted standard for measuring motor efficiency.

There is a glut of information on cost, efficiencies, and extraneous factors which manufacturers use to make their product "look" better than their competitors. There are also many methods used to measure operating characteristics. This results in information which is often confusing. When comparing motors, the barrage of data can lead to a poor choice of motors.

When there is an energy-efficiency program, it historically emphasizes savings in process heat and steam to the exclusion of electricity. If there is an electrical efficiency-program, it is usually oriented towards lighting or HVAC. When there is a drivepower efficiency program, it usually only examines the use of energy efficient motors and adjustable speed drives. There is rarely an attempt to examine the entire drivepower system.

Drivepower systems are often maintained by ordinary staff. When one considers that, one 100 hp motor in continuous operation consumes $41,000 per year worth of electrical energy, it may be worthwhile to consider retraining the staff or redirecting their priorities. It may also be practical to implement an incentive program to further improve energy efficiency.

Few industrial managers appreciate the importance of drivepower efficiency to their profitability especially since the cost of electricity may be only 3% of the total production cost. Why improve something which is a small part of the total production cost?

MOTORS

Electric motors are very efficient energy conversion devices. Some very large motors have been built with efficiencies exceeding 98%. For motors larger than 10 hp, the efficiency is typically greater than 80%. For motors larger than 125 hp, the efficiency is generally greater than 90%.

The efficiency of motors is continually being improved by new technology. This efficiency gain will be useless if these motors are not used in new and existing facilities.

Loss Mechanisms in Motors

All motor losses can be grouped under no-load and load-dependent losses. The no-load losses are:

- Friction losses.
- Lubrication losses.
- Windage losses.
- Cooling losses.
- Heater losses.
- Core losses.

The load-dependent losses are:

- Resistive losses.
- Stray-load losses.

Frictional losses occur in bearings, seals, brushes and slip rings, and at any point where two surfaces rub together. These losses are dependent on the relative speed between the two surfaces. Because most motors operate at or near a constant speed, these losses are generally considered constant.

Lubrication losses are generally the result of an auxiliary (motor-driven) lubrication system. An auxiliary system is typically used with large hp motors. It requires 0.3-0.55% of the input energy. This type of loss mechanism is speed and load independent. In smaller motors, lubrication losses are the result of oil sling-rings or shearing within lubricants. This loss mechanism is speed dependent.

Windage losses are due to the drag that occur as the rotor and cooling fan pass through the air. These losses are proportional to the square of the motor's speed.

Cooling losses are the result of moving gaseous or liquid media through a motor to remove excess heat. In some motors, this consists of a fan mounted on the rotor shaft. The fan moves air around the stator and rotor of the motor. In large hp motors or motors that experience extended periods of low shaft speed, auxiliary systems satisfy the cooling requirements. In large total enclosed fan cooled (TEFC) motors, a shaft-mounted fan circulates air inside the motor enclosure. A second shaft mounted fan or auxiliary equipment circulates a gaseous or liquid cooling media about the external motor housing. Depending on the method of cooling, these losses may or may not be speed dependent.

Heater losses result from applying heat to a motor.to keep moisture from condensing on the windings. There are two general methods of heating motor windings. In one method, a heating element is applied to the heater windings. This heater can be connected such that it operates continuously or only when the motor is off. In the second method, a voltage of 10 to 20% of the name-plate voltage-rating is applied to a single winding when the motor is off. These losses are speed and load independent.

Core losses are the result of eddy-currents and hysteresis in the rotor and stator magnetic materials. Eddy-currents are produced when a time varying magnetic field passes through an electrically conductive material. Because the conductive material has resistance, I^2R losses result. Hysteresis losses are the result of the magnetic field changing the orientation of the magnetic domains within the core. The core losses are proportional to the square of the applied voltage.

Load dependant resistive losses (also known as I^2R losses) are the result of current flowing through the stator and rotor windings. These losses are proportional to the square of the current. The current in a motor is nearly proportional to the applied load.

Stray-load (load-dependent) losses are the catch-all for the remaining loss mechanisms in a motor. These losses are roughly proportional to the square of the current or load. Stray-load losses include:

- Saturation effects in rotor and stator iron.
- Leakage flux.
- Space harmonics.
- Manufacturing imperfections.

Figure 2.1 shows the percentage of losses due to different loss components as a function of horse-power.

Efficiency Measurements

Efficiency is defined as the fraction of the input power delivered to the load. It is usually expressed as a percentage. The methods used throughout the world to measure efficiency differ significantly. The IEEE standard number 112 test procedure provides efficiencies which are two to three percentage points lower than most other international testing procedures. This is generally due to international testing procedures ignoring or estimating certain loss mechanisms. As a result, foreign manufactured motors may have artificially high efficiencies. In very large hp motors (greater than 1000 hp), the differences in efficiencies measured by the various techniques is less significant.

In the United States, the nominal efficiency of polyphase induction motors of NEMA design A or B with a 1 to 125 horsepower rating is stamped on the nameplate. The standard (NEMA standard MG1-12.542) consists of a table of nominal and minimum efficiencies as shown in Table 2.1. The full-load efficiency stamped on the nameplate is selected from the nominal efficiencies in this table. This nominal efficiency is "not greater than the average efficiency of a large population of motors of the same design," which were tested using the IEEE 112 standard. The actual efficiency of a motor when operated at rated voltage and frequency shall not be less than the minimum efficiency.

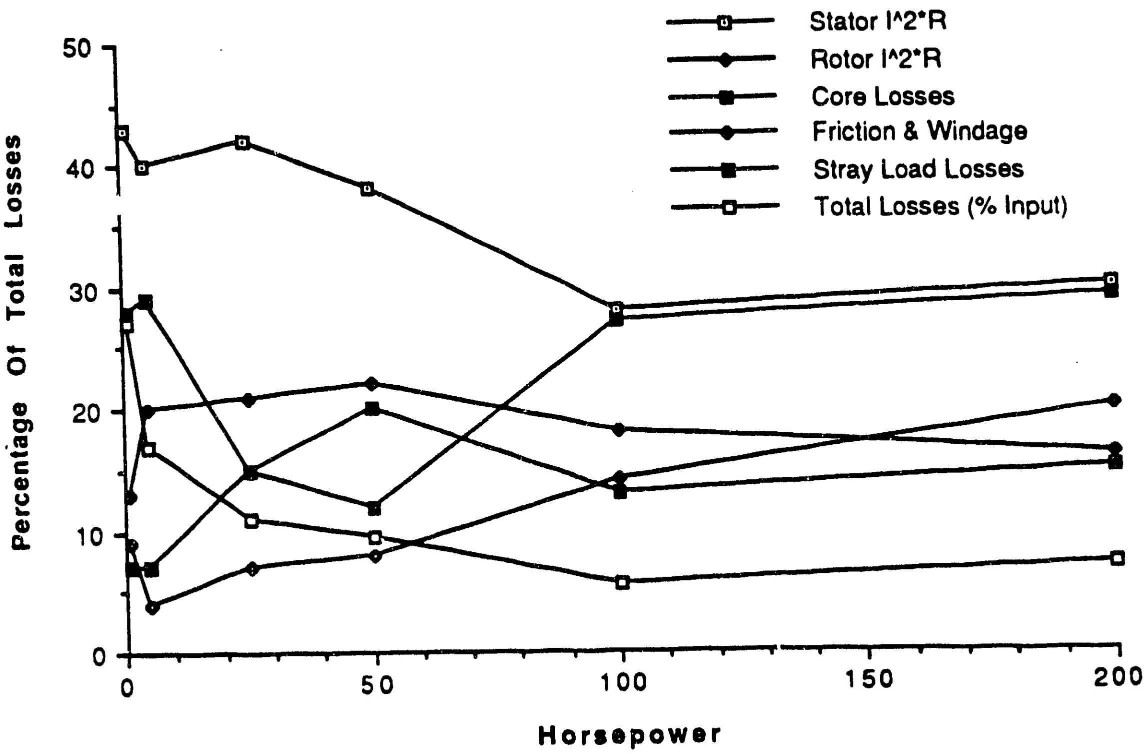

Figure 2.1 • Percent Losses in Various Motor Sizes.

Table 2.1 • NEMA Motor Nameplate Efficiency Guideline

Nominal Efficiency (%)	Minimum Efficiency (%)	Nominal Efficiency (%)	Minimum Efficiency (%)
98.0	97.6	87.5	85.5
97.8	97.4	86.5	84.0
97.6	97.1	85.5	82.5
97.4	96.8	84.0	81.5
97.1	96.5	82.5	80.0
96.8	96.2	81.5	78.5
96.5	95.8	80.0	77.0
96.2	95.4	78.5	75.5
95.8	95.0	77.0	74.0
95.4	94.5	75.5	72.0
95.0	94.1	74.0	70.0
94.5	93.6	72.0	68.0
94.1	93.0	70.0	66.0
93.6	92.4	68.0	64.0
93.0	91.7	66.0	62.0
92.4	91.0	64.0	59.5
91.7	90.2	62.0	57.5
91.0	89.5	59.5	55.0
90.2	88.5	57.5	52.5
89.5	87.5	55.0	50.5
88.5	86.5	52.5	48.0

Some manufacturers use apparent efficiency which is the product of efficiency and power factor. With this method, low efficiency can be masked by a high power factor or a high efficiency can be derated by a low power factor. Specifications should **not** be written using apparent efficiency.

Accurate efficiency measurements cannot be done in the field because a dynamometer test and core temperature measurements are required. Field testing of efficiency will provide results with slight errors (about 1%) which can still be useful. The best procedure is to test the no-load losses of the motor prior to installation. The load-dependent losses can then be measured under normal operating conditions.

A quick field test of the motor's approximate efficiency can be performed if the personnel performing the test are careful. The voltage delivered to the terminals of the motor should be the at the rated voltage of the motor otherwise significant errors can occur. The test procedure takes advantage of the nearly linear relationship between the slip of an induction motor and the load it is driving when the motor is operating between about 25 to 100% of its full load power capacity. Use a watt-meter to measure the power being used by the motor and measure the motor's shaft speed using a tachometer accurate to within 1 rpm. The approximate efficiency of the motor can be determined using the following formulas:

$$\text{Load Power Requirement} = \text{Full Load Power} \times \frac{\text{Synchronous Shaft Speed - Measured Shaft Speed}}{\text{Synchronous Shaft Speed - Rated Shaft Speed at Full Load}}$$

$$\%\ \text{Efficiency} = 100\% \times \frac{\text{Load Power Requirement} \times 0.746\ \text{kW/HP}}{\text{Measured Power Requirement}}$$

where:

Synchronous Shaft Speed is the speed the shaft would turn if there was no load and no losses in the system. For a line frequency of 60 Hz, this is 7200 RPM divided by the number of poles in the motor.

Measured Shaft Speed is the speed of the shaft of the motor while it is driving the load.

Rated Shaft Speed at Full Load is the speed the shaft of the motor will turn when the motor is driving its rated full load.

Rated Full Load is the biggest load the motor was designed to drive in horse-power.

Measured Power Requirement is the actual amount of power, as measured by the watt-meter, that the motor required to drive the load in kilowatts.

0.746 kW/HP is the scaling factor to convert from horse-power to kilowatts.

[Energy-Efficient Motor Systems, by S. Nadel, M. Shepard, G. Katz, and A. de Almeida, American Council for an Energy-Efficient Economy © 1991, page 63]

Reducing Motor Losses

One simple method of improving efficiency in motors is to use more and better conductors and core materials. This was the trend until the 1950s when the cost of energy began to decrease. Nowadays, the efficiencies are even better than those of the pre-1950s due to improved design techniques, materials, and computer optimization.

One obvious improvement was the reintroduction of copper instead of aluminum for windings. This reduced the resistance in equal cross-sections of conductor by about 60%. Aluminum is still used in the construction of some squirrel cage rotors due to ease of manufacturing.

Insulating materials have improved with time. The breakdown voltages and operating temperatures have increased, reducing the percentage of volume required by the insulator. This has lead to increased current densities in the wire and increased operating temperatures of the motor.

There have been significant improvements in magnetic materials over the past century. This started with the introduction of silicon steel. This was followed with single- and double-grain oriented silicon steel. In recent years, amorphous magnetic materials were introduced. They promise to almost eliminate eddy current and hysteresis losses. Because these amorphous materials are brittle, they are currently used in very limited applications.

Other changes have been made in the design of motors to reduce losses. Some of these changes are the results of using better components. Other changes requires complex computer programs to optimize more than 100 interdependent parameters. Thus, a small change in a parameter, such as the number of turns of wire in a coil or the wire size, can detrimentally affect other parameters in a computer optimized motor.

Energy Efficient Motors

Energy efficient (EEM) motors can cost 10 to 30% more than equivalent standard efficiency (SEM) motors. This price premium was found to vary widely between manufacturers. In many cases, the efficiency of energy efficienct (premium) motors is clearly identified while the efficiency of standard efficiency (SEM) motors is sometimes unlisted or otherwise unattainable.

Some manufacturers have EEM motors available off-the-shelf but in limited sizes. Other companies only stock SEM motors. A few companies write specifications which award a bonus or a penalty based on the actual efficiency of a delivered motor.

With both SEM and EEM motors, their efficiency decreases with decreasing load. The SEM motors have a lower efficiency and tend to decrease in efficiency faster at partial loads than EEM motors. Since motors rarely operate at 100% load, this is important in calculating payback period. Also, since most currently installed motors operate at less than 60% load, the energy cost savings can be significant. The only similarity is that SEM and EEM motors have relatively flat efficiency versus percentage load curves down to approximately [illegible]% load.

The simple payback period of the price differential between SEM and EEM motors is a function of price, efficiency, and duty cycle. Table 2.2 demonstrates the cost of operating a 100 hp motor with a $.06 kilowatt-hour tariff for electrical energy. The cases for both 23 and 100% duty cycles are examined.

Table 2.2 • Simple Payback Period of an Energy Efficient Motor (100 hp, $.06 kW-h).

	Standard Efficiency	High Efficiency
Purchase Price	$3,000	$4,000
Efficiency	92%	95%
Energy costs (2000 hours per year)	$9,730	$9,423
Difference in energy costs	------	$307
Payback (years)	------	~3.25
Energy costs (8766 hours per year)	$42,648	$41,302
Difference in energy costs	------	$1,346
Payback years	------	~0.75

The dollar savings can be calculated using

$$S = 0.746 \times C \times N \times P \times \{100/E_s - 100/E_e\}$$

where:

C is the horse power rating of the motor.

N is the hours per year of operation (duty factor).

P is the dollar cost per kilowatt-hour for electrical energy.

E_s is the efficiency of the SEM motor.

E_e is the efficiency of the EEM motor.

S is the dollar savings per year if the EEM is used in place of the SEM motor.

This calculation is generally done assuming full load operation; but a more accurate cost estimate will be obtained if the efficiencies under actual loading are used. If the load is cyclic, the actual savings will have to be integrated over the operating period.

Replacement of failed or in-service motors depends on such factors as the application, loading, duty cycle, duty factor, and power factor. If a SEM motor fails, the rewinding and bearing replacement costs may justify replacing it with a EEM motor. The simple payback period will generally be on the order of two years. If the motor drives a throttled process, the throttling device should be replaced with a variable (adjustable) speed control. The process flow rate or system pressure can be controlled by a variable speed drive and the replacement EEM motor. The decrease in system-wide losses will be significant. If the system has a throttling value and is driven with belts or chains, the gear ratio should be altered to more closely match the flow rate or pressure required by the system when the throttling value is almost 100% open.

All in-service motors should be evaluated to determine those that are economical to replace and if they should be replaced either immediately or upon failure. With a meter which will measure voltage, current, power, and power factor, a user can determine if a motor is a good candidate for replacement. At the same time, this equipment can also be used to identify the duty factor, and duty cycle of a motor.

The EEM motor should have longer insulation and bearing lives due to reduced temperature rise. This translates into reduced downtime, fewer rewinds, and lower change-out costs.

If SEM motors are not replaced, the most efficient SEM motors should be rotated into jobs with the highest duty factor and duty cycle. Lower efficiency motors should be used in areas with light duty factors and duty cycles.

Some of the advantages of EEM motors are:

- They should have a longer life (approximately 50 to 100%) because of lower temperature rise, better insulating systems, and better bearings.
- They may have an extended warranty.

- Their smaller air gaps require high quality bearings be used. This, with cooler operation, results in extended mean-time-between failures (MTBF) for the bearings which are the most frequent cause of motor failures.
- Cooler operation and a higher service factor allows for better overload characteristics.
- Lubrication cycles can be extended due to cooler operation.
- They can better tolerate thermal stress resulting from frequent starts, stalls, overloads, and restricted ventilation.

Some of the disadvantages of EEM motors are:

- SEM motors are typically available off-the-shelf while EEM motors may be special-order items.
- EEM motors tend to have higher starting currents. This results in larger voltage drops in the electrical distribution system. This is especially true with across-the-line starting or large motors in electrically weak distribution systems.
- EEM motors are almost always more expensive than the same size SEM motor.

New Motor Technologies

Due to the development of permanent-magnetic materials, electrically-commutated permanent-magnet (ECPM) dc motors show great promise in replacing dc drives and variable speed ac drives. In these motors, the rotor field is produced by a permanent magnet. The stator field is electronically switched between coils to produce a rotating magnetic field. In general, ECPM controllers are equivalent in complexity to pulse-width-modulated (PWM) drives (one type of adjustable speed drive). These motors show an improved efficiency because of the elimination of rotor I^2R losses and associated stray-load losses. As of 1988, the largest available motor was 125 hp but a 200 hp motor was scheduled for introduction in 1989. In addition, these motors can operate at higher speeds than ac motors making them a prime candidate to replace ac motors and gear drives used to increase shaft speeds.

Permanent-magnet synchronous motors are entering the market place in sizes from 1/4 to 5 hp. These motors tend to have a lower efficiency than ECPMs, but higher efficiencies than the best EEM induction motors. They are more expensive than ECPMs. These motors are operating at 15,000 RPM with operation contemplated at 20,000 RPM.

Homopolar motors, controlled by PWM drives, are being produced with shaft speeds of 50,000, 25,000, and 20,000 RPM in 1, 5, and 50 hp sizes, respectively. Developers expect to build motors of several thousand hp with speeds less than 20,000 RPM and a 25 hp motor with a shaft speed of 100,000 RPM. These motors are now being used to replace turbines in some high shaft speed applications.

The switched-reluctance motor is currently being investigated. This motor, with its electronic drive, has significant advantages over an equivalent induction motor and ASD in efficiency, reliability, and cost. This motor has just recently (as of 1991) started to enter the commercial market.

Technological advances will lead to continued improvement in the operating characteristics of electric motors and drives. All new technologies should be examined when selecting motors and drives for a new project, when replacing an in-service motor, or modifying a process.

Motor Sizing

Figure 2.2 shows a comparison of the efficiencies of EEM and SEM motors as a function of loading. The 5 hp SEM motor shows a rapid decrease in efficiency below 50% loading. The other motors show a rapid decrease in efficiency below 25% loading. Clearly the efficiency of the 5 hp EEM motor is superior to the 5 hp SEM motor. There is less difference between the 150 hp EEM and SEM motors. The EEM motor has a flatter efficiency curve than SEM motors. This makes them a better and more efficient match to cyclic and variable loading.

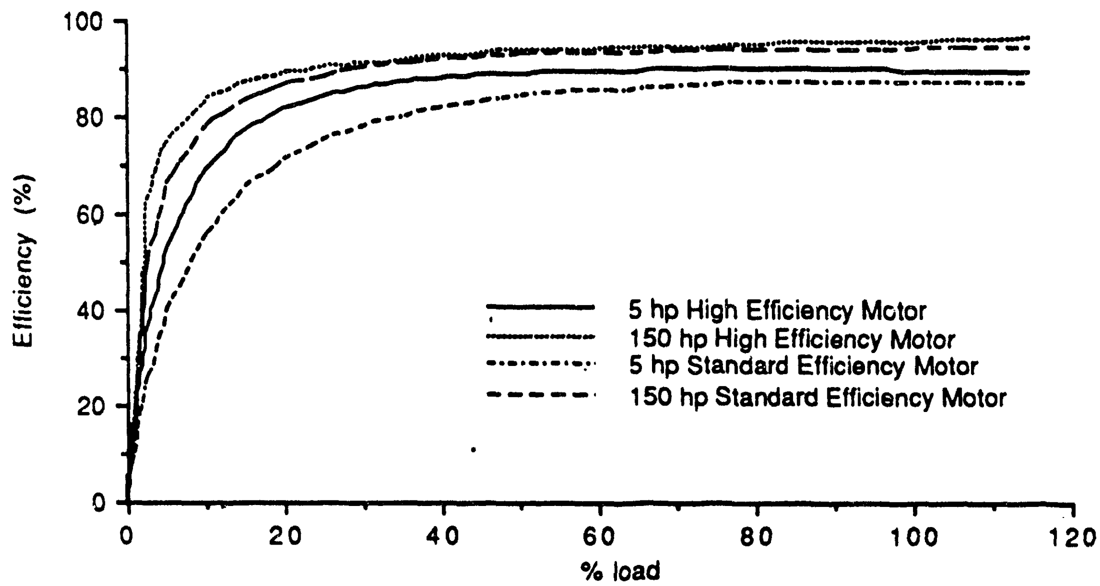

Figure 2.2 • Comparison of EEM and SEM Motor Efficiencies as a Function of Loading (NEMA Design B polyphase TEFC induction motors, 1986).

As Figure 2.2 demonstrates, the efficiency of a motor is dependent on loading. Though sections of these curves appear to be flat, they are not. Peak efficiency generally occurs below 100% loading. If the most efficient operating point of the motor is to be utilized, a motor must be properly matched to the load. The EEM motor has a flatter efficiency curve than SEM motors. This makes them a better and more efficient match to cyclic and variable loading.

It would seem that motor sizing is not a problem if EEM motors are used due to their flatter efficiency.vs.percentage load curves. In reality, light loading produces low power factor which incurs a power factor penalty in the utility billing. The low power factor also increases the losses in the distribution system between the motor and the utilities metering which you pay for.

When sizing a motor, the following must be considered:

- Present and expected load pattern.
- Reliability requirements.
- Starting torque and current requirements.
- Ambient temperature and humidity.
- Air quality.
- Motor enclosures and cooling requirements.
- Cost.
- Electrical supply system and voltage variation.
- Overheating.
- Altitude.
- Starting frequency.

Rewinding

Almost all motors will have to be rewound at least once in their lifetime. If a motor is rewound by unqualified personnel using inappropriate techniques, the efficiency of the motor can be seriously degraded. The result will be higher operating costs when the motor is returned to service. Every SEM motor should be evaluated for replacement or repair. It may even be economically justifiable to replace a SEM motor prior to failure. When evaluating motors for replacement or rewinding the following should be considered:

- Failed SEM motors should be scrapped and replaced with EEM motors or those using new motor technologies. In large hp sizes, the economic advantage of scrapping should be evaluated carefully taking into account such factors as the potential energy savings, mean time between failure (MTBF), cooler operation, and correct sizing.
- Motors with aluminum windings should be rewound with copper wire, replaced immediately, or scrapped upon failure.
- Only low temperature stripping methods should be used to remove damaged windings. Burnout ovens can, and do, damage core insulation resulting in decreased motor efficiency.
- Core testing should be performed on any machine where core damage is suspected. If the core damage cannot be corrected, the motor should be scrapped.
- The rewinder should not alter the number of turns, wire size, or other properties of the windings or core without contacting the manufacturer and the owner of the motor. Because of the interdependence of over 100 variables in a motor, any changes in one variable will alter other variables and may even reduce efficiency.
- Replace bearings with only the highest quality bearings available.
- Keep accurate records on each motor including test measurements, maintenance, and rewinding data.
- Use only the most qualified rewinder who uses modern stripping and rewinding techniques. **Do not** be tempted by low bids for rewinding jobs. **Do not** use the services of rewinding shops which do not use low temperature burnout ovens.

The efficiency of a motor can be maintained or improved only with sound rewinding techniques. A motor's efficiency may be improved by:

- Replacing aluminum windings with copper.
- Carefully hand-winding coils in order to pack large-diameter wire into the slots. Remember, the wire size should be changed only in consultation with the motor's manufacturer.
- Correcting previous rewinding errors.
- Repairing core damage.

Many of the motors purchased today have been designed using a computer. The computer is used to optimize interdependent variables. Any change in one variable affects other variables. A rewinder **must not** alter the design of the motor. It is possible to unintentionally alter the design of a motor. A motor's efficiency can be decreased by:

- Modifying the motor's original design. For example, using smaller diameter wire or reducing the number of turns.
- Using a dull tool when turning the rotor on a lathe.
- Denting, burring, or overpressuring the core.
- Damaging the core during the removal of windings by overheating or chemical stripping.

Instruments are now available to test for unseen core damage. Most reputable rewinding facilities will have the equipment to perform these tests. Every motor should be tested for core damage. If found, the core must be repaired or the motor scrapped.

3. CONTROLS

Because the energy demands of a process are rarely constant, the energy supplied by the motor should match the requirements of the process. This is rarely the case. Motor's are typically supplied with a line voltage and frequency that causes them to run at full speed and supply more energy than the process needs. The excess energy, which can be significant, is dissipated across a throttling device. This section looks at methods of matching the energy requirements of the process to the input energy supplied by the motor.

As an example, the input power requirements of fans, pumps, blowers, and some compressors are proportional to the cube of the shaft speed. These applications are all good candidates for ASDs because a small change in speed corresponds to much larger changes in the power requirements of the load. Figure 3.1 shows the pressure.vs.flow characteristic curves of a fan. In a throttled process, the fan operates at a fixed speed. The excess pressure at a given flow rate is dropped across the throttling device. This is inefficient. In an unthrottled process, the shaft speed of the fan is altered in order to match the pressure requirements of the system at a given flow rate. Notice that the operating curve for the unthrottled process almost matches the constant efficiency curves.

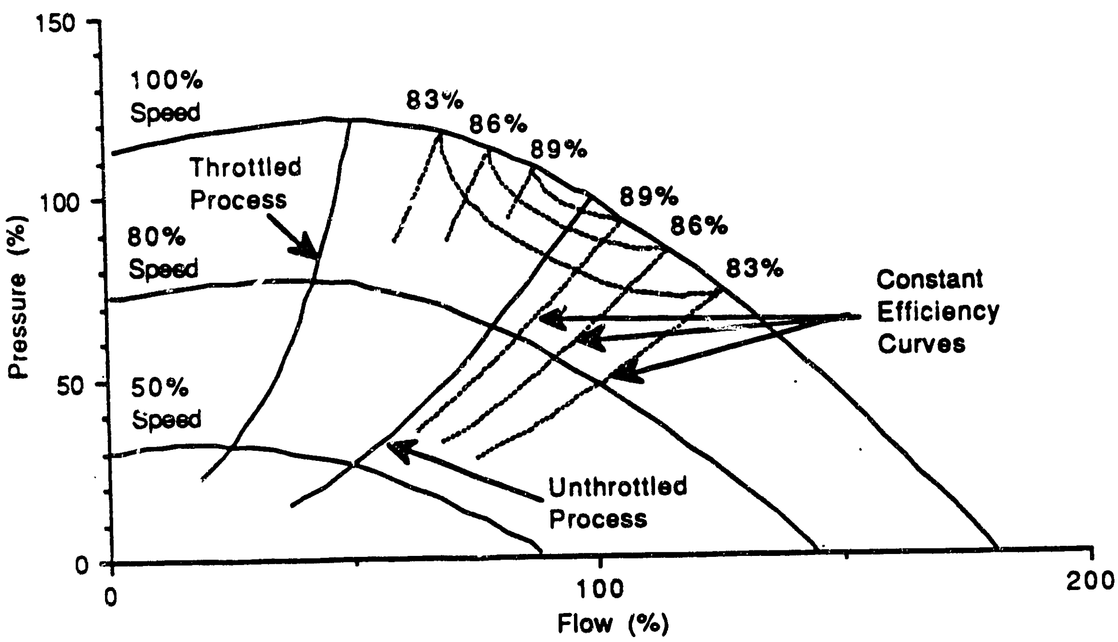

Figure 3.1 • Typical Characteristic Curves of a Fan.

Adjustable Speed Drives (ASDs)

Adjustable speed drives are defined here as electronic packages which supply variable frequencies and variable voltages to ac motors. These drives are also referred to as variable speed drives, variable-frequency drives, variable-frequency inverters, and frequency converters. They control the shaft speed of an ac motor by applying variable frequency to the motor. The terminal voltage is varied in order to maintain the voltage-frequency ratio of the motor.

In an existing installation, the economic potential for the application of ASDs can be evaluated by examining the type of load being driven and the duty cycle (proportion of operating time that the equipment runs at various fractions of full load) and duty factor (number of hours per year the equipment operates). The duty cycle can be obtained with a recording ammeter or power meter. Almost any throttled fan, blower, or pump is an excellent candidate for ASDs. The final evaluation will depend upon the duty factor and the duty cycle of the motor. Some experts consider equipment that runs more than 10 hours per day to be a good ASD candidate.

The advantages of ASDs are:

- A motor's shaft speed can be ramped up to operating speed. This can prolong the life of all mechanical and electrical components due to reduced starting inrush currents and mechanical stress, respectively.
- A motor's shaft speed can be ramped down to zero in a controlled manner.
- ASDs reduce overall energy consumption by matching the energy requirements of the process to the energy supplied by the motor.
- The overcurrent protection in ASDs can significantly reduce or eliminate core damage during short circuits by sensing the short circuit and shutting down the drive. This will limit the localized heating of the core during the short circuit.
- ASDs provide finer control of a motor's shaft speed.
- ASDs respond faster to changes in operating set points.
- A properly specified and installed ASD may be used for regenerative breaking (returning power to the electrical supply).
- ASDs can ride through an interruption (a few cycles) in the power supply.
- ASDs are less sensitive to frequency and voltage variation than motors driven with full line voltages.
- Some ASDs can drive multiple motors.
- ASDs are easier to install than equipment which is placed between the motor and load shafts.
- ASDs may be driven from dc supplies.
- ASDs can supply frequencies higher than frequency of its power supply.

Power-Factor Controllers

Certain motors in the industrial environment experience large variations in load such as escalators, conveyors, crushers, lumber saws, sewing machines, and injection molding machines. The work these motors perform is controlled by the load (speed independent). They momentarily operate overloaded and then operate unloaded or lightly loaded until the start of the next job. During periods of light loading the power factor of the motor is very low. The motors used in these applications are excellent candidates for power factor controllers (PFCs). The savings are incurred through reduced losses in the distribution system feeding the motor and reduced I^2R

losses in the motor.

PFCs are available in sizes up to 800 hp. Most PFCs are applied to motors under 50 hp. They save energy by reducing the motor's terminal voltage. This reduces the magnetizing current in the motor to a point which satisfies the torque requirements of the load. As a result, the power factor of the motor is improved which reduces the losses in the motor (I^2R losses) and distribution system feeding the motor. PFCs may be supplied with circuits which anticipate the torque requirements of the load. This will prevent stalling during sharp increases in load torque.

PFCs are only effective on motors which spend a significant amount of time at less than 25% load. It may be more economical to simply turn the motor off if it is unloaded but this could conflict with the starting frequency limits of the motor. Figures 3.2 and 3.3 shows the power savings versus percent time at full load for three-phase and single-phase PFCs, respectively. From this, it is clear that the more time a motor spends at light load or no-load, the more significant the savings potential of PFCs.

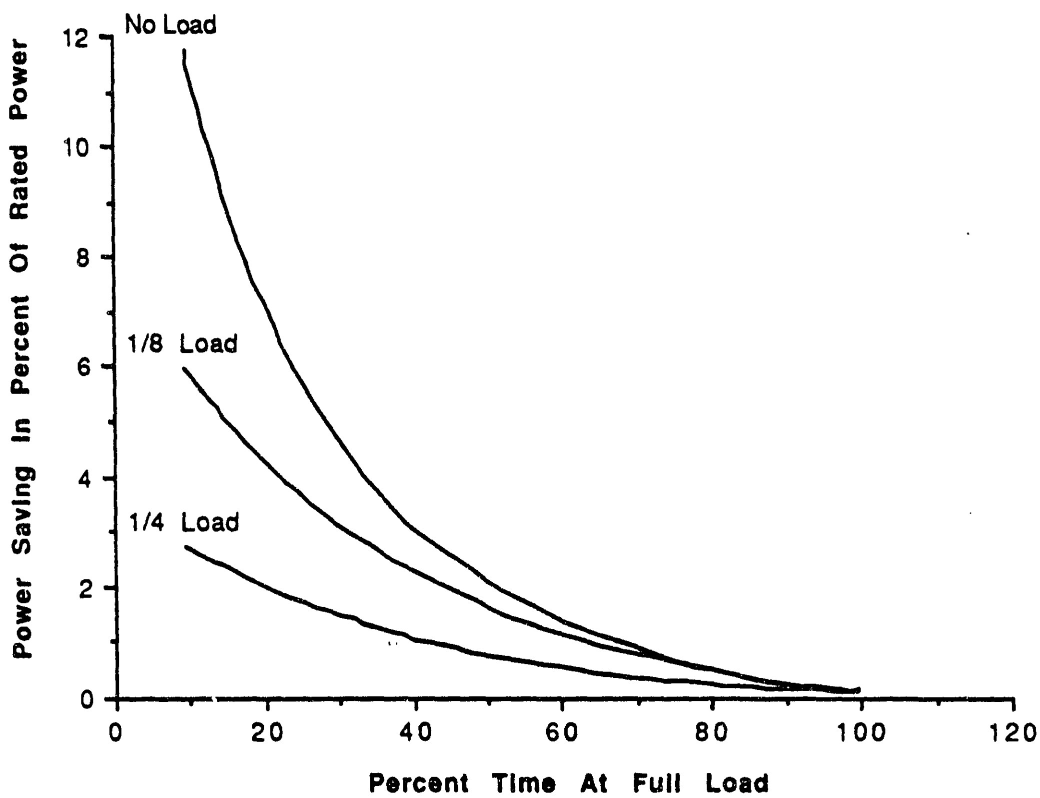

Figure 3.2 • Savings potential of a Three-Phase Power-Factor Controller (at rated voltage)

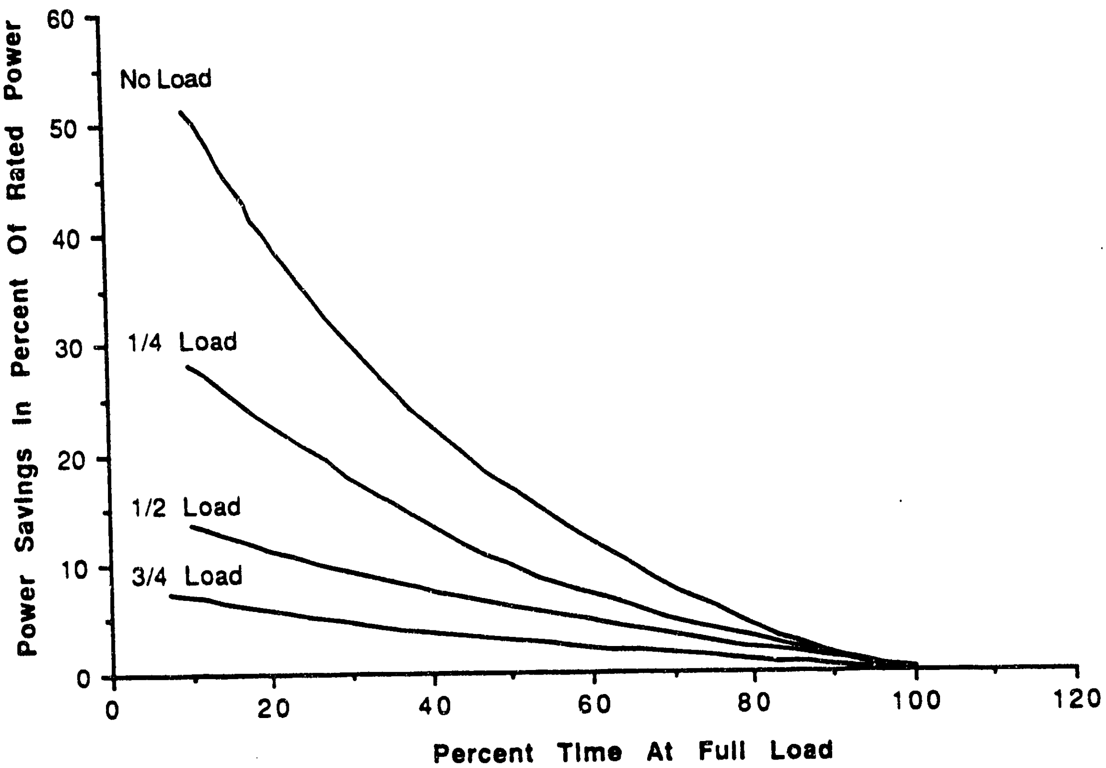

Figure 3.3 • Savings potential of a Single-Phase Power-Factor Controller (at rated voltage)

Wound Rotor Induction Motors

Wound rotor induction motors are designed with coils of wire instead of a squirrel cage rotor. The windings are connected to external variable resistors through shaft mounted slip rings and stationary brushes. Varying the external resistance changes the current in the rotor which changes the torque supplied by the motor. The motor and load will adjust to a new shaft speed as determined by their characteristic curves.

Electronic means may be used to alter the apparent resistance seen by the wound rotor. Some of these electronic controllers provide no advantage over external resistors except for ease of control. Other electronic packages return power to the supply thus reducing the overall losses in the drive systems.

Wound rotor motors are inefficient at low speeds because of the power dissipated in the external resistors. At full speed, when the resistors are shorted out, this motor has an efficiency slightly lower than induction motors with squirrel cage rotors. Electronic drives which return power to the supply (dynamic breaking) have efficiencies equivalent to ASD driven induction motors (squirrel cage rotor).

This type of motor is used extensively in cranes and hoists but can be used in fan, blower and pump applications. They generally have a lower efficiency than equivalent ASDs but are significantly more efficient than a throttled process

Eddy-Current Drives

In eddy-current drives, mechanical energy is coupled between two noncontacting metal elements through a magnetic field. One metal element is connected to the input shaft and the other is connected to the output shaft. The effective coupling is controlled by a dc magnetic field. Approximately 2% of the mechanical input power is dissipated as heat in the drive. In large hp installations, auxiliary equipment must be used to remove this heat. Eddy current drives are rugged and reliable but have a volume roughly twice that of the motor which drives it. They must be installed between the shaft of the motor and the load. The popularity of eddy current drives is decreasing in favor of ASDs but they are still considered to be viable for systems where a small range of shaft speed is required.

Multispeed Induction Motors

Induction motors may be designed with two, three and even four operating speeds. The speed choices are limited to ratios such as 2:1, 3:1, 3:2, or 4:3 by the characteristics of the induction motor. They may be economically superior to other variable speed methods when an application calls for multiple discrete speeds. They tend to be less efficient than ASD-driven high-efficiency induction motors. Multispeed induction motors are bulkier and are about twice the cost of a standard-efficiency motor. The different speeds are obtained through various interconnections of their multiple stator coils. Thus requiring multiple starters and the associated control circuits to operate them.

"Fast Controllers"

The loads served by centrifugal and axial compressors vary widely even in continuously operating plants. These compressors are subject to a phenomenon called surge which can seriously damage or destroy the compressors. Surge is the rapid oscillation (period of 1 to 2 seconds) in fluid flow through a compressor. For example, it can occur during low flow rates when pressure builds up in the system to a point that fluid flow through the compressor reverses. Surge has previously been prevented by recirculating compressed product or bleeding off pressure to atmosphere. Both methods are obviously inefficient. Electronic controllers ("fast controllers") have been developed which match the output of compressors to the demands of the system. Energy savings are the result of matching the requirements of the system to the output of the compressors, reduced need for bleeding or bypassing, and more efficient load sharing in multi-compressor (paralleled) installations. These controllers also detect the onset of surge and make appropriate adjustments in the operation of the compressors to prevent it.

Hydraulic Motors and Pumps

Hydraulic motors and pumps may provide a comparable or superior alternative to other electrical, electronic, and mechanical speed control methods. This is especially true in the lower hp (less than 10 hp) ranges where motor efficiencies tend to decrease. There are four basic types of variable-speed hydraulic drives: hydrostatic, hydrodynamic, hydromechanical, and hydroviscous. Most drives are of the hydrostatic or hydrodynamic design. All of these drives have the advantage of small size and can operate in environments (very high humidity or excessive exposure to moisture) that are unsuitable for ASDs. Some of these hydraulic drives are available in sizes up to 30,000 hp and shaft speeds of 3,000 RPM. Their efficiencies range from 70% to over 90%. Some types of hydraulic drives have low efficiency at low speeds.

Mechanical Variable Speed Drives

Mechanical drives have been developed which allow for speed changing. They are variable-speed belt drives, variable-speed chain drives, adjustable gear drives, and traction drives. Under the traction drive category there are ball variator drives, ring roller drives, ring cone drives, and friction drives. All of these drives have specific hp and speed ranges over which they operate best. Their efficiencies are in the 70% to over 90% range.

Mechanical drives have the following advantages. They:

- Do not inject harmonics into the electrical distribution system.
- Do not degrade power factor.
- Can operate in harsh environments.
- Are usually explosion-proof.
- Are less costly then ASDs.

Load Management Controllers

Drive systems and processes that can have their operation interrupted are excellent candidates for load management. Load management is typically applied to lighting and HVAC systems but can also be applied in industrial environments. Electronic and computer packages are available to control the operation of drive systems and processes based on overall electrical demand. For example, let the demand margin be the difference between the peak demand set-point and the current demand. If the current demand is near the peak demand set-point, systems with a higher historical demand greater then the current demand margin, are disabled to prevent startup. Systems, with historical demands lower than the current demand margin are enabled for startup at the operator's discretion. When a system is started, the demand controller is informed of the startup. If more than one process is started and the combined historical demand for these systems will exceed the current demand margin, the demand controller will select processes that are to be disabled. The controller will inform the operators of this decision and give the operators time to make their own decision on which systems to shut down. If corrective action is not taken, the controller will shut down and disable a process. This process of controlling the starting and operation of drive systems and processes is called load management.

Load Management Controllers work best with lighting, HVAC, and small industrial systems. They are most appropriate for use with cyclical or intermittent loads. Industrial processes that require a large block of power can be monitored and controlled by a load-management system but the most effective method of load management is scheduled operating periods. The most effective load management program is one fully supported by management and enthusiastically implemented by the work force.

A properly setup load management control system contributes to energy efficiency by preventing the electrical distribution system from being overloaded. When an electrical distribution system is overloaded, the voltage of the system typically decreases which in turn usually leads to an increase in system current. As a result, the resistive losses of the system increase.

Load management controllers can also be used to reduce operating expenses in other ways. Many utilities charge their industrial customers based upon the peak demand. Since it is the purpose to prevent the peak demand from exceeding a predetermined set-point, the peak demand that the utility charges for should not exceed the set-point. Without the load management controller, the peak demand could be much higher. Some utilities also base their rates on **when** power is used, with the highest rates during the peak demand period. A load management controller can be used to schedule cyclical loads, such as pumping water into a storage tank, to take advantage of the lowest rates.

Process Controls and Motor Intelligence

Electronic technology will continue to improve adjustable speed drives and process controls. The adjustable speed drives will become more energy efficient, easier to repair, more reliable. More types of ASDs will be available for use with large horse-power motors. Improvements in ASDs will be the result of:

- Increased current handling capabilities of the electronic switching devices.
- Increased voltage handling capabilities of the electronic switching devices.
- Increased switching speed of the electronic switching devices.
- Low power control electronics being incorporated onto the same chip as the power electronic switch. As a result, ASDs will be less expensive and better able to protect the switching device during short circuits.
- Improved algorithms to control the switching devices in the drive. This will result in lower harmonics and higher over all efficiency.

Process control systems will become more computerized. The computer will adapt the control algorithm in response to changes in the characteristics of the process. In many cases, the increased controllability of the process can be of more economic value than the energy saved through the application of ASDs. Process controls will be improved through:

- The ever increasing computational speed of computers and microcomputers will enhance the control options available to the control engineer.
- Complex algorithms will be used to model the process and optimize the control of the system based on factors such as pressures, temperatures, flow rates, chemical composition, humidity, density, and weight.
- The application of process control to variables which were previously ignored.

4. ELECTRICAL TUNE-UPS

All electrical distribution components (such as transformers, switch gear, circuit breakers, and conductors) which carry electrical energy to loads (motors, drives, lights, heaters, computers, and control systems) will dissipate some of the electrical energy that they carry. These losses typically account for 2 to 5% of the losses in the distribution system after utility metering. Most losses in the distribution equipment are sensitive to power factor. In addition, motor losses are sensitive to phase imbalance (three-phase systems), voltage variation, and harmonics.

Phase Imbalance

Voltage (phase) imbalance is defined by the (U.S.) National Electrical Manufacturers Association (NEMA) as 100 times the maximum deviation of the line voltage from the average voltage on the three-phases divided by this average voltage. For example, the line voltages in a three-phase system are 462.1V, 462.5V, and 455.4V which gives a 460V average. The voltage imbalance is:

$$\left(\frac{460 - 455.5}{460}\right) 100\% = 1\%$$

NEMA requires derating of motors that experience more than a 1% voltage imbalance and specifies that this imbalance should not exceed 5%. The losses in a motor increase rapidly as voltage imbalance increases. This results in increased winding temperatures which decreases insulation, bearing, and lubrication lifetime. Voltage imbalance also increases vibration.

Only polyphase motors can experience phase imbalance. It exists in three-phase systems when the magnitude of the voltages between the three-phases are not equal, the phase shift between phases is not 120°, or the impedances in the three-phase load are not equal. These imbalances cause an unbalanced current to flowing into a motor, which causes torque pulsations, reduced torque, increased noise, increased mechanical stress on the motor and load, excessive heating, reduced efficiency, and reduced motor life.

Phase imbalance may be caused by:

- An unbalanced or unstable polyphase utility supply.
- Improper selection or matching of transformer tap settings.
- Single-phase transformers or single-phase loads on a three-phase system.
- A failed or disconnected transformer in a three-phase delta connected bank.
- An open phase on the primary side of a three-phase transformer.
- Faults in a power transformer especially to ground.
- Asymmetrical wound transformer.
- Asymmetrical capacitor load due to a blown fuse.
- Faulty operation of automatic power-factor correction equipment.
- Some types of single-phase failures in ASDs and other control equipment.
- Unequal impedances in the phase conductors of a polyphase system.
- Unbalanced three-phase loads.
- Certain kinds of motor defects.
- Mismatched single-phase transformers in a three-phase transform bank.

Voltage imbalance should be suspected in every electrical system until proven otherwise. Generally, the utility will provided balance three-phase voltage to your facility, but this should be checked and corrected if necessary. With the utility supplying balanced three-phase voltage, the rest of the distribution system can be tested for voltage imbalance. The measuring instruments and transducers must have an accuracy far in excess of 1% if voltage imbalance in excess of 1% is to be measured. Voltage imbalance under no-load conditions is caused by the utility, transformers, or transformer tap settings.

Voltage imbalance under loaded conditions may be caused by the source or the load. If rotating the phase connections to a load rotates or redistributes the imbalance, the imbalance is totally or partially caused by that load. Because small variation in voltage imbalance may occur at any time, go undetected for long periods of time, and significantly increase losses (decrease efficiency), it may be cost effective to install monitoring equipment. In all cases, voltage imbalance should be reduced as much as possible.

Voltage Variation

The variation of voltage away from motor nameplate values will affect motor efficiency. The efficiency will even increase with increased voltage but only until saturation (a radical change in the relationship between current flowing into the motor and the magnetic field it produces) is reached.

Most motors operate with excessive terminal voltage. This is typically due to selecting transformer tap settings for full-load conditions and then partial loading the transformer. The partial loading results in less voltage drop within the transformer and distribution system, thus the overvoltage condition.

Tap changing transformers can minimize the effects of voltage variation. When the output voltage of the transformer deviates from the nominal voltage for a preselected length of time, the tap changer selects a new tap setting. This tap setting will return the output voltage of the transformer to a near nominal value. The tap changer should be set to ignore secondary voltage variations caused by motor starting.

Tap changers are typically used in main distribution transformers. They should be installed in distribution transformers down stream from the main distribution transformer. If their use is not economically feasible, transformer tap settings should be selected that will provide a voltage closest to motor nameplate values for normal operating conditions within the plant. As operating conditions change, so will the loading of a transformer. A monitoring program, either by permanently installed equipment or by monthly/quarterly inspections, should be implemented to monitor system voltage. Deviations away from nominal values should be corrected.

Since motor efficiency is affected by voltage variation, only motors with compatible voltage ratings should be used within a system. For example, three-phase motors are built with voltage ratings of 440V, 460V, and 480V. Use of a 480-volt motor in a 460-volt system will result in reduced efficiency and increased heating. That same motor in a 440-volt system will have even lower efficiency.

Power Quality

Motors are designed to operate with a single sinusoidal frequency applied to its terminals,.but the utility supplied voltage is not a pure sinusoid. Harmonics are present because of the non-sinusoidal flux distribution in generators, nonlinear characteristics of transformers, and the injection of harmonics by electronic power supplies and drives.

Harmonics increase losses in a motor. Only the in-phase components of voltage and current produce torque in an ac motor. All other frequency components contribute to losses, torque pulsations, and reduced motor torque.

Harmonics in the electrical system are increasing due to the use of switching power supplies, dc drives, ac drives, electrically commutated, pulse-width modulated (ECPM) drives (a type of ASD), welders, to name a few. If harmonics are to be controlled, they are most effectively controlled at their source. In the future, utilities will probably add penalties to their billing procedure for the injection of harmonics into their electrical system. Therefore, only the best quality electrical equipment should be purchased and this equipment must be properly installed.

Power Factor

Power factor is the ratio of watts to volt-amps (VA) or the cosine of the phase angle between the voltage and current. If the current lags the voltage (inductive load), the power factor is lagging. If the current leads the voltage (capacitive load), the power factor is leading. A purely resistive load has a power factor of one. Decreasing power factor indicates a load which is increasingly more inductive or capacitive. Because magnetic fields are required in motors to produce torque, they are inductive (lagging power factor). Figure 4.1 shows that power factor decreases with decreasing load. When compared to Figure 2.2, it is apparent that power factor decreases more rapidly than efficiency with decreasing load.

Power factor can be corrected with capacitors via two general techniques. Capacitors can be clustered at a single location. This will increase the power factor seen by the utility's metering and decrease the power factor penalty paid to the utility but it will not decrease the losses in the distribution system. This arrangement also requires a switching system to modify the capacitive loading as the power factor or system loading changes.

In the second method, the capacitors are installed at or near the source of the low power factor and matched to the inductive load. With this arrangement, the power factor will be improved in the distribution system and at the utility's metering. This method has a higher capital cost because it requires more capacitors of smaller size and the resizing of the overload protection devices for the motor. This method also has the advantage of increasing the capacity of the distribution system and transformers because the volt-amps (VAs) passing through them has decreased while the watt loading has remained constant.

Power factor can also be corrected with synchronous motors which are designed to operate with a .8 leading power factor. It is not cost effective to purchase synchronous machines solely for correcting power factor but if they already exist, they can economically be operated to take advantage of their leading power factor. Not all synchronous motors can perform this function.

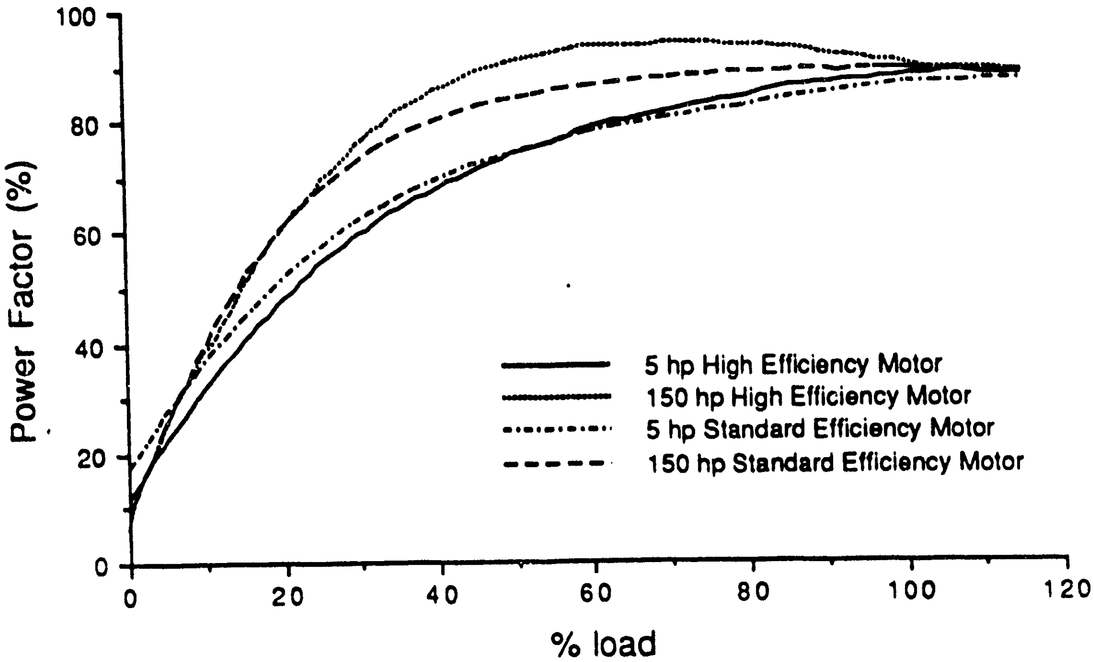

Figure 4.1 • Power Factor in Induction Motors as a Function of Load.

Because achievement of 1% change in a 95% power factor is more costly than a 1% change in an 80% power factor, it is not cost effective to excessively increase power factor. In addition, a power factor which is near one or leading can introduce voltage instability which may damage electrical and electronic equipment.

Wire Sizing

Losses within the distribution system can be further reduced by using wire one size larger than recommended by the appropriate electrical code. Most cities and counties have adopted the National Electrical Code (NEC). Upgrading the wire size is generally impractical in an existing system because the oversized wire may not fit in the existing conduit. In new construction, the increased wire size will increase capital costs only slightly. In future plant expansions or modifications, the oversized wire provides increased current carrying capacity.

5. MECHANICAL EFFICIENCY

Mechanical components (such as gear drives, belt drives, chain drives, seals, bearings, and couplers) are typically used to couple the motor's shaft to the shaft of the driven equipment. These components are used to match the shaft speed of the motor to the load, change the direction of shaft rotation, and couple motor and load shafts when a direct-drive system is not practical. Each of these components add to the inefficiencies of the overall system.

Maximum system efficiency is only possible when mechanical components have been properly selected and installed. The peak efficiency is obtained when all mechanical components are removed. This is often impractical.

Gear Drives

Gear drives are used to make the output shaft speed different than that of the input shaft, change the direction of shaft rotation, change shaft orientation to something other than parallel, or drive multiple pieces of equipment with a single motor. Losses within gear drives are the result of seals, friction, oil churning, and windage. Table 5.1 shows various types of gear drives, their range of efficiencies, and their operating characteristics.

Table 5.1 • Range of Characteristics for Various Types of Gear Drives.

Reducer Type	Ratio Range	Efficiency Range	Maximum HP	Maximum Torque (10^3 Ft-lb)
Helical	2:1 - 400:1	92 - 98%	10000	375
Bevel	1:1 - 5:1	97%	2000	25
Bevel / Helical	5:1 - 200:1	92 - 95%	3500	208
Planetary	3:1 - 1000:1	91 - 97%	900	21
Worm (single reduction)	5:1 - 70:1	55 - 94%	800	32
Worm / Helical	20:1 - 1750:1	55 - 94%	150	40
Cycloidal	6:1 - ∞	85 - 93%	200	43

Typical efficiency curves for helical gears are shown in Figure 5.1. Like motors, there is a sharp drop in efficiency at partial loading. Therefore, oversizing helical gear drives has the same detrimental effect as oversizing motors. Under sizing a gear drive will lead to premature failure and over heating.

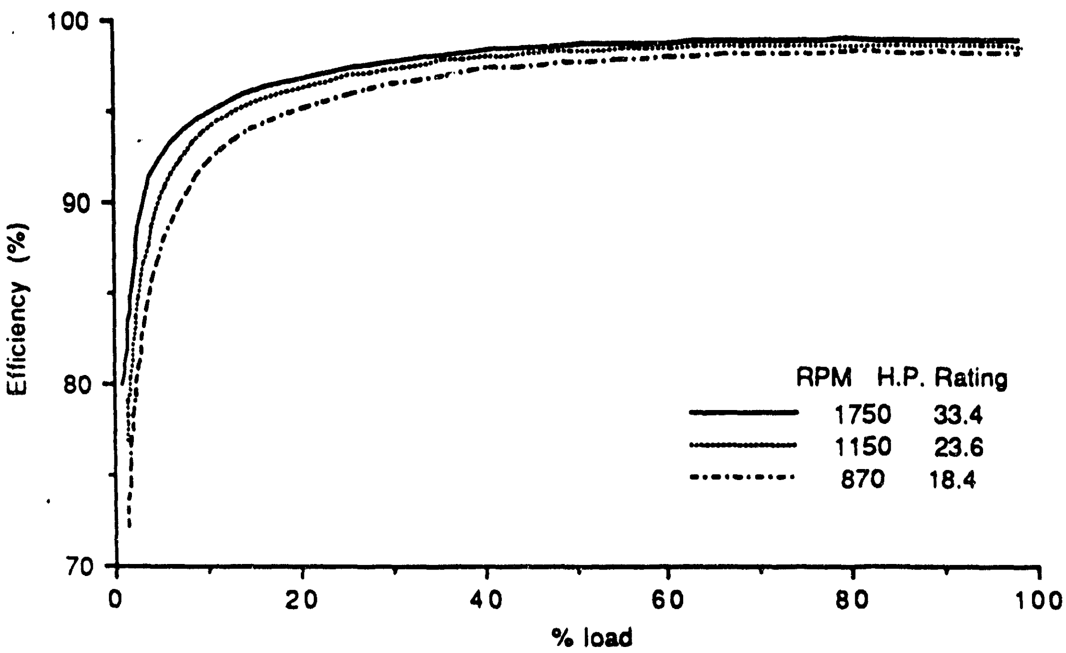

Figure 5.1 • Efficiency Curves for Helical Gear Drives.

Chains and Chain Drives

Two common types of chains are roller and silent. The advantages of chain drives are:

- No slippage.
- Negligible stretch.
- High load capacity.
- Good surge (shock) load characteristics.
- Long life when properly lubricated.
- Operable in hostile environments.
- Long lengths.
- Long shelf life.
- Generally quick and easy repair.

Disadvantages of chains are:

- Efficiency is dependent on lubrication.
- Low speed operation.
- The overall length of the chain increases due to wear.
- Sprockets wear and are typically replaced when the chain is replaced.
- Generally noisy operation.

Roller and silent chain have efficiencies of 85 to 98% depending on lubrication, configuration, loading, and sprocket size.

Belts and Belt Drives

V-belts, synchronous belts, and flat belts are the most common types of belts used in belt drives. V-belts are the most common. They have efficiencies ranging from 90 to 96%. V-belts can be used in applications with shock loading.

Friction between the V-belt and sheave is used to transfer power. If insufficient friction is available, slippage will occur. Because slippage will damage or destroy the belt and sheave, V-belts must be periodically checked for proper tension. Excessive tension can lead to premature failure of the bearings which support the sheave.

The losses in V-belts are due to windage, flexing, bending, centrifugal effects as the belt changes direction around the sheave, entrance/exit friction between the belt and the sheave, creep, and slip. Some V-belts are constructed with transverse notches or cogs which reduce bending losses as the belt moves around the sheave. This results in a 1 to 2% improvement in efficiency over standard V-belts. Proper belt tension will reduce slippage losses.

Synchronous belts transfer power by directly exerting force between the teeth of the sheave and the teeth of the belt. This results in efficiencies of 94 to 99%. The increase in efficiency is primarily due to the elimination of slip and creep losses. Because power is not transferred by friction, the belt tension can be lowered. This reduces bearing loading and increases bearing life. Synchronous belts should not be used in applications with surge loading.

Flat belts have efficiencies of 94 to 97%. They are more common in Europe then the U.S. Flat belts may be used in applications with shock loading.

If practical, belt drives should not be used in new installations. For reduced maintenance and higher system efficiencies, loads should be direct driven or with gears. When belt drives must be used, synchronous belts should be specified except when surge loading is present. Flat belts should be specified in applications with surge loading.

Bearings

Bearings come in many shapes, sizes, and styles. They support moving parts and consume energy in the process. Bearings applied to rotating shafts must support radial or thrust loads. Losses in bearings are due to friction, oil shear, and windage.

Bearing failure can be catastrophic and very costly in terms of damaged equipment and lost production. Proper selection of bearings requires knowledge of many load parameters such as speed, reliability, temperature, environment, and allowable deflection.

Types of bearings are plain, roller, and magnetic. In the plain bearing, radial loads are supported by a sleeve while thrust loads are supported by endplates, flanges, or washers. Bushings are types of plain bearings. Roller bearings use a rolling element between the shaft and the support housing. Ball, needle, and tapered roller bearings are all types of roller bearings. Magnetic bearings, which are rare, support radial and thrust loads with electronically controlled magnetic fields.

Magnetic bearings may be used in applications with shaft speeds less than 300,000 RPM and shaft diameters of 3 to 12 inches. Shaft speeds of 800,000 RPM are possible but eddy current losses become significant. This type of bearing saves approximately 90 to 99% of the energy lost in conventional bearings.

Tribology

Tribology is the study of friction, wear, and lubrication of interactive surfaces in relative motion. While extensive research has been made in this area in the past, it is still considered by many to be a "wish-craft" area requiring judgment calls and experience. This is an area which should be cautiously examined since lubrication caused failures can be catastrophic and very costly.

Lubricants are sensitive to heat and moisture. Chemical are added lubricants to mask odor, resist oxidation and pressure, reduce foaming, inhibit bacterial growth, change vapor pressure, reduce surface tension, alter color, reduce corrosion, and other functions. Teflon has been added to lubricants to reduce friction but teflon is almost indestructible in the environment and human body. There is also the possibility that teflon is a carcinogen. Molybdenum disulfide (MoS_2) has also be added to lubricants to decrease frictional losses.

One of the most important elements of a lubrication system, and one of the most neglected, is the filtration of the lubricant. Circulating lubricants pick up grit and absorb soluble contaminants as they flow through the system. A properly designed filtration system can extend the life and protective properties of the lubricant by purging most of the contaminants.

Grease is a mixture of soap and lubricating oil. Oil is released from the grease when it is heated or agitated. An incorrectly applied grease can release insufficient amounts of lubricant resulting in premature failure of a piece of equipment. Over greasing increases friction losses and splatters greases into unwanted places. A properly selected and correctly applied grease will decrease maintenance costs and improve overall system efficiencies.

6. MAINTENANCE, COOLING, AND CLEANING

A properly implemented maintenance program can reduce overall operating costs. This is generally the result of less unscheduled downtime caused by equipment and motor failures. With less unscheduled down, the personnel who normally repair equipment and motors can implement the maintenance program. A good maintenance program must include proper installation of equipment, mechanical maintenance, operating inspections, appropriately applied lubrication, electrical system monitoring, and thermal monitoring.

A good maintenance program has many facets. These include:

- **Installation**

  Any good maintenance program starts with the proper installation of the equipment. Properly installed equipment has the following properties:

  1. All equipment is mounted with adequate support.
  2. Vibration is reduced to an acceptable level.
  3. Slotted shims are installed under the equipment for proper alignment.
  4. Couplings are properly aligned.
  5. End-play is properly adjusted.
  6. Belts are properly aligned and correctly tensioned.
  7. All equipment bases are properly grouted.

- **Operating Inspections and Maintenance**

  Operating inspections can catch problems before they cause unscheduled downtime. This allows scheduling of repair work at non critical times. The inspections should include:

  1. Vibrational analysis of all rotating equipment.
  2. Insulation testing of motors, transformers, and wire in the distribution system.
  3. Regular inspection for loose mounting bolts, setscrews and other fasteners.
  4. Belt tension and alignment should be checked.
  5. Wear in sleeve bearings should be checked.

  In addition, the motor air inlets should be regularly cleaned along with the inlets to fans, pumps, and compressors.

- **Lubrication**

  Lubrication is a very important part of any maintenance program. Only with proper lubrication can the most common cause of equipment downtime, bearing failures, be reduced. A lubrication program should have these aspects:

1. Lubricating instructions mounted on all equipment.
2. Skilled personnel performing equipment lubrication and record keeping.
3. Expertly chosen lubricants which are periodically reviewed.
4. A color coding scheme to easily identify each lubricant and its place of application.
5. A procedure for purging old grease from equipment.
6. Periodic inspection and evaluation of the filtration system.

- **Electrical System Maintenance**

The electrical system should be monitored and maintained just like all other parts of a facility. An electrical maintenance program should include:

1. Insulation testing in the distribution system and motors.
2. Testing the winding resistance in all motors.
3. Visual inspection of brushes, commutators, and slip rings.
4. Inspection of all electrical connections and contacts for arcing, corrosion, and tightness.
5. Testing for phase imbalance.
6. Testing for voltage variation on each phase.
7. Evaluation of harmonic distortion.
8. Measurement of power factor.
9. Measurement of phase currents in motors and transformers.

- **Thermal Monitoring**

Thermal monitoring can be a valuable addition to any maintenance program because almost all losses in a system manifests itself as heat. Infrared cameras can detect small changes in the amount of heat being released by a piece of equipment. An increase in temperature can indicate a potential problem long before the piece of equipment fails.

Noncontact thermal monitoring with an infrared camera is the most versatile but the equipment is expensive. The camera may be used to:

1. Detect loose or corroded connections in electrical systems without de-energizing the system.
2. Detect hot spots in motors and electrical equipment.
3. Detect increased losses in mechanical equipment.
4. Detect a potential bearing failure.

Even well-placed thermometers or liquid crystal thermometers can be valuable tools in detecting equipment problems.

• Record Keeping

A maintenance program is only as good as the record keeping. If incomplete records are kept, historical information cannot be used to improve the maintenance program. Equipment will not be lubricated in a timely and efficient manner, thus allowing system components to become damaged or over lubricated. Thus, the benefits of a maintenance program will not be realized.

Maintenance records must be kept on each piece of equipment. If a piece of equipment contains may subsystems, a record should be kept on each subsystem. Even though a motor is a part of a piece of equipment, individual records should be kept on each motor. During the lifetime of a typical motor, it might be installed in many different pieces of equipment. Therefore, maintenance records should include:

1. The purchased date of the equipment.
2. The electrical characteristics of the motor such as the winding resistance, insulation properties, efficiencies, and current.
3. Types of lubricants the equipment requires.
4. Time line data on lubrication, maintenance, and repair.
5. Model numbers and order data on the components which are in a piece of equipment such as bearings, seals, gears, belts, sheaves, and chains.
6. Vibrational analysis data.
7. Thermal records of the state of the equipment.

Due to the large volume of data associated with any good maintenance program, all data should be stored on a computer. This is a good application for a database management program which would allow for efficient retrieval and display of historical data. The computer can also be used to print out maintenance schedules.

7. MANAGEMENT

Effective and efficient management of drivepower systems is a challenging and interdisciplinary task. Motivated personnel must be placed in managerial positions and given the freedom to develop and implement programs which will improve drivepower efficiency. There must be coordination of:

- Design.
- Specification.
- Procurement.
- Receiving.
- Installation.
- Operation.
- Maintenance.
- Record keeping.
- Analysis.
- Training.

An effective program is not the responsibility of one person. It must be supported by plant-wide personnel, including upper management. Personnel which use, repair, and maintain drive systems must be educated about their purpose, proper operating procedure, and proper maintenance and repair. Incentive programs should be implemented which reward energy efficiency ideas in the application and modification of drive systems.

8. COMBINED EFFECTS

Drivepower systems in the United States consumed 1464 billion kilowatt-hours of electrical energy in 1986. Of this, 403 to 877 billion kilowatt-hours could have been saved if efficient drivepower systems were in place. At 4.5¢ per kilowatt-hour, this amounts to 18 to 40 billion dollars per year. Including reduced maintenance costs, the savings potential is probably in excess of 25 to 50 billion dollars. The savings potential in each of the previously discussed areas is shown in Table.8.1. Figure 8.1 is a bar graph representation of Table 8.1.

Table 8.1 • Maximum and Minimum Potential Energy Savings by Category.

	Savings Potential (Billion Kilowatt-hours)	
Category	Minimum	Maximum
High-Efficiency Motors	63.0	63.0
Correcting Bad Rewinds	23.0	43.0
Correcting Oversizing	11.0	34.0
Correcting Phase Imbalance	6.0	34.0
Reducing Harmonics	0.0	6.0
Power Factor Correction	9.0	63.0
Correcting Over- or Under-voltage	0.0	76.0
Heater Operation	1.0	1.0
Reduced Distribution Losses	41.0	78.0
Idle-Off Savings	2.0	7.0
Adjustable Speed Drives and Power-Factor Controllers	176.0	345.0
Fast Controllers	2.0	6.0
Drive Train & Bearings	31.0	68.0
Lower Temperature & Better Maintenance	0.0	2.0
Heating,Ventilation, & Air Conditioning Savings	25.0	32.0

High-efficiency motors, ASDs, and PFCs are responsible for more than half of the energy savings potential but improvement of the complete drivepower system will reap additional energy savings. Some savings such as over- and under-voltage, phase imbalance, heater operation, and idle-off savings are obtained at little or no additional cost.

Of the energy delivered to drivepower systems within the United States in 1986, 44% ±16% of that energy could have been saved if all of these suggestions on efficient drivepower systems were in place. Figure 8.2 identifies a range of percentages in five major areas where this energy could be saved. The percentages are not additive due to interactions between components.

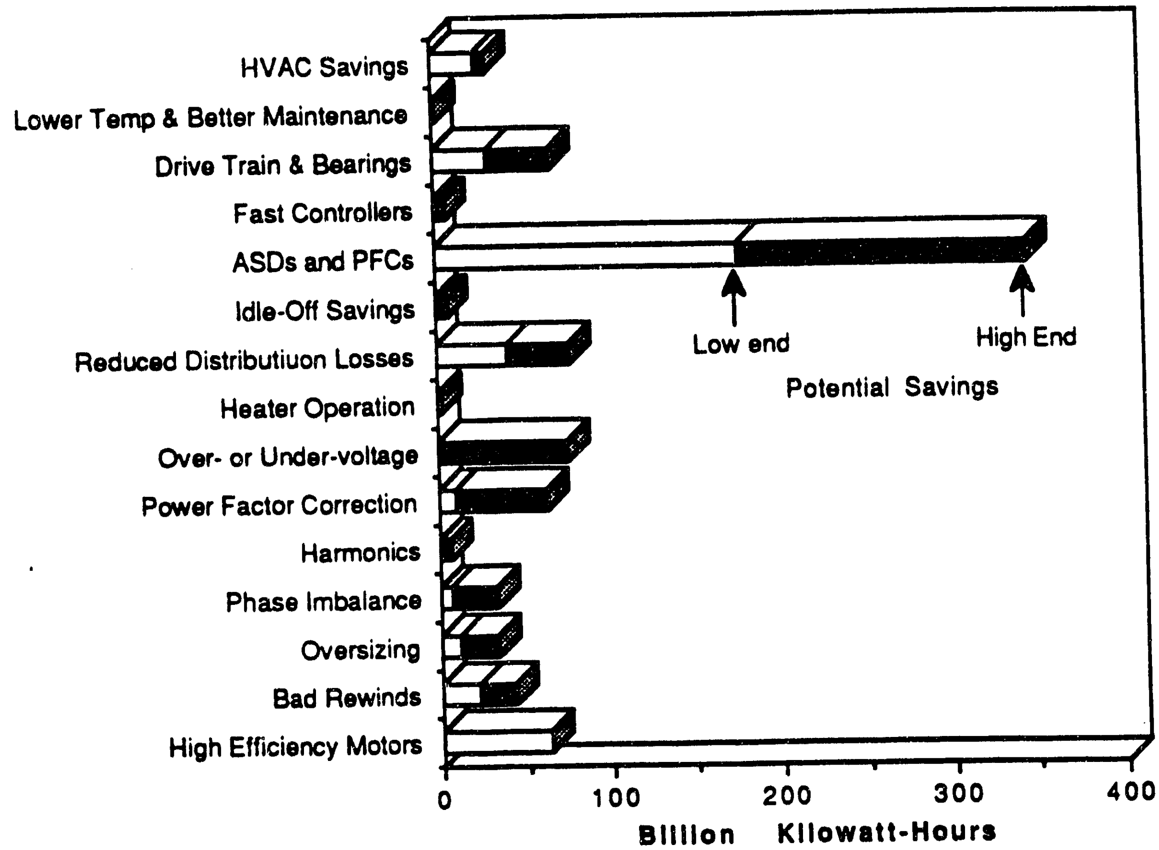

Figure 8.1 • Maximum and Minimum Potential Energy Savings by Category.

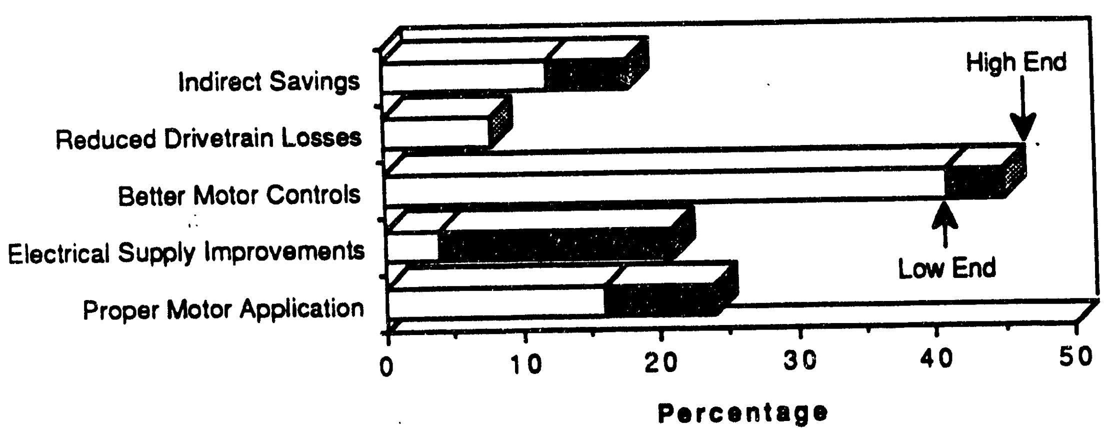

Figure 8.2 • Percentage of Total Losses Attributed to Each Category.

9. RECOMMENDATIONS

All drivepower systems should be examined for energy efficiency operation by competent personnel. They should examine the entire drivepower system. In-plant personnel may be used but they must have a thorough understanding of Electrical Engineering, Mechanical Engineering, process control, fluid flow, lubrication, etc. Since few, if any, in-plant personnel will have the knowledge or experience to thoroughly examine drivepower systems, the assistance of drivepower specialists should be solicited. Regardless of who evaluates drivepower systems, they should:

- Match high-efficiency motors to the loads.
- Replace all throttled systems with ASD driven systems.
- Correcting voltage variation, phase imbalance, harmonics, and power factor.
- Design a maintenance program which:
  1. Adequately lubricates all machinery without over lubrication.
  2. Properly matches lubricates to each application.
  3. Checks alignment, end-play, belt tension,
  4. Implements vibrational analysis.
  5. Implements insulation testing of motors, transformers, and distribution wiring.
  6. Cleans inlets to fans, pumps and compressors.
  7. Checks that motors and other equipment are properly cooled.
  8. Implements a thermal monitoring program.
  9. Develops a thorough record keeping procedure, preferably on a computer.
- Identifies qualified motor rewinding shops.
- Eliminate unnecessary heaters and inefficient use of motor heaters.
- Install controls which shut off idle motors.
- Properly apply power-factor controllers.
- Install "fast controllers" on all appropriate turbomachinery.
- Examine all lighting and HVAC systems for energy savings potential.
- Examine new technologies for applicability and improved efficiency.

END

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