Motor Efficiency, Selection, and Management

A Guidebook for Industrial Efficiency Programs

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Consortium for Energy Efficiency

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In the fiercely competitive global marketplace, minimizing operational costs can mean the difference between success and failure for many companies. Recent reports estimate that motor-driven systems are the largest electrical end use in the industrial sector[1]. As a result, optimizing motor system efficiency can significantly reduce operational costs. However, in many ways, motors are critical to keep facilities operating, and making changes to such a critical function requires careful evaluation of any potential impacts on overall system performance. Given the complexity of these systems, it is important to understand not only motor efficiency, but other selection considerations such as motor design, speed, and the opportunity to use adjustable speed drives (ASDs).

This Guidebook is an informational resource that identifies motor-related considerations that affect the overall efficiency of motor-driven systems. The audience who will find this Guidebook most useful are those that need a basic, non-engineering overview of general purpose motors, motor efficiency, and motor management fundamentals, particularly in the context of optimizing motor system performance. The target audience includes efficiency program staff, efficiency program implementers and others who work to promote motor system efficiency and management to commercial and industrial customers. Commercial and industrial facility operations and procurement personnel may use this Guidebook as a refresher that describes motor efficiency and motor selection considerations related to efficiency. For all audiences, a basic understanding of motor efficiency, motor selection considerations, and management can become the basis for taking action to optimize motor system efficiency through appropriate equipment selection and practicing motor management.

The Guidebook is not intended to replace highly technical resources or as a reference to instruct motor installation or servicing[2]. As an informational resource, the purpose of the Guidebook is to highlight key considerations in motor decision making so that users may appropriately consider them and seek additional expertise where necessary, from local efficiency programs and other credible experts.

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[1] *Assessment of Achievable Potential from Energy Efficiency and Demand Response Programs in the US*, EPRI, January 2009, http://mydocs.epri.com/docs/public/000000000001018363.pdf

[2] See Terms of Use Section 7.5 Terms of Use, for additional details.

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1.0 Introduction

Achieving motor system optimization requires careful consideration of the overall motor system and selecting the right equipment, including efficient motors and, where appropriate, drives. To ensure that motor-driven systems continue to perform optimally over time, it is critical to develop and maintain a motor management plan. This informational Guidebook outlines several key motor system considerations associated with three-phase squirrel cage induction motors, which are the most common type of general purpose motor:

- How to estimate savings available with efficient motors Chapter 3
- Key motor selection criteria to suit application needs such as Design, duty, and size Chapter 4
- Energy savings opportunities with adjustable speed drives Chapter 5
- Motor management strategies to ensure the appropriate information is available to facilitate informed motor decisions and prevent unanticipated motor failure and downtime Chapter 6

1.1 Target Audience

This Guidebook is an informational resource for a wide range of personnel involved in commercial and industrial motor decision making, including professionals responsible for operating and maintaining motor systems and others working to promote energy efficiency. Facility and procurement personnel can use this Guidebook to identify key motor and system efficiency opportunities, including how to get started with a motor management plan. Similarly, efficiency program staff and third-party efficiency program implementers can use this Guidebook to understand the complexity of motor decisions that industrial customers face and identify opportunities for customers to receive assistance from their local utility. The Guidebook is not intended to replace highly technical resources, but to highlight a few fundamental concepts related to motor decision making and efficiency so that users may appropriately consider these issues and seek additional technical expertise where necessary.

What resources do CEE members offer?
CEE members include utilities and other organizations that provide resources to assist customers in optimizing their motor-driven systems, including incentives for efficient equipment, such as motors and drives, comprehensive facility energy audits, education and training, and incentives for customized improvements to pumps, fans, and compressed air systems.

1.2 Technical Resources

The References and Resources chapter includes additional technical resources such as answers to frequently asked questions, a glossary of terms used in this Guidebook and links to the technical references consulted to develop this Guidebook. Green text indicates a hyperlink within the Guidebook. Blue text indicates a hyperlink to a resource that is available from the full list of external sources referenced in this Guidebook, which are also listed in Chapter 7. Additional assistance, including financial incentives and technical expertise may be available from states, local utilities, and regional organizations. The CEE Summary of Efficiency Programs for Motors & Motor Systems includes information describing assistance offered by more than seventy such organizations throughout the United States and Canada.

1.3 About the Consortium for Energy Efficiency

CEE is an award-winning consortium of efficiency program administrators from the United States and Canada that unifies program approaches across jurisdictions to increase impact in fragmented markets. By joining forces at CEE, individual electric and gas efficiency programs are able to partner not only with each other, but also with other industries, trade associations, and government agencies. Working together, administrators leverage the effect of their ratepayer funding, exchange information on successful practices and, by doing so, achieve greater energy efficiency for the public good.

2.0 Efficiency Standards and CEE Program Resources for General Purpose Motors

This chapter summarizes federal minimum efficiency levels and CEE resources available to voluntary programs that exceed minimum levels.

2.1 Federal Motor Efficiency Requirements

The Energy Policy Act (EPAct) of 1992, effective 1997, required 1-200 horsepower (hp) general purpose motors manufactured or imported for sale in the United States to meet federal minimum efficiency levels. These efficiency levels are equivalent to NEMA MG 1 Table 12-11[3] and generally referred to as EPAct. In 1995, Canada passed Energy Efficiency Regulations which established similar efficiency levels for these motors.

Effective December 19, 2010 the 2007 US Energy Independence and Security Act (EISA) updated the EPAct minimum efficiency levels and requires 1-200 hp general purpose motors to meet minimum efficiency levels equivalent to NEMA MG 1 Table 12-12 levels, which are equal to NEMA Premium® efficiency levels, and generally referred to as EISA levels. NEMA MG 1 Table 12-12 efficiency levels are approximately 0.8% to 4% higher efficiency than the corresponding Table 12-11 efficiencies. Manufacturers can no longer manufacture or import 1-200 hp general purpose motors with efficiency levels below the new federal minimum efficiency levels (NEMA MG 1, Table 12-12).

Following the same timeline, the US also established new federal minimum efficiency levels for motor types whose efficiencies were previously unregulated, including 201-500 hp general purpose motors and a newly established category, "Subtype II" motors. Subtype II motors include 1-200hp: U-frame, design C, close-coupled pump, footless, vertical solid shaft normal thrust (tested in a horizontal configuration), 8-pole (900 rpm), and motors of not more than 600 volts (other than 230 or 460 volts). After December 19, 2010, manufacturers cannot manufacture or import 201-500 hp general purpose motors or subtype II motors with efficiencies below NEMA MG 1, Table 12-11 levels.

2.2 Efficiency Levels That Exceed Federal Minimum Requirements

The Consortium for Energy Efficiency (CEE) establishes efficiency tiers at levels that exceed federal minimum requirements for appliances and equipment. In general, efficiency tiers designate products or services that achieve superior energy efficiency without trade-offs in performance or quality and that offer attractive financial payback on any additional initial purchase costs. These efficiency tiers provide definitions that are recognized across the US and Canada to identify high efficiency products and services that efficiency programs can voluntarily adopt to use for their incentive programs.

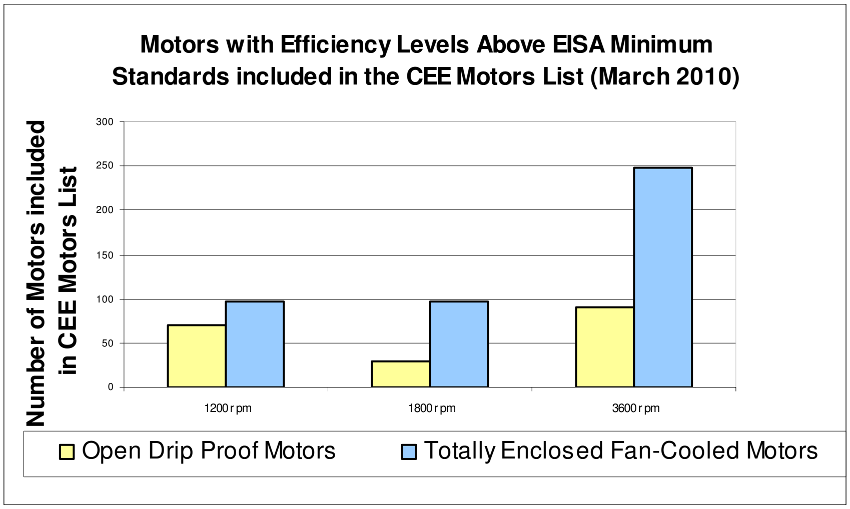
In 2001, CEE and NEMA aligned their specifications for 1-200 hp motors, as listed in NEMA MG 1 Table 12-12. When federal minimum efficiency requirements are equivalent to the CEE specification levels, CEE will transition its specification to retirement. Accordingly, many efficiency programs are considering how to transition their incentive programs for this equipment.

[3] NEMA Table 12-11 includes efficiency values for 1-500 hp 3600, 1800, 1200, and 900 rpm motors. Whereas the Energy Policy Act established minimum efficiency values for 1-200 hp 3600, 1800, and 1200 rpm motors; minimum efficiency values for 201-500 hp motors were not established until the 2007 Energy Independence and Security Act (EISA).

For some motors, the highest efficiency motor available is on that meets federal minimum efficiency levels, for others, motors that exceed federal minimum levels are available. CEE has developed the CEE Premium Efficiency Motors List, which identifies available 1-200 hp motors with efficiency levels that exceed the new EISA minimum level. The availability of motors that exceed EISA minimum levels is illustrated in Figure 1, product availability as of March 2010.

Prior to EISA, a minimum efficiency level did not exist for 201-500 hp general purpose and Subtype II motors. The new EISA federal minimum for these motors (NEMA Table 12-11) is below NEMA Premium®[4] efficiency levels. CEE established a Guidance Specification for 250-500 hp General Purpose Motors as a resource for efficiency program administrators designing programs for these motors.

Figure 1 Motors in the CEE Premium Efficiency Motors List



Following the enactment of EISA, many utility efficiency programs will consider changes to their programs for general purpose motors. See the CEE Summary of Motors & Motors Systems Programs for information about available programs for motors, motor management, and motor system optimization.

2.3 Summary
Table of Federal Efficiency Levels and CEE Resources

Table 1 summarizes the federal law, technical reference, and available CEE resources for the three motor product categories discussed in this section: 1-200 hp and 201-500 hp general purpose squirrel cage motors and the newly established EISA subtype II motors.

Table 1 Federal Minimum Efficiency Levels and CEE Resources

Product Category	Federal Minimum Levels		CEE Resources	
	Law, Effective Date	**Technical Reference**	**CEE Efficiency Program Resource**	**Technical Reference**
1-200 hp general purpose motors Design A/B, 1200, 1800, 3600 rpm	EPAct, 1997	NEMA MG 1 Table 12-11	CEE Premium Efficiency Motors List	Exceeds NEMA MG 1 Table 12-12
	EISA, 2010	NEMA MG 1 Table 12-12		
201-500 hp general purpose motors Design B, 1200, 1800, 3600 rpm	EISA, 2010	NEMA MG 1 Table 12-11	CEE Guidance Specification	NEMA MG 1 Table 12-12
EISA Subtype II Motors: o U-frame, design C o close-coupled pump o footless o vertical solid shaft normal thrust o 8-pole (900 rpm) o Motors of not more than 600 volts (other than 230 or 460 volts)	EISA, 2010	NEMA MG 1 Table 12-11	N/A	N/A

[4] NEMA Premium® is a trademark owned by the National Electrical Manufacturers Association, www.nema.org.

3.0 Selecting Efficiency and Estimating Savings

Lower operating and maintenance costs, coupled with relatively short payback periods, make efficient motors a sound business investment. In short, efficient motors accomplish more work per unit of electricity than their less efficient counterparts. Estimating savings associated with efficient motors requires understanding a few basic concepts, applying the correct formulas, recording the results, and identifying the right opportunity to upgrade.

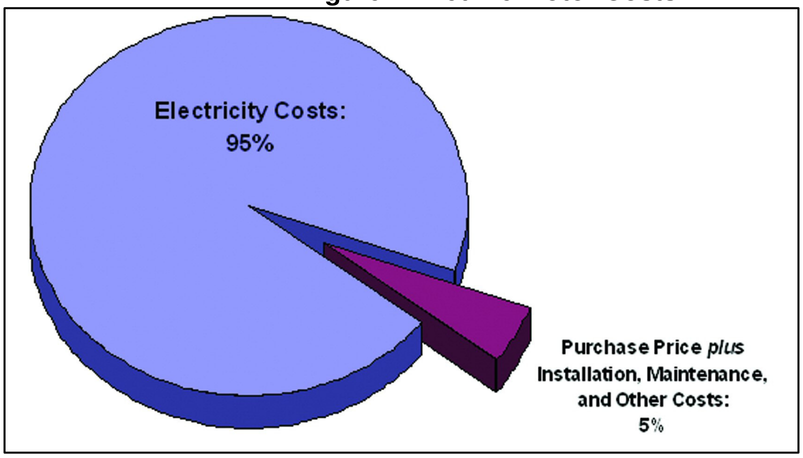
3.1 Motor Selection

It is important to use a consistent measure to compare the efficiency of one motor to another. Motor nominal efficiency is defined by NEMA to be the average motor efficiency value obtained through standardized testing of a given motor model population[5]. "NEMA Nominal efficiency" is required to appear on the motor nameplate. In addition to nominal efficiency, it is also important to know the motor load factor for a given application to compare motors using nominal efficiency at the expected load factor.

3.2 Estimating Energy and Cost Savings

As depicted in the adjacent illustration, electricity costs typically account for approximately 95% of the cost to own and operate electric motors over a ten-year operating period.

Figure 2 Lifetime Motor Costs



Source: MDM "Motor Planning Kit", www.motorsmatter.org

To demonstrate potential cost savings, this chapter includes calculations associated with replacing a 150hp motor with an efficiency level below EPAct levels with a 150hp NEMA Premium® efficiency motor[6]. To simplify the calculations, several costs have not been included, such as the labor cost associated with motor change-out. In the case of failed motors, labor cost is less significant as all options for repair-replacement would require motor change-out. In addition to understanding efficiency opportunities associated with selecting more efficient motors, it is important to evaluate whether motors are properly matched to meet application needs.

Table 2 on the adjacent page identifies the required information for the calculations to demonstrate potential energy savings through upgrading motor efficiency, shown in the equations and calculations which follow.

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[5] NEMA Standards Publication MG 10-2001 *Energy Management Guide for Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors,* www.nema.org/stds

[6] These simplified calculations also include the following assumptions: (a) the calculation applies to one motor only, (b) the new motor has the same power as the replaced motor, (c) the load profile is at constant power for the annual working hours period, (d) the electricity price remains constant over the annual working hours period.

Table 2 Required Information for Motor Efficiency Upgrade Calculations

<table>
<tr><td>Motor Power (hp)</td><td>Horsepower (hp) is a unit of power that indicates the rated output of a motor.</td></tr>
<tr><td>Load Factor (LF) [%]</td><td>The ratio of $\frac{average\ motor\ load}{rated\ motor\ load}$ for a given period of time.</td></tr>
<tr><td>Annual Operating Time [hours]</td><td>The number of hours that the motor operates each year. Manufacturing sector estimates[7]:
<table>
<tr><th>Motor hp</th><th>Annual Operating Hrs</th><th>Motor hp</th><th>Annual Operating Hrs</th></tr>
<tr><td>1-5</td><td>2,745</td><td>51-100</td><td>5,329</td></tr>
<tr><td>6-20</td><td>3,391</td><td>101-200</td><td>5,200</td></tr>
<tr><td>21-50</td><td>4,067</td><td>201-500</td><td>6,132</td></tr>
</table></td></tr>
<tr><td>Power Conversion</td><td>1 hp = 0.746 kilowatts output. To convert hp to kW, multiply hp by 0.746kW/hp</td></tr>
<tr><td>Motor Efficiency (E_{motor}) [%]</td><td>Motor efficiency appears on the nameplate attached to the motor or in the product catalog as the NEMA Nominal efficiency.</td></tr>
<tr><td>Electricity Cost ($\frac{\$}{kWh}$)</td><td>The average electricity cost expressed as $/kWh, appears on the utility electric bill.[8]</td></tr>
</table>

Equation 1 Motor Efficiency Energy Cost Savings Equation

$$Annual\ Energy\ Savings = HP \times LF \times 0.746 \frac{kw}{hp} \times \frac{hours}{year} \times \left(\frac{100\%}{E_{motor1}} - \frac{100\%}{E_{motor2}} \right) \times \frac{\$}{kWh}$$

Equation 2 Example Annual Energy Cost Savings Calculation with Upgrade to NEMA Premium®

Estimated annual dollar savings associated with replacement of a totally enclosed fan cooled (TEFC) 150 hp, 1800 rpm motor below EPAct efficiency motor with a NEMA Premium efficiency of the same size and type. This calculation assumes both motors have the same load factor, 75%.

Example Data:

Motor Power (hp):	150hp	Motor 1 Efficiency:	93.0%, Estimated below EPAct[9]
Load factor (LF) [%]:	75%	Motor 2 Efficiency:	95.8%, NEMA Premium
Annual operating hours:	5,200 hours	Electricity cost ($/KWh):	$0.07/kWh

$$Annual\ Energy\ Savings = 150hp \times 0.75 \times 0.746 \frac{kW}{hp} \times 5{,}200 \frac{hours}{year} \times \left(\frac{100\%}{93.0\%} - \frac{100\%}{95.8\%} \right) \times \frac{\$0.07}{kWh} = \$640\ per\ year$$

Equation 3 Motor Energy Demand Savings Equation

In addition to potential energy and cost savings associated with hourly energy use, it is also useful to understand associated potential electric power demand costs and savings. This simplified equation provides an estimate of potential savings. Additional information describing how energy demand is calculated is available from your local utility[10].

$$Electric\ Demand\ Savings\ (\Delta ED) = 0.746 \frac{kW}{hp} \times \left[\frac{hp}{E_{motor}1} - \frac{hp}{E_{motor}2} \right]$$

Equation 4 Example Energy Demand Savings Calculation with NEMA Premium Motor

$$\Delta ED = 0.746 \frac{kW}{hp} \times \left[\frac{150hp}{.930} - \frac{150hp}{.958} \right] = 4\ kW$$

3.3 Available Software Tools to Estimate Savings

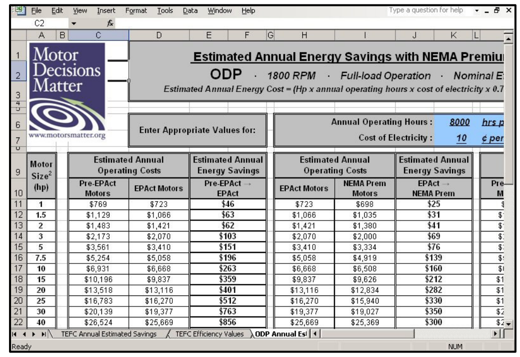
[7] US Department of Energy, *Industrial Electric Motor Systems Market Opportunities Assessment*, 1998, www1.eere.energy.gov/industry/bestpractices/pdfs/mtrmkt.pdf

[8] Energy Information Administration, Average Retail Price of Electricity to Ultimate Customers by End-Use Sector. As of July, 2010, the average retail price of electricity for the industrial sector is 7.31 cents/kWh www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html

[9] Estimated TEFC Efficiency Values, MDM Simple Savings Chart www.motorsmatter.org/tools/index.asp

[10] For example description of electric demand: www.nationalgridus.com/niagaramohawk/non_html/eff_elec-demand.pdf

Free software tools, such as the *Motor Decisions Matter*[SM] Simple Savings Chart and MDM MotorSlide Calculator, are designed to quickly identify potential savings when upgrading motor efficiency. The three most common efficiency classes are included in both tools: below EPAct, EPAct, and NEMA Premium® efficiency levels[11]. After entering hours of operation and cost of electricity in this spreadsheet, a side-by-side comparison of annual energy costs and annual energy savings is provided. The software includes calculations for totally enclosed fan cooled (TEFC) and open drip proof (ODP) motors and is available at www.motorsmatter.org.



The US Department of Energy (DOE) publishes MotorMaster+, a free software tool that can be used to estimate savings associated with motor replacement and repair. MotorMaster+ is a comprehensive savings calculation and motor inventory tool that also includes product information for motors 1 to 5000 hp. It includes resources to record and maintain a customized motor inventory. Available at www1.eere.energy.gov/industry/bestpractices/software_motormaster.html.

CanMost, the Canadian Motor Selection Tool, is a free software tool for motor selection maintained by Natural Resources Canada (NRCan). It is modeled after MotorMaster+, and also includes a database of 60 Hz North American and 50 Hz European motors from 1 to 800 hp. CanMost is available at http://oee.nrcan.gc.ca/industrial/equipment/software/intro.cfm?attr=24.

3.4 Identifying Opportunities to Upgrade Motor Efficiency

There are several motor decision opportunities when efficiency can be considered including at the time of motor purchase, motor failure, motor repair, and when considering motor right sizing.

Motor Purchase

Whereas motors with higher efficiencies tend to have higher purchase prices, as described in Section 3.2, the purchase price represents approximately 5% of the overall lifetime motor costs. In general, efficient motors are most cost effective in industrial applications with any of the following characteristics:

- annual operation exceeds 2,000 hours
- high electricity rates
- motor repair costs are a significant portion of the price of motor replacement
- rebates and incentives are available from local efficiency programs

Motor Failure

Since the system is already offline, motor failure is an ideal opportunity to identify potential improvements, including replacement with more efficient motors, right-sizing, and other motor-related changes. Analyses, such as the one shown in Chapter 3, or by using calculation tools such as the MDM *1*2*3 Spreadsheet* or DOE MotorMaster+, can be used to estimate the life cycle costs associated with motor repair and replace decisions.

For example, as demonstrated in Section 3.2, replacing a low efficiency motor, e.g. below EPAct minimum efficiency levels, with a higher efficiency motor, e.g. NEMA Premium or above, can yield significant energy savings over the motor's operating life. Another potential opportunity for savings may be to replace oversized motors. Oversized motors are those whose horsepower is larger than the actual power needed for the application resulting in the motor operating at significantly less than 75% load; motors operate most efficiently at 75-80% load. In some cases, downsizing the motor may yield energy demand savings.

Before assessing potential opportunities for efficiency improvements, it is important to first identify why the currently installed motor is sized as it is and assess the potential implications to the motor system or process of downsizing. Generally, replacing motors from a low efficiency class, e.g. below EPAct efficiency, with higher efficiency motors, e.g. NEMA Premium® or higher, achieves greater savings than downsizing to a smaller horsepower within the same efficiency class. To ensure efficiency benefits

[11] The tools focus on the efficiency classes that are most prevalent in the installed motor population and represent the largest energy savings opportunity through retrofit.

associated with motor downsizing are achieved, it is important that the motor match power supply, environment, load, reliability, and business requirements. For example, some motors are oversized to meet specific environmental or operational needs.

Motor Repair

When considering motor repair, it is important to work with your motor service provider to ensure repairs are done according to best practices and that the motor is returned to its nameplate efficiency. The Electrical Apparatus Service Association (EASA) defines best practices for motor rewinds in ANSI/EASA AR-100, *Recommended Practice for the Repair of Rotating Electrical Apparatus*. Canadian Standard C392-11, *Testing of Three-Phase Squirrel Cage Induction Motors During Refurbishment* provides guidance for testing to verify that the refurbishment process has maintained or enhanced motor efficiency and evaluating potential changes to the motor's condition. Additionally, specialty and very large motors, i.e. above 500 hp, are often custom built with high efficiencies and may be more cost effective to repair than replace, underscoring the importance of establishing a repair policy to ensure that any repairs do not negatively affect motor efficiency. Additional details about developing a motor management plan are included in Chapter 6. Some utility efficiency programs provide financial incentives for best practice motor repair and other motor management strategies. See the CEE Summary of Programs for Motors & Motor Systems for details.

4.0 Motor Selection Considerations

The most common type of general purpose motors found in industrial motor systems are squirrel cage induction motors. These motors are generally referred to as, more simply "general purpose motors". The squirrel cage name is derived from the shape of the motor's rotor, which is shaped like a cylinder constructed from bars and rings, which resembles a hamster's cage. To optimize system efficiency, it is important to select the appropriate motor to meet the needs of the application. This chapter summarizes several basic characteristics of general purpose motors, including enclosure type, speed, and design. For more detailed information, the National Electrical Manufacturers Association (NEMA) Motor Generator Section maintains standards for squirrel cage induction, NEMA Standards Publication MG 1 – 2010.

4.1 Motor Enclosure Type

NEMA defines twenty types of motor enclosures, which fall into two broad categories: open and totally enclosed. Open motors have ventilation openings allowing for air-cooling of the motor enclosure (windings). The most common open motor is the open drip-proof (ODP) in which ventilation openings are positioned to keep particles and water from falling into the motor. Most motors found in commercial buildings are ODP motors. For example, splash-proof motors add protection from material that may enter the motor from below, while guarded motors use screens or baffles to protect the motor from particle entry.

Totally enclosed motors are designed to prevent free exchange of air between the inside and the outside of the motor. The most common totally enclosed motor is the totally enclosed fan cooled (TEFC) in which a fan on the opposite end of the motor from the load draws air over the case to provide cooling. For example, explosion-proof motors are designed to prevent the ignition of external gas or vapor by motor sparks and heat, and to withstand an inadvertent internal explosion of gas or vapor. Other TEFC motors, such as explosion proof, washdown duty, and IEEE 841 motors are specifically designed for severe environments such as those where there is a lot of debris, e.g. dust, wood chips, etc.

4.2 Motor Speed

The rated, or full load, speed of squirrel cage induction motors describes the rate at which the rotor rotates when the motor is in operation. For induction motors, the synchronous speed is determined by the number of magnetic poles in the stator. See calculations below, note that 120 is a constant:

Equation 5 Synchronous Speed Calculations

$$Synchronous\ speed = \frac{120 \times 60Hz}{(number\ of\ \ poles\ of\ the\ motor)}$$

$$For\ 2\ pole\ motor\ = \frac{120 \times 60Hz}{(2\ poles)} = 3600\ rpm \qquad For\ 6\ pole\ motor\ = \frac{120 \times 60Hz}{(6\ poles)} = 1200\ rpm$$

$$For\ 4\ pole\ motor\ = \frac{120 \times 60Hz}{(4\ poles)} = 1800\ rpm \qquad For\ 8\ pole\ motor = \frac{120 \times 60Hz}{(8\ poles)} = 900\ rpm$$

Source: ACEEE, "Energy Efficient Motor Systems: A Handbook on Technology, Program, and Policy Opportunities", 2002

For squirrel cage induction motors, the motor operating speed is always slower than the synchronous speed. The difference between operating speed and synchronous speed is known as slip, which is expressed in rpm or as a percentage of rated speed. Since power consumption is related to speed, slip is an important consideration related to motor efficiency and system performance. This is particularly important in centrifugal applications such as fans and pumps, where power consumption is related to the cube of the speed. For example, motors with higher operating speed, i.e. small slip, that drive centrifugal loads where power increases with the cube of speed, the higher speed can lead the motor to draw more power. Additionally, motors with small slip have a lower starting torque than those with high slip and may not be appropriate for applications where a high starting torque is needed.

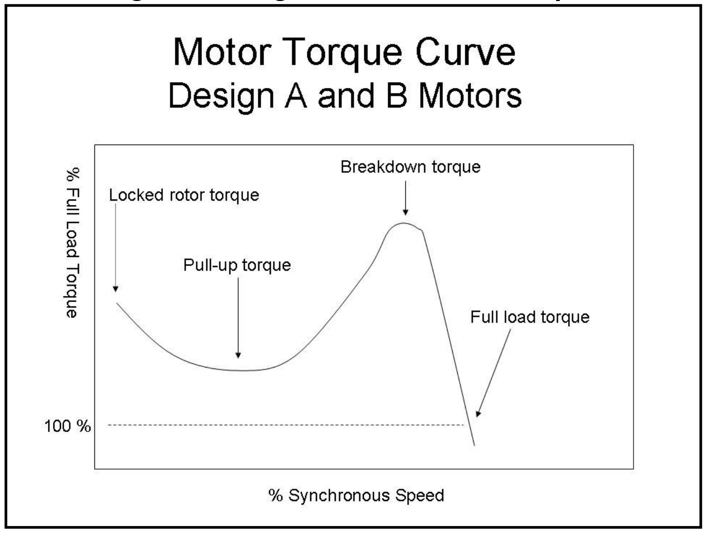
Motor speed can vary across motor designs, with efficient motors tending to have higher rated speed than less efficient equivalent motors. It is important to closely match motor speed to the requirements of the load noting that actual operating speed decreases as load increases.

4.3 Motor Torque

Torque is the twisting force exerted by the motor shaft on the load. Several key terms to describe torque as it relates to speed for general purpose NEMA Design A and B motors, the most common motor general purpose motor design, are described below and illustrated in shown in Figure 3.

1. Locked rotor torque (i.e. breakaway torque, starting torque): the amount of torque required to start the machine rotating from its position of rest.
2. Pull-up torque: the lowest torque developed by the motor between zero speed and the speed which corresponds to the breakdown torque when the motor is supplied at the rated voltage and frequency.
3. Breakdown torque: the maximum torque developed by the motor during that period of acceleration between the speed corresponding to pull-up torque and the full load speed.
4. Full load torque: the operating torque, the torque developed at full-load speed to produce the nameplate output power of the motor.

Figure 3 Design A and B Motor Torque Curve



Source: Engineering Toolbox, "Torques in Electrical Induction Motors," www.engineeringtoolbox.com,

4.4 Motor Designs A-D

Standardization enables interchangeability of motors from different manufacturers in common applications. Standard designs for general purpose motors are grouped into four designations: A, B, C, and D. Table 3 summarizes each motor designation and identifies common applications.[12]

Table 3 Summary of Common Applications for NEMA Motor Design Classifications

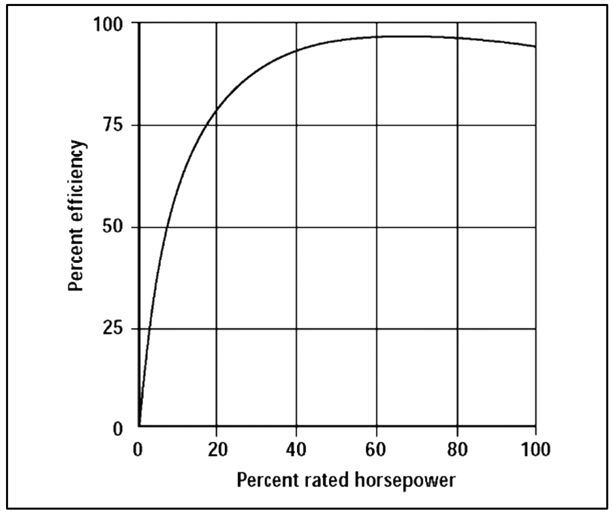
NEMA Design Classification	Design A	Design B	Design C	Design D
Summary Description	Similar to design B but have higher starting current	Most popular motor design, commonly referred to as general purpose motors, and are used in most applications	Intended for applications that require a high starting torque	High torque and slip, designed to handle shock-loads seen in some manufacturing operations
Common Applications	fans, blowers, centrifugal pumps and compressors	fans, blowers, centrifugal pumps and compressors	conveyors, crushers, stirring motors, agitators, reciprocating pumps and compressors	punch presses, shears, elevators, extractors, winches, hoists, oil-well pumping and wire-drawing motors

[12] This information summarizes information in NEMA MG 1 Table, *Typical Characteristics and Application of Fixed Frequency Small and Medium AC Squirrel Cage Induction Motors*, www.nema.org.

4.5 Motor Load

Rated motor load describes the capacity of the motor to do work. Most electric motors are designed to operate at 50%-100% rated load, and operate most efficiently at 75% load[13]. Figure 4 demonstrates the relationship between motor load and efficiency. Load factor, expressed as a percentage, describes the relationship between the average motor load and its rated motor load for a given period of time.

Figure 4 Efficiency vs Load Curve for Induction Motors



Source: Courtesy EASA. *Understanding Energy Efficient Motors*. Out of print.

4.6 Motor Duty Cycle

Motor duty cycle describes the duration and magnitude of loads, periods without load, and periods where the motor is not in operation. Required information to assess motor duty includes motor load inertia and required acceleration, expected number of starts and stops per hour, magnitude and duration of load, and other characteristics such as environmental considerations.

4.7 Inverter Duty

Inverter duty motors are designed according to the requirements of NEMA MG 1, Part 31, "Definite Purpose, Inverter Fed Motors" and have performance characteristics for wide constant torque loads. Inverter duty motors have improved insulation systems that do not degrade as readily when subjected to transient voltage spikes. Improved insulation systems include voltage spike-resistant, inverter-grade magnet wire that enable the motor to withstand voltage overshoots of 1,426 Volts on a 460 Volt motor. Larger inverter duty motors typically include a constant speed auxiliary blower to provide adequate cooling. Inverter duty motors are usually required on high performance applications requiring full torque at low speed. Terms such as "inverter-friendly" and 'inverter-ready" are marketing terms and are not interchangeable with inverter duty. The motor specification indicates if it meets NEMA MG1 requirements for inverter duty.

4.8 Temperature Ratings

Motors are also available in different temperature ratings, which are identified by different insulation classes. The most common insulation is Class B, which is used for general purpose applications. Class F and H insulation are used in motors intended for high ambient temperature applications, or where high operating temperatures are anticipated, as may occur from frequent overloading of the motor or from the use of variable frequency drives. See NEMA standards for additional details, www.nema.org.

[13] *Determining Electric Motor Load and Efficiency,* US DOE Motor Challenge, a program of the US Department of Energy, www1.eere.energy.gov/industry/bestpractices/pdfs/10097517.pdf.

5.0 Introduction to Drives

A drive is a device that is used with a motor to reduce the overall system power consumption by varying motor speeds in applications that do not need to operate constantly at full speed. This variation enables the motor power and energy consumption to follow the load variation, rather than unnecessarily operating continuously at full speed. This chapter identifies common drives terminology, outlines the potential for improving the overall efficiency of motor-driven systems through the use of adjustable speed drives (ASDs), and suggests applications where ASDs may not achieve energy savings.

5.1 Common Drive Technologies

There are several technologies and devices used in motor-driven systems to control motor operation that may be referred to as "drives". This chapter and related sections of the Guidebook focus on drives which alter the frequency and voltage of the electrical power supplied to the motor. This section defines this technology and subsequently identifies other types of drive technologies that are used in motor-driven systems.

Inverters, Adjustable Speed Drives (ASD), Inverter-Type ASD, Variable Speed Drives (VSD), and Variable Frequency Drives (VFD) are terms that are often used interchangeably to describe a device that controls the frequency and voltage of the electrical power supplied to the motor to reduce the motor's rotational speed to match application needs. The terms VFD and Inverter-type ASD only describe devices that control the frequency and voltage of electric power and are not used to describe mechanical control devices. Additionally, the Institute for Electrical and Electronics Engineers (IEEE)[14] defines ASD as controlling the frequency and voltage of electrical power supplied to the motor.

The terms ASD and VSD are sometimes used to describe devices that mechanically control motor speed rather than controlling the frequency and voltage of electric power. Mechanical, electromechancial, and hydraulic speed controls are devices that alter the operational speed for the applied load when the motor operates at constant speed. Examples include fluid couplings, adjustable pulley systems, and magnetically coupled speed control. Other mechanical transmissions used in conjunction with motor operation include belt drives, chain drives, and gear boxes.

Some motor technologies have advanced to combine the capabilities of both a motor and drive, and may be considered a type of drive technology. Advanced motor technologies require power electronics and microprocessor for operation. Examples include: switched reluctance, permanent magnet, brushless motors, all of which may be used in various applications such as compressors, fans, pumps, conveyors, cooling towers, and paper mill machines. Some advanced motors have become available as general purpose motors used in various applications.

5.2 Estimating Energy and Cost Savings with ASDs

Matching motor speed to application requirements through the use of ASDs, also referred to as VFDs or inverters, can achieve significant electricity savings when connected to motors in appropriate applications such as centrifugal pumps and fans. Motor systems that are likely to be appropriate for ASDs are those with the following characteristics:

- Drive a centrifugal fan, pump, or blower and operate long hours (> 2000 hours/yr)
- Fluid or air flow varies over time and control systems such as valves, throttles, or dampers are used to regulate the flow and pressure

The energy savings achieved by using ASDs to conserve motor power use through speed control are illustrated by engineering laws known as the Affinity Laws. In pump and fan systems these engineering laws express the relationship between flow, head or pressure, and consumed power as they relate to speed, summarized as:[15]:

Affinity Laws: Change in power consumption is proportional to the cube of the change in speed, where change in flow is proportional to the change in speed, and change in head or pressure is proportional to the square of the change in speed.

[14] IEEE 100 *Standard Dictionary of Electrical and Electronics Terms*, http://ieeexplore.ieee.org
[15] Engineering Toolbox, Affinity Laws, http://www.engineeringtoolbox.com/affinity-laws-d_408.html

This chapter includes calculations that demonstrate the potential energy savings associated with using an ASD to reducing speed to an average of 70% flow rather than using a throttling valve to accomplish the same result in a pumping system. Diagrams are included for each scenario.

All of the calculations are simplified. For example, the affinity law equations are theoretical and assume that the percent full rated speed is cubed (^3). In a less simplified scenario, the affinity law relationship could be calculated with a value in the range ^2.0 to ^2.7. The calculations do not account for costs such ASD purchase and maintenance or utility demand charges. Additionally, it is important to address any potential harmonics on the electrical transmission and distribution system, e.g. use appropriate corrective measures such as line reactors, advanced technology drives, etc., which may affect both the motor and overall system efficiency. It is also important to ensure that good system grounding and wiring practices are followed. The calculations also assume no static head against the pump.

Table 4 Required Information for Motor and ASD Savings Calculations

Motor Power (P) [hp]	Horsepower is a unit of power that indicates the rated output of a motor.
Percent Full Rated Speed	The ratio $\frac{motor\ speed}{full\ rated\ motor\ speed} \times 100$.
Load Factor (LF) [%]	The ratio of $\frac{average\ motor\ load}{rated\ motor\ load}$ for a given period of time.
Annual Operating Hours	The number of hours that the motor operates each year[16].
Power Conversion	1 hp = 0.746 kilowatts. To convert hp to kW, multiply hp by 0.746kW/hp.
Motor Efficiency (E_{motor}) [%]	Motor efficiency appears on the nameplate attached to the motor or in the product catalog as the NEMA Nominal efficiency.
Drive Efficiency (E_{ASD}) [%]	Drive efficiency appears on the nameplate attached to the drive or in the product catalog. ASDs are very efficient when operating at full load, approximately 97%[17].
Electricity Cost ($\frac{\$}{kWh}$)	The average electricity cost expressed as $/kWh, appears on the utility electric bill.[18]

Equation 6 Annual Energy Cost Equation for Motor-Driven System with ASD
This equation is derived from the affinity law described above.

$$Annual\ Energy\ Cost = \frac{P[hp]}{E_{motor}} \times LF \times 0.746 \frac{kW}{hp} \times (\%\ full\ rated\ speed\ expressed\ as\ a\ decimal)^3 \times hrs \times \frac{\$}{kWh} \times \frac{1}{E_{ASD}}$$

Example Data:

Motor Power (hp):	50 hp
Motor Efficiency E_{motor}	0.93 (1800 rpm, TEFC, EPAct efficiency)
Load Factor (LF) [%]	75%
Percent full rated speed	100%
Annual operating hours	4,067 hours
Electricity cost	$0.07/kWh
ASD Efficiency E_{ASD}	97%

16 See Table 2, Chapter 3 for US DOE estimates for the manufacturing sector.
17 Natural Resources Canada, VFD Reference Guide, http://oee.nrcan.gc.ca/industrial/equipment/vfd-ref/page-05.cfm.
18 Energy Information Administration, Average Retail Price of Electricity to Ultimate Customers by End-Use Sector. As of July, 2010, the average retail price of electricity for the industrial sector is 7.31 cents/kWh www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html

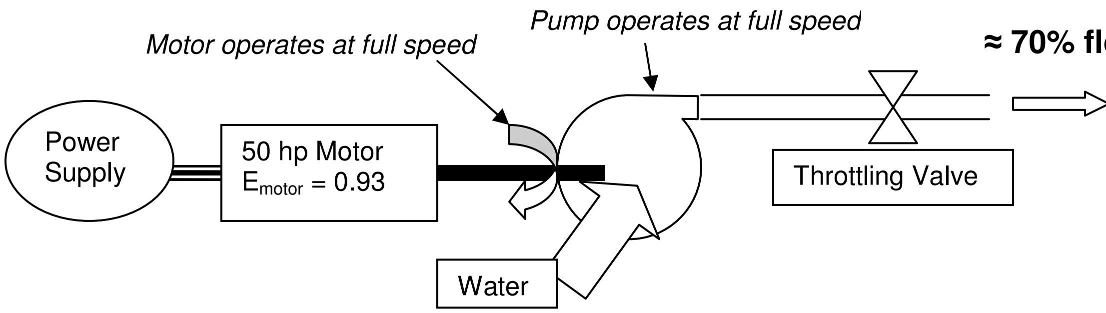
5.2.1 Pump System Example: Potential Savings with ASD on Centrifugal Loads

Below, a 50hp centrifugal pump operating 4,067 hours annually running at full speed, with a 75% load factor, and uses a throttling valve to regulate flow to 70% on average.

Equation 7 Example Annual Energy Cost Calculation with Throttling Valve in Pump System

$$Annual\ Energy\ Cost\ (Throttling\ Valve) = \frac{50hp}{0.93} \times 0.75 \times \frac{0.746kW}{hp} \times (1.0)^3 \times 4{,}067hrs \times \frac{\$0.07}{kWh} = \$8{,}564\ per\ year$$

Figure 5 Pump System Diagram with Throttling Valve

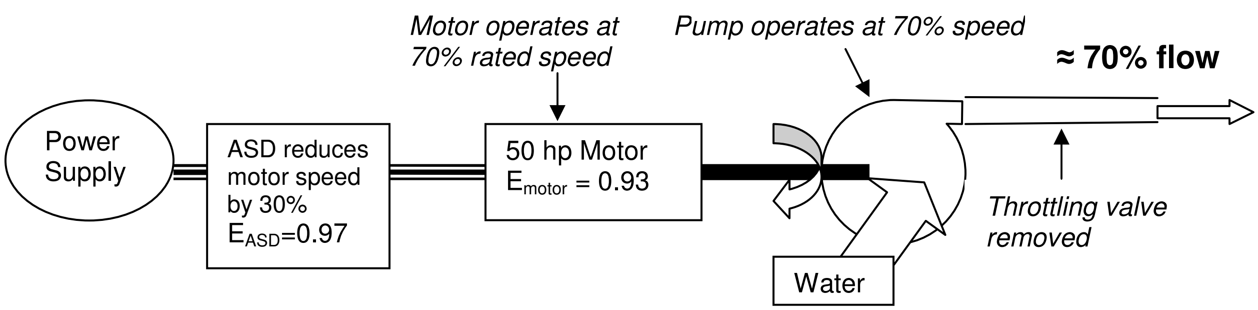


The same system appears below, except an ASD replaces the throttling valve to achieve the same flow regulation by varying the motor's rotational speed.

Equation 8 Example Annual Energy Cost Calculation with ASD in Pump System

$$Annual\ Energy\ Cost\ (ASD) = \frac{50hp}{0.93} \times 0.75 \times \frac{0.746kW}{hp} \times (0.70)^3 \times 4{,}067hrs \times \frac{\$0.07}{kWh} \times \frac{1}{0.97} = \$3{,}028\ per\ year$$

Figure 6 Pump System Diagram with ASD



Using the information from each scenario, potential savings are calculated: replacing the throttling valve with the ASD can achieve approximately $5,500 in annual energy cost savings (Equation 9) and saves approximately 19kW of electric demand (Equation 11)[19].

Equation 9 Example Annual Energy Savings Calculation Associated with ASD in Pump System

$$Annual\ Energy\ Cost\ (Throttling\ Valve) - Annual\ Energy\ Cost\ (ASD) = \$8{,}564 - \$3{,}028 = \$5{,}535\ per\ year$$

Equation 10 Electric Demand Savings Equation with ASD in Pump System

$$Electric\,Demand\ Savings\ (\Delta ED) = \frac{hp}{E_{motor}} \times LF \times \frac{0.746kW}{hp} \times \left[(\%\ full\ rated\ speed\ (motor))^{3.0} - \frac{(\%\ full\ rated\ speed\ (drive))^{3.0}}{E_{ASD}} \right]$$

Equation 11 Electric Demand Savings Calculation with ASD in Pump System

$$\Delta ED = \frac{50hp}{0.93} \times 0.75 \times \frac{0.746kW}{hp} \times \left[(1.0)^{3.0} - \frac{(0.7)^{3.0}}{0.97} \right] = 19kW$$

19 Demand savings are realized in proportion with ASD speed reduction coincident with facility's peak demand. Contact your utility for additional information.

5.3 Summary of Motor Load Type, Common Applications and Energy Considerations with ASDs

Variable torque, constant torque, and constant power are three basic load types for motor-driven systems. For each of these load types, the table below summarizes common applications for which ASDs may be considered and associated energy considerations.

Table 5 Motor Loads and ASDs: Common Applications and Energy Considerations

Motor Load Type	Common Applications	Energy Considerations
Variable Torque Load • Power [hp] varies as the cube of the rotational speed • Torque varies as the square of the rotational speed	- centrifugal fans - centrifugal pumps - blowers - axial fans - HVAC systems	Lower speed operation results in significant energy savings as shaft power of the motor drops with the cube of the rotational speed
Constant Torque Load • Torque remain constant at all rotational speeds • Power [hp] varies directly proportional with rotational speed	- mixers - conveyors - compressors - printing presses	Lower speed operation saves energy in direct proportion to the rotational speed reduction
Constant Power [hp] Load • Develops the same power [hp] at all rotational speeds • Torque varies inversely proportional with the speed	- machine tools - lathes - milling machines - punch presses	No energy savings at reduced speeds; however, energy savings can be realized by attaining the optimized cutting and machining speeds for the part being produced; a time limiting switch device controlling no load operating time saves energy, too.

5.4 System Design Considerations with Motors and ASDs

Although ASDs consume a small amount of energy, when applied to the appropriate application, ASDs facilitate large overall system savings, much greater than the amount consumed by the ASD alone. The overall system efficiency can vary based on the operation of the motor-driven system. As described in Chapter 3, motor efficiency varies based on motor load. Similarly, the efficiency of the drive also varies based on motor load and pump or fan efficiency[20] varies with the flow of the substance it moves. A simplified equation[21] to demonstrate system efficiency appears below, where the total system efficiency is calculated from the product of the efficiencies for each device in the motor-driven system:

Equation 12 Simplified Motor System Efficiency Calculation

$$\text{System Efficiency } (E_{System}) = E_{Drive} \times E_{Motor} \times E_{Equipment\ (pump,\ fan,\ etc.)}$$

System design considerations related to pairing motors and ASDs include:

- Minimize the cable length from the VFD to the motor to avoid voltage overshoots or spikes
- Use a harmonic compensated line reactor or filter to minimize nuisance tripping, assist with voltage notch reduction, and harmonic attenuation
- Use insulated couplings and inverter duty motors to protect the motor

5.4.1 ASDs and Soft Starts

Many ASDs have built-in soft-start capabilities. Soft starters are electrical devices that can be installed to reduce the electrical stresses associated with motor start up. Soft starters gradually ramp up the voltage applied to the motor to reduce the start-up current. Where appropriate, induction motors can be fitted with electronic soft starters to reduce power system stresses, increase the motor system life on frequently started motors, or increase the efficiency of motors operated continuously below 50% load.

ASDs used for the purpose of preventing equipment failure at start up, or to reduce demand charged by soft starting motors does not save significant energy. While properly specified soft starters reduce the

[20] Pump and fan efficiency are further defined in the Glossary, Section 7.3.

[21] US DOE, ASD Part Load Efficiency, Motor Tip Sheet #11, www1.eere.energy.gov/industry/bestpractices/tip_sheets_motors.html

motor starting in-rush current to acceptable system levels, they do not reduce the system peak power demand or associated demand charge since peak system demand is averaged over a 15 minute time interval and motor starting is completed in a few milliseconds. As a result, using soft starters or an ASD for its soft start function alone are generally not a cost-effective approach to energy savings.

5.4.2 Other Benefits of ASDs

In addition to energy savings through matching the motor speed to application needs, ASDs can provide additional benefits related to energy efficiency[22]:

- Improved process control, such as speeding up or slowing down a machine or process
- Inherent power factor correction
- Bypass capability in the event of an emergency
- Protection from overload currents

5.5 When Drives May Not Save Energy

ASDs can enable motor system energy savings if applied to the appropriate applications, installed properly, use appropriate controls, and any potential harmonics issues are addressed. However, ASDs are not appropriate for all applications. Examples where ASDs are not likely to save energy include:

1. **Constant power [hp] applications** that develop the same power at all rotational speeds (torque varies inversely proportional with the speed) do not achieve energy savings by reducing speed with ASDs. However, energy savings can be realized in some cases by optimizing the speed for the specific application needs (e.g. cutting and machining speeds to produce a specific part).

2. **Constant speed applications:** Pairing an ASD with a constant speed motor, or a motor that is set to run constantly at full speed, will not save energy and can result in higher overall energy usage. If the drive is set to run less than optimal efficiency, it still may be more expensive to operate the overall system because of the drive efficiency losses.

3. **High static pressure installations:** A system that is static head dominated (open loop) is one where the pump is working to overcome static head (i.e. gravity or liquid elevation). Examples of these applications include: boiler feed water pumps, submersible pumps or any above ground pumps that operate systems with a high static dominated pressure level and those that lift water fill a reservoir. In these applications, ASDs may not achieve overall energy savings as a control option; however, they may make sense where the ASD is used to address water supply demand that modulates continuously.

4. **Poor Sequencing:** The best sequencing for ASD systems depends on the end use application. For example, cooling towers or evaporator fans are often set up in lead-lag fashion where each fan immediately turns on and off based upon demand, which is good practice. Adding an ASD to the existing lead-lag configuration may consume more energy because the drive's programming algorithm could activate multiple fans to start earlier, operate longer and at a higher energy consumption level; furthermore, drive loss factors compound the inefficiencies.

5. **Installing an ASD to soft start motors to reduce in-rush current or demand:** An ASD used for the purpose of eliminating equipment failure at start up, or to reduce demand charged by soft starting motors does not save significant energy. Soft starters can provide this functionality.

[22] Natural Resources Canada, *Energy Efficiency Resources Guide*, http://oee.nrcan.gc.ca/industrial/equipment/vfd-ref/page-05.cfm

6.0 Motor Management

Recognizing that energy consumption represents approximately 95 percent of a motor's life cycle costs, efficiency programs, manufacturers, the Electrical Apparatus Service Association (EASA) and other motor industry stakeholders launched the *Motor Decisions Matter*^{SM} (MDM) Campaign to promote motor management. The benefits of motor management include reduced energy use and the associated costs and carbon emissions. Implementing motor management involves strategies such as calculating the full range of motor costs, planning ahead for motor failure, documenting critical information, and ensuring the right motor is available when needed. Visit the MDM web site (www.motorsmatter.org) to download resources to get started, such as the MDM *Motor Planning Kit*, *Simple Savings Chart*, and case studies that demonstrate how others have successfully implemented motor management. Several basic motor management concepts are summarized below.

6.1 Motor Specification

Motors at all efficiency levels can vary widely in speed, starting current, and starting torque. After selecting a motor that meets the motor system performance requirements it is important to record these requirements in a motor specification record so that relevant staff have ready access to critical information to make timely motor decisions. A comprehensive motor specification:

- defines performance requirements
- describes the environment in which the motor operates
- identifies reliability indicators
- documents maintenance conditions
- is a critical component of a motor management plan

As described in the *MDM Motor Planning Kit*, "keeping track of operational data means that the motor's history will be readily available if a failure occurs, and will allow facility managers to make more informed decisions."

6.2 Motor Inventory

Motors are an important asset for commercial and industrial customers. To manage them effectively, it is important to ensure that all motors are accounted for and critical information is centrally recorded and accessible. A first step to motor management is to conduct a motor survey and create an inventory of all the motors in a facility. The survey might include only motor nameplate data, or it might also include actual measured data for a given application. A comprehensive motor inventory includes information such as motor maintenance records, motor specifications, and application type so that that engineers and facility operators have easy access to critical motor information. An initial inventory may focus on a subset of the motor population, such as motors running critical applications, those with the longest run times, those with the highest failure rates or those that are the oldest. MotorMaster+, available from the US Department of Energy, includes the tools to create and maintain an inventory of all of your motors: www1.eere.energy.gov/industry/bestpractices/software_motormaster.html.

6.3 Motor Purchasing Policy

Motor purchasing policies define the criteria to be used when selecting which motors to purchase. A detailed purchasing policy indicates which motor size, model number, and other characteristics should be purchased for specific applications and identifies available incentive programs to help offset the purchase price. With a purchasing policy established before motor purchase decisions need to be made, the time elapsed between motor failure, motor replacement, and return to productivity is streamlined. The purchasing policy can also be a tool to demonstrate the benefits of energy efficiency, including the cost savings associated with selecting motors based on life cycle cost analysis, rather than purchase price alone. In addition, when purchasing policies are distributed widely to all personnel involved in motor decision making, a purchasing policy can guide consistent procurement decisions throughout a facility or company.

6.4 Motor Repair Policy

As described in Section 3.4, in addition to considering efficiency when purchasing new motors, there are also efficiency considerations for motor repair. Repair services done according to best practice standards, such as *ANSI/EASA AR-100 Recommended Practice for the Repair of Rotating Electrical Apparatus*; maintain motor efficiency by returning the motor to its nameplate efficiency. Standards such as C392-11, *Testing of Three-Phase Squirrel Cage Induction Motors During Refurbishment* provide guidance for service centers to verify that efficiency has been retained during refurbishment. The EASA web site includes resources to locate motor service providers in your area.

6.5 Predictive and Preventative Maintenance

Implementing a maintenance program that incorporates both predictive and preventive measures as part of a motor management plan facilitates anticipating and preventing motor failure before it occurs. Preventive maintenance, such as proper lubrication, helps maintain motors in good operating condition, thereby reducing the risk of unexpected motor failure. Predictive maintenance involves the use of monitoring equipment to assess overall motor "health" and identify factors that may eventually lead to failure. With this information available, facility managers have the opportunity to reconfigure, repair, or replace components before failure occurs, or to predict when motor failure is likely and prepare accordingly.

7.0 References and Resources

7.1 Frequently Asked Questions and Answers

1. **Aren't efficient motors harder to repair, thus losing more efficiency during repair? Can you maintain efficiency over time?**
   Higher efficiency motors are no more difficult to repair than lower efficiency motors. It is essential to communicate with your motor service professional and work with them to develop specifications indicating that the procedures, materials, and verification tests required for your motor repairs be done following best practices. Motor repair specifications are available from the motor manufacturer. Best practice motor repair standards are available from the Electrical Apparatus Service Association (EASA).

2. **Is it true that efficient motors have a lower starting torque and may not be able to accelerate the load?**
   No. Starting torque, also referred to as locked rotor torque, is the minimum torque produced by the motor at rated voltage and frequency, at all angular positions of the rotor. On average, starting torque does not vary significantly for motors with different efficiency levels of the same size. In selecting a motor, it is important to specify needed starting torque since it varies widely across motor sizes and models. This is especially critical when sizing a higher efficiency motor replacement for a pre-NEMA motor.

3. **If higher efficiency motors may have a higher starting current than lower efficiency motors, do they cause breakers to trip?**
   Starting current, also known as inrush current, is a spike, extremely short in duration (milliseconds), which occurs during startup. Because motors with higher efficiencies have lower transient reactance than lower efficiency motors, their inrush current can spike higher than the full load current of less efficient motors. However, starting current varies widely at each efficiency level. Per NEMA design requirements, Design A motors may have a higher inrush current than Design B motors. Breaker design, specification, and settings can help with controlling nuisance trips.

4. **Are higher efficiency motors suitable for use with adjustable speed drives (ASDs)?**
   Higher efficiency motors with appropriate insulation (inverter type) are suitable for use with ASDs. However, if ASDs are improperly installed or applied to unsuitable applications, negative side effects may occur when applying ASDs to motors, regardless of the motor's efficiency, such as greater vibration, heat rise, and an increase in audible noise. The high switching frequency that may occur with ASDs can cause a high rate of voltage rise, which in turn can cause insulation breakdown of the end turns of motor windings. However, inverter duty motors are designed with improved insulation systems to meet or exceed the voltage amplitudes and rise times that may occur with ASDs. Several NEMA Premium® efficiency motors are inverter duty. Check with the manufacturer or motor specification to ensure that a motor meets the most current specifications defined by NEMA MG 1 and your application-specific requirements.

7.2 Motor System Optimization: Guidelines for Getting Started

These Guidelines for Getting Started summarize the selection and application considerations outlined in this Guidebook by highlighting four important steps toward optimizing industrial motor systems. For technical assistance, contact your local utility or motor service provider.

1. Size the selected motor properly

The common practice of motor oversizing results in less efficient motor operation and lower power factor. Some situations may require oversizing for peak loads, but otherwise select a motor that will operate with a load factor between 75% and 80%. Peak motor efficiency typically occurs at 75-80% of rated load.

2. Match the motor to the needs of the driven equipment

It is important to check the motor specifications and closely match the motor's rated speed to its load requirements. Matching speed is particularly important for centrifugal loads where power draw is proportional to the cube of speed. Coupling a higher speed motor to a centrifugal load may dramatically increase overall power consumption if the rated speed is not matched correctly. If the driven load does not require constant speed at all times, investigate the opportunity to use adjustable speed drives (ASD). ASDs control speed and reduce overall motor system power consumption. However, if the driven load requires constant speed at all times, such as to ensure the constant movement of air or fluid, an ASD may decrease overall system efficiency. Overall power savings depend on application requirements, system characteristics, and motor performance including efficiency and rated speed. See Chapter 5 for additional information.

3. Correct adverse operating conditions

Even with a properly specified motor, several parameters can impair efficiency. The following adverse operating conditions can apply to any motor and should be investigated to ensure optimal motor system performance.

- *Voltage Variations:* If actual voltage varies from rated voltage both efficiency and power factor are affected. Deviations of 1-2% can lead to significant increases in energy use and prolonged deviation from rated voltage can be detrimental to motor life and performance.
- *Phase Voltage Unbalance:* Phase voltage unbalance can dramatically increase motor losses and heat generation, which both decrease the efficiency of the motor and shorten its life. It is recommended that the voltage unbalances at the motor terminals not exceed 1%. According to NEMA MG1, the current at normal operating speed with unbalanced voltages will be greatly unbalanced in the order of approximately 6 to 10 times the voltage unbalance. The unbalanced currents caused by unacceptably high unbalanced voltages will significantly increase heating and reduce efficiency.
- *Motor alignment:* Correct shaft alignment, mechanical placement of the motor, and mechanical transmission are critical to the successful operation of any motor. After installation of a new motor, vibration readings will verify that the alignment is correct.
- *Environmental conditions:* Conditions, such as high temperature, excessive dust or moisture can adversely affect both motor performance and motor life. Moisture, for example, can deteriorate a motor's insulation or bearing grease, thus reducing motor life. Excessive dust can also deteriorate lubrication. In environments with a lot of debris (e.g. dust, wood chips, etc.), motor types designed for these conditions may be appropriate, such as severe duty, explosion proof or IEEE 841 motors.
- *Single Phasing:* System conditions may exist where any one phase of a three-phase system may be temporarily unavailable. The loss of one phase on the utility side of the meter due to a broken conductor, connection failure, blown fuse, etc or a loss of phase condition on the load side of the meter can be detrimental to a motor. If this occurs while the motor is running, the motor will continue to run however, excessive currents in the unaffected phases may create excessive heat and damage the motor. The practice of depending upon motor overload fuses in the motor starter may not adequately protect the motor. It is recommended to install loss-of-phase protective relays to safely open all three phases when this phase loss condition occurs.

4. **Establish a motor management plan**

Ensure that motors are recorded in a facility-wide motor inventory, operational data is recorded in a motor specification, and the criteria for making future motor decisions based on life cycle cost analysis are easily accessible and communicated to all appropriate personnel.

7.3 Glossary

Adjustable Speed Drive (ASD), also referred to as inverters, variable frequency drives (VFD), and variable speed drives (VSD): is an electronic control device that changes the voltage and frequency of the electrical power supplied to the motor. The terms ASD and VSD are also used to describe devices that mechanically control motor speed rather than controlling the frequency and voltage of electric power. However, the terms VFD and Inverter-type ASD only describe devices that control the frequency and voltage of electric power and are not used to describe mechanical control devices. See Chapter 5.

Affinity Laws: These engineering laws are used to express the relationship between flow, head, and consumed power in relation to shaft speed for pump and fan applications. See Chapter 5.

Brake horsepower (bhp): The brake horsepower is the amount of real horsepower to the pump, fan, or other equipment, not the horsepower used by the motor, typically measured in kilowatts (kW).

Current (in amperes or percent of rated current): The amount of current the motor draws at a particular time or under particular operating conditions. There are many points of defined current which can be important considerations in a given application. NEMA recognizes and describes two components of starting current: (1) instantaneous peak inrush current, the momentary transient current that occurs within ½ cycle after contact closure and which may range from 1.8 to 2.8 times the locked-rotor current at ambient temperature and (2) locked-rotor current, the steady-state current taken from the line, with the rotor locked and with rated voltage applied.

Design: NEMA design criteria are defined by NEMA MG 1-2010. NEMA MG 1 standard designs for three-phase squirrel cage induction motors fall into four basic categories. See Chapter 4.

Duty Cycle (and the use of Variable Frequency Drives): Duty is an account of the duration and magnitude of loads, no loads and rest periods, to which the motor is subjected. Necessary information required to assess duty suitability are listed below. See Chapter 4.

- Load inertia referred to the motor speed
- Magnitude and duration of load
- Details of any no-load periods
- Number of starts and stops per hour
- Method of stopping
- Cycling Duration Factor

Efficiency: The ratio (in percent) of mechanical power output to the electrical power input. NEMA's MG 1-2010 defines efficiency levels for open and closed enclosures for each motor size between 1 and 500 hp. See Chapter 2.

Enclosure Type: NEMA defines 20 types of motor enclosures, which fall into two broad categories: open and totally enclosed. The most common is the open drip proof (ODP) in which ventilation openings are positioned to keep particles and water from falling into the motor. Totally enclosed motors are designed to prevent free exchange of air between the inside and the outside of the motor. The most common design is the totally enclosed fan cooled (TEFC) motor in which a fan on the opposite end of the motor from the load draws air over the case to provide cooling. See Chapter 4.

Fan Efficiency: Fan efficiency is the ratio of the power imparted to the airstream to the power delivered by the motor, as captured by the Total Efficiency equation:

Equation 13 Fan Efficiency Calculation

$$\textit{Total Efficiency} = \frac{\textit{Total Pressure} \times \textit{Airflow}(\textit{cubic feet per minute})}{\textit{bhp} \times 6{,}362\ (\textit{unit conversion})}$$

Source: "US Industrial Electric Motor Systems Market Opportunities Assessment", US Department of Energy, 1998

An important aspect of a fan performance curve is the best efficiency point (BEP), where a fan operates most cost-effectively in terms of both energy efficiency and maintenance considerations. The operating point of centrifugal fans at which their efficiency is highest is known as the best efficiency point (BEP). Operating a fan at or near its BEP also decreases loads on the fan and maintenance requirements. Static efficiency is another term that can be used to describe fan efficiency. Static efficiency uses static pressure rather than total pressure in the above equation. When evaluating fan performance, it is important to know which efficiency term is being used.

Full Load Amps: The amount of current the motor can be expected to draw under full load (torque) conditions when operating at the rated voltage and frequency. This value is printed on the nameplate.

Horsepower (hp): a unit of power equal to 550 foot pounds per second and approximately 745.7 watts. Horsepower indicates the rated output of a motor. This information appears on the motor nameplate.

Hours of Operation: The more hours a motor operates, the greater the opportunity for energy savings with efficient motors. This is especially true for large motors as they require proportionally more power to operate than smaller motors. Larger motors generally experience long operating hours, often two to three shifts per day. For example: 8 hours/shift × 3 shifts/day × 5 days/week ×50 weeks/year = 6000 operating hours/year

Inrush Current: Inrush current is a spike, extremely short in duration, which occurs during startup. See also current.

Inverter Duty: Inverter duty motors are designed according to the requirements of NEMA MG 1 Part 31 "Definite Purpose, Inverter Fed Motors". Among other things, under usual service conditions, the stator winding insulation system of an inverter duty motor is designed to operate (with a base rating voltage <= 600 Volts) up to a peak voltage (or voltage overshoot) of 3.1 times the rated voltage with an inverter rise time equal to or exceeding 0.1 microseconds. This provides the ability to withstand voltage overshoots of 1,426 Volts on a 460 Volt motor. "Inverter ready" or "inverter rated" are marketing terms and are not synonymous with inverter-duty.

Load Factor (expressed as percent): Load factor is the ratio of $\frac{\textit{average motor load}}{\textit{rated motor load}}$ for a given period of time. Several methodologies are available to calculate motor load. For additional information, including sample calculations see the US Department of Energy resource, *Determining Electric Motor Load and Efficiency*. http://www1.eere.energy.gov/industry/bestpractices/pdfs/10097517.pdf

Motor Class: The Energy Policy Act defined three broad motor classes:
1. General purpose motors: motors without special mechanical construction that can be used in usual service conditions without restrictions to a particular application or application type
2. Definite purpose motors: motors with standard rating or construction that are designed to operate under unusual conditions or in a particular application
3. Special purpose motors: motors with special mechanical construction or operating specifications

Motor Connections: Motor connection describes how the motor interacts with the rest of the system. (E.g. whether the motor is connected to a VFD, experiences an across-the-line, part winding, or soft start).

Motor Sizing: Many motors are oversized for their applications, running far below their rated loads. Motors that are severely under-loaded often operate far below their nameplate efficiency. For these motors, downsizing may reduce energy consumption. It is important to first verify the motor's full range of operating parameters. Referencing motor efficiency curves also provides accurate savings projections at various loads.

Motor Specification: A comprehensive motor specification defines performance requirements, describes the environment in which the motor operates, identifies reliability indicators, and documents maintenance conditions. A detailed list of motor specification requirements appears below:

- Motor type and frame size
- Rated motor power (in horsepower)
- Service factor
- Rated speed, voltage supply, and frequency
- Rated and starting current
- Rated efficiency (at least at full load)
- Winding temperature rise and insulation class
- Starting torque and starting classes
- Enclosure type and degrees of protection
- Use of motor controls
- Key dimensions and measurements
  - Mounting
  - Shaft extension
- Duty, including:
  - Expected number of starts per hour
  - Magnitude and duration of load
  - Number of stops per hour and stopping method
  - Details of any no-load periods
  - Cycling duration factor

Motor System Optimization: involves ensuring that motor-driven systems achieve their performance requirements with the highest overall efficiency. Achieving motor system optimization requires careful consideration of the overall motor driven system and selecting the right equipment, including efficient motors and, where appropriate, drives.

Nameplate NEMA Nominal Efficiency: The average expected full load efficiency for a group of motors with the same specifications. Motor nominal efficiency appears on the motor nameplate as "NEMA Nominal Efficiency" or "NEMA Nom. Eff." Per NEMA requirements, the actual measured efficiency of a motor may vary from the value stated on the nameplate, but may not be less than the stated minimum efficiency. For details about testing and determining nominal efficiency, see Chapter 9.2.1 of NEMA MG-1 Standards Publication, Information Guide for General Purpose Industrial AC Small and Medium Squirrel Cage Induction Motor Standards. www.nema.org

NEMA Efficiency Bands: A NEMA efficiency band represents the series of efficiency increments for motors of a specific design. See NEMA Standards Publication Condensed MG-1 Table 12-10 for details. www.nema.org.

Power Factor (expressed in percent or ratio): The ratio between the real power (measured in W or kW) and the apparent power (measured in VA or kVA). Power factor is related to core length, material properties, and air gap, among other things. It is generally higher for larger motors than for smaller ones. Capacitors are often used to correct for low power factor.

Pump Efficiency: The efficiency of a pump can be measured by dividing the fluid power by the pump shaft power, where

Equation 14 Pump Efficiency Equation

$$Fluid\ Power = \frac{head\,(ft.) \times flow\ rate\,(gallons\ per\ \min ute)}{3{,}960\,(unit\ conversion)} \times specific\ gravity\ of\ fluid$$

and pump shaft power is the brake horsepower (bhp) of the motor. Pumps have varying efficiency levels, ranging from 35% to more than 90%. Pump efficiency is a function of many design characteristics. The operating point of centrifugal pumps at which their efficiency is highest is known as the best efficiency point (BEP). Operating a pump at or near its BEP also decreases loads on the pump and maintenance requirements.

Slip (in percent or rpm): The difference between the motor's synchronous (design) speed and its actual speed. Slip is particularly important in centrifugal applications since power consumption is related to the cube of the speed and characteristic of the motor load.

Soft starters: Soft starters are electrical devices used with AC electrical motors to temporarily reduce the load and torque during motor startup to reduce the associated electrical and mechanical stresses.

Speed: The rated (or full load) speed of a squirrel cage induction motor describes the rate at which the rotor rotates. For induction motors, the synchronous speed is determined by the number of magnetic poles in the stator. See Chapter 4.

Service Factor: The capacity of the motor to withstand prolonged overload conditions. For example, if the service factor is 1.15, the motor can work at 1.15 times its rated horsepower satisfactorily, although the insulation life will be reduced. In general, it is not good practice to operate a motor for extended periods in the service factor area; efficiency may be lower and additional heating can lessen motor life.

Temperature Rise: The amount of temperature rise above the surrounding air temperature that can be expected within the windings of the motor at full load and continuous operation.

Torque (in foot-pounds, inch-pound, ounce-feet, kilogram-meters, or percent of full-load torque): The twisting force exerted by the motor shaft on the load.

Voltage Unbalance: Occurs when there are unequal voltages on the lines to a polyphase motor resulting in a dramatic increase in motor losses and heat generation. Both decrease the efficiency of the motor and shorten its life and may also reduce motor torque. Voltage unbalance in a three phase systems can be calculated as follows:

Example Data	
Voltage Measurement 1	462 volts
Voltage Measurement 2	463 volts
Voltage Measurement 3:	455 volts

Equation 15 Voltage Unbalance Equation and Calculation

$$Voltage\ Unbalance\ Calculation = \frac{(Average\ measured\ voltage - \max imum\ deviation\ measured\ voltage)}{Average\ measured\ voltage} \times 100$$

$$Average\ \ measured\ voltage\ = \frac{(462 + 463 + 455)}{3} = 460\ volts \qquad Voltage\ Unbalance\ = \frac{(460 - 455)}{460} \times 100 = 1.1\%$$

Source: "Energy-Efficient Motor Systems: A Handbook on Technology, Program, and Policy Opportunities, ACEEE, 2002

7.4 Resources

The resources below informed the development of this Guidebook:

- ANSI/EASA AR 100 Recommended Practice for the Repair of Rotating Electrical Apparatus, 2010, http://www.easa.com/sites/default/files/AR100-2010_1010-2.pdf
- CanMost the Canadian Motor Selection Tool – a motor selection software tool, includes a database of 60-Hz North American and 50-Hz European from 1 to 2000 hp. http://oee.nrcan.gc.ca/industrial/equipment/software/intro.cfm?attr=24
- Canadian Standard C392-11, *Testing of Three-Phase Induction Motors During Refurbishment,* http://www.csa.ca/cm/ca/en/home
- CEE Motors & Motor Systems Initiative Resources: CEE Summary of Motors and Motors Systems Programs, CEE Guidance Specification for 250-500hp, Low Voltage, General Purpose Motors, CEE Premium Efficiency Motors List http://www.cee1.org/ind/mot-sys/mtr-ms-main.php3
- *Determining Electric Motor Load Factor*, Electric Ideas Clearinghouse, Bonneville Power Administration, 1991. http://www.p2pays.org/ref/36/35469.pdf
- *Determining Electric Motor Load and Efficiency*, MotorChallenge, a program of the US Department of Energy, http://www1.eere.energy.gov/industry/bestpractices/pdfs/10097517.pdf
- Electrical Apparatus Service Association (EASA). www.easa.com, The Electrical Apparatus Service Association, Inc. (EASA) is an international trade organization of over 2,100 electromechanical sales and service firms in 58 countries.
- *Model Repair Specifications for Low Voltage Induction Motors*, Bonneville Power Administration, Electric Power Research Institute, and United States Department of Energy, 1994. http://www1.eere.energy.gov/industry/bestpractices/pdfs/repair_specs_motors.pdf
- *Energy Efficiency Reference Guide: Electric Motors*, Natural Resources Canada http://oee.nrcan.gc.ca/industrial/equipment/motors-ref/index.cfm?attr=24
- *Energy Efficient Motor Selection Handbook*, Bonneville Power Administration, United States Department of Energy, 1995, http://www.wbdg.org/ccb/DOE/TECH/ce0384.pdf
- *Energy Efficient Motor Systems: A Handbook on Technology, Program, and Policy Opportunities.* Steve Nadel, et al., American Council for an Energy Efficient Economy, 2002
- *HorsePower Bulletin: How to Develop and Implement a Policy for Cost Effective Management of Industrial Motor Purchase, Operation, and Repair*, Advanced Energy. www.advancedenergy.org/md/knowledge_library/resources/Horsepower%20Bulletin.pdf
- *ÍEEE 519, Recommended Practices and Requirement for Harmonic Control in Electrical Power Systems*, http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=22445
- IEEE 100 *Standard Dictionary of Electrical and Electronics Terms*, http://ieeexplore.ieee.org
- *Improving Fan System Performance: A Sourcebook for Industry.* US Department of Energy Industrial Technologies Program, http://www1.eere.energy.gov/industry/bestpractices/pdfs/fan_sourcebook.pdf
- *Improving Motor and Drive System Performance: A Sourcebook for Industry*. US Department of Energy Industrial Technologies Program, http://www1.eere.energy.gov/industry/bestpractices/pdfs/motor.pdf
- *Improving Pumping System Performance: A Sourcebook for Industry.* US Department of Energy Industrial Technologies Program. http://www1.eere.energy.gov/industry/bestpractices/pdfs/pump.pdf
- *Motor Right-Sizing for Platinum Mine Concentrator Pump Applications*, D. Janicijevic and L. Hauptfleisch, http://active.cput.ac.za/energy/public/index.asp?pageid=535, 2005
- *Motor Decisions Matter*SM Campaign Tools and resources http://www.motorsmatter.org.
- National Electrical Code, National Fire Protection Association (NFPA), http://www.nfpa.org
- National Electrical Manufacturers Association, Motor Generator (MG) Standards. NEMA Standards Publication Condensed MG1-2007, *Information Guide for General Purpose Industrial AC Small and Medium Squirrel cage Induction Motor Standards*. http://www.nema.org/stds/
- National Electrical Manufacturers Association, Motor Generator (MG) Standards. NEMA Standards Publication MG 10-2001, *Energy Management Guide for Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors.* http://www.nema.org/stds/
- Natural Resources Canada (NRCan), *Variable Frequency Drives Energy Efficiency Reference Guide,* http://oee.nrcan.gc.ca/industrial/equipment/vfd-ref/page-06.cfm
- *Rewound High-Efficiency Motor Performance*, Vancouver, British Columbia, Canada: BC Hydro in association with Powertec Labs Inc., 28, August, 1992. Zeller, Markus
- United States Industrial Motor Systems Market Opportunities Assessment, US DOE http://www1.eere.energy.gov/industry/bestpractices/pdfs/mtrmkt.pdf

- US Department of Energy Industrial Technologies Program, Motor Tip Sheets, http://www1.eere.energy.gov/industry/bestpractices/tip_sheets_motors.html:
    - Adjustable Speed Drive Part-Load Efficiency
    - Avoid Nuisance Tripping with Premium Efficiency Motors
    - Eliminate Excessive In-Plant Distribution System Voltage Drops
    - Eliminate Voltage Unbalance
    - Estimating Motor Efficiency in the Field
    - Extend Your Motor's Operating Life
    - Improve Motor Operation at Off-Design Voltages
    - Is it Cost Effective to Replace Old Eddy-Current Drives
    - Magnetically Coupled Adjustable Speed Motor Drives
    - Minimize Adverse Motor and Adjustable Speed Drive Interactions
    - Replace V-Belts with Cogged or Synchronous Belt Drives
    - The Importance of Motor Shaft Alignment
    - Turn Motors Off When Not in Use
    - When to Purchase NEMA Premium Efficiency Motors
    - When Should Inverter-Duty Motors Be Specified?
- US Department of Energy Industrial Technologies Program Motor-Driven System Software Tools http://www1.eere.energy.gov/industry/bestpractices/software.html.
- *Understanding Electric Demand for National Grid's Commercial Customers in New York*, http://www.nationalgridus.com/niagaramohawk/non_html/eff_elec-demand.pdf
- *Variable Frequency Drives: Energy Efficiency Reference Guide*, Natural Resources Canada, http://oee.nrcan.gc.ca/industrial/equipment/vfd-ref/page-05.cfm

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