DOE Motor and Drive Assessment Leads to Energy Savings for Power Drive Systems

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Abstract – Petroleum and chemical refining, along with all other process industries, utilizes a large number of electric motors to meet power demands. This paper will discuss results of an assessment survey of installed motors and drives performed by Lawrence Berkeley National Laboratory (LBNL) and funded by the US Department of Energy (DOE) [1]. A key finding was that there are energy savings available with the addition of adjustable speed drives (ASDs). The National Electrical Manufacturers Association (NEMA) is collaborating with the Northwest Energy Efficiency Alliance (NEEA) and Cadeo Group to develop a prescriptive process to allow for rebates for Power Drive Systems (PDSs) consisting of a premium efficiency electric motor and an ASD. Most Efficiency standards NEMA MG 1 [2], or IEC 60034-30-1 [4] today focus on the efficiency of the components, with or without an ASD, rather than focusing on energy saving through optimized process management NEMA MG 10011 [3]. Organizations are now starting to instead look at the combined energy use of the PDS, especially on variable torque loads such as pumps, fans and compressors that are commonplace in process industries.

Index Terms — Motors, efficient drive systems, extended product approach, premium efficiency, energy efficiency, DOE, appliance regulations, IEC, IEEE.

I. INTRODUCTION

In 1998 the US Department of Energy (DOE) conducted a Motor System Market Assessment (MSMA) with the goal to characterize the installed motors and motor-driven equipment (pumps, fans, compressors) base in industrial and commercial facilities. This study concluded that over 70% of energy used in manufacturing plants was from motor-driven systems. When this study was conducted, premium efficient motors were not yet mandated by law and were an optional upgrade.

Then in 2016, the Advanced Manufacturing Office (AMO) of the DOE contracted with LBNL to design another assessment. Working with NEMA and other stakeholders, this new survey was to re-examine electric motor systems but also identify ASD usage, advanced motor technology adoption and motor repair practices.

Recently NEMA has identified the need for a method to compare energy savings in motor-driven systems after adding an ASD for optimization. This system is not based on efficiency but on energy savings of the combined PDS. This is explained in greater detail later when defining the Power Index (PI) in clause IV.

II. MOTOR SYSTEM MARKET ASSESSMENT RESULTS

The most recent MSMA (2021 MSMA) collected a statistically representative sample of motor systems in industrial and commercial facilities. For the industrial sector, subsectors were identified using the North American Industrial Classification System (NAICS) at the three digit-level [6]. Within this classification system, 324 and 325 are Petroleum Refining and Chemicals, respectively. Assessments were performed between 2017 and 2019 and included 246 industrial facilities overall, with 13 performed at Petroleum Refineries and 18 at Chemical facilities. The assessments sought to collect information on the installed components of all electrically driven polyphase motor systems greater than or equal to 1 hp at the plant. The information collected included nameplate (e.g., size, efficiency) and operational (e.g., operating hours, load factors) information. The motor system components considered included the drive (e.g., ASD, referred to as Variable Frequency Drive in the 2021 MSMA), motor, power transmission (e.g., gearbox, belts), driven equipment (e.g., pump, fan, air compressor, refrigeration compressor), and the distribution system (e.g., compressed air lines). The methodology and results have been documented in the MSMA Volume 1 report and relevant results are presented here [1]. In order to stay consistent with NAICS and the 2021 MSMA classification, Petroleum Refining and Chemicals will be presented separately.

Table 1 summarizes the motor system electricity consumption for the Petroleum Refining and Chemicals subsectors. Motor systems account for 80% of the electricity consumption in the Petroleum Refining subsector and 79% in the Chemicals subsector. This is more than the share of electricity consumption for motor systems industry-wide, which stands at 69%. Using an average electricity cost for the industrial sector of $0.087/kWh, the annual electricity expenditures for motor systems are $3.4B in the Petroleum Refining subsector and $9.2B in the Chemicals subsector. Key to reducing electricity consumption and costs in these subsectors is reducing the energy consumption of motor systems.

Diving deeper into the specifics of the motor system's electricity consumption, there are 299,199 and 1,287,307 motors in the Petroleum Refining and Chemicals subsectors, respectively, constituting 15% of all motors in industry. On average, motor systems for these subsectors are larger than they are for the remainder of industry. The average motor size across industry was found to be 27 hp (20.1 kW), whereas it is 62 hp (46.2 kW) and 40 hp (29.8 kW) in the Petroleum Refining and Chemicals subsector, respectively. Operating hours for motor systems in these sectors are slightly less than industry averages. Motors in industry run on average 5,912 hours per year, whereas they run 5,234 hours per year and 5,718 hours per year in the Petroleum Refining and Chemicals subsectors, respectively.

TABLE 1
SUMMARY OF MOTOR SYSTEM ELECTRICITY USAGE FOR THE PETROLEUM REFINING (PET. REF) AND CHEMICALS (CHEM.) SUBSECTORS

	Energy Usage (GWh/yr)	Electricity Usage (GWh/yr)	Motor system electricity Usage (GWh/yr)	% Of electricity Usage for motor systems
Pet. Ref.	1,029,555	48,904	39,269	80
Chem.	1,033,658	134,327	105,699	79
Total	2,063,213	183,231	144,968	79

The penetration rate of Premium Efficiency motors was indeterminable with statistical confidence through the MSMA. This is due to the significant portion of motors without a legible nameplate (44% across the industrial subsector). In lieu of this, the motor age was sought, but here too information was difficult to collect. Without a legible nameplate, determining the age of the motor relied on facility staff knowledge. This is a challenge for older motor systems that were installed before facility staff were employed at the facility. Regardless, when determinable, it was found that 49% of Chemical subsector and 55% of Petroleum Refining subsector motors were older than 10 years. This predates regulations requiring installation of Premium Efficiency motors (2007 for 1 – 200 hp motors and 2014 for 201 – 500 hp) and these motors are likely to operate at sub-Premium Efficiency levels. Further, of the motors where age could not be determined (67% in the Chemical subsector and 60% in the Petroleum Refining subsector), it stands to reason that these motors likely precede facility staff and/or their nameplates are illegible due to age. It is speculated that a significant portion of these motors have a nameplate efficiency that is below the Premium Efficiency level.

A closer examination of the variability of loads and the prevalence of ASDs in each subsector by driven equipment type is provided in Table 2. Only those driven equipment types that would typically realize energy savings from installation of ASDs are shown. These are driven-equipment types that typically utilize centrifugal forces to generate fluid power. In both subsectors, a significant portion of the motor system electricity consumption is for variably loaded centrifugal systems (VLCS) – 34% in the Petroleum Refining subsector and 44% in the Chemicals subsector. The degree to which the load varies will impact energy savings (e.g., a system that is variably loaded but operates above 75% load will realize far less energy savings than a system that is variably loaded but operates below 40% load). However, all VLCS will realize some energy savings from installation of an ASD. Much of the VLCS loads for these subsectors are not equipped with an ASD, particularly in the Petroleum Refining subsector where only 6% operate with an ASD. ASDs are more prevalent in the Chemical subsector, where 43% of variably loaded centrifugal motor systems loads operate with one.

TABLE 2
MOTOR SYSTEM ELECTRICITY USAGE FOR THE PETROLEUM REFINING AND CHEMICALS SUBSECTORS BROKEN DOWN BY DRIVEN EQUIPMENT, LOAD TYPE, AND ASD PENETRATION RATE. “REFRIG.” STANDS FOR REFRIGERATION. “COMP.” STANDS FOR COMPRESSOR.

	Motor system electricity consumption (GWh/yr)	% Of electricity consumption for VLCS	% Of VLCS load not on an ASD
Petroleum Refining	39,269	34	94
Pumps	16,470	49	97
Fans	4,437	66	81
Air comp.	3,002	78	-
Total*	23,909	56	94
Chemical	105,699	44	57
Pumps	27,021	47	30
Fans	17,431	68	42
Air comp.	9,669	75	87
Refrig. Comp.	17,908	81	-
Total*	72,029	64	64

*Total of pump, fan, air compressor, and refrigeration compressor

Given the magnitude of motor system energy consumption in the Petroleum Refining and Chemical subsectors, the age of the installed motor-base, the characteristics of the load profile, and the penetration rates of ASDs, it stands to reason that significant energy and cost reductions are possible through implementation of Premium Efficiency motors with ASD controls.

III. ENERGY RELATED STANDARDS FOR PDS AND CONPONENTS

Until recently the standards industry has focused on test procedures and establishing Minimum Efficiency Performance Standards (MEPS) based on efficiency levels for induction motors. Reliable and proven test procedures capable of achieving consistent results by all testing labs are first required before MEPs can be set by regulators, such as the US Department of Energy (DOE).

Over the past 5 years the focus has switched to establishing system-related energy conservation standards and test standards that will support this new direction. A summary of testing standards is provided in Table 3.

It wasn’t until 2015 with the introduction of European Norm (EN) 50598-1&2 [7] and then in 2017 with IEC standard IEC 61800-9-1&2 [8][9] (which superseded EN 50598), was there any consideration for ASD or system loss determination or testing. It was easier to establish and regulate motor MEPS. However, component efficiency regulation is at a point of diminishing returns.

Though most of the energy conservation in the future will come from the use of an ASD and smart process control, it is still important to have consistent and proven test procedures. In addition, when evaluating system energy consumption, a test method for verification is necessary even though the component losses will be insignificant as compared to the energy savings potential. For completeness these test procedures will be discussed in this section.

NEMA and the CEMEP (European Committee of Manufacturers of Electrical Machines) have stated in a published whitepaper that further gains from future component regulation is minimal and should be avoided. There are significantly greater energy savings opportunities when considering energy system conservation from the system approach of Power Drive Systems (PDS).

Test procedures and IE classes have now been established for the use of ASDs in a PDS. The potential savings in regulating individual ASDs is small. Although the savings is small, the latest regulations in the EU have now set MEPS for ASDs. There remains a much greater opportunity for energy conservation through a robust system evaluation with smart process control that minimizes energy consumption. This is more complex, and new procedures are needed, but the savings are extensive. We now need to move away from focusing on efficiency and start looking at energy conservation. When operating a PDS the best energy conservation may result in poorer component or system efficiency so we will need to avoid that term. This may not be obvious to all, but to give an example, running a variable torque (VT) pump at low speed on an ASD when the flow is not required will result in huge energy savings due to the reduction in demand, which reduces by the cube of the speed change, which is demonstrated later in this paper and shown in figure 5. Meanwhile, the motors may likely have a lower efficiency at that speed and the ASD will add losses to the system.

A. Induction Motor and ASD

The test procedures used today were verified for accuracy and repeatability through multiple round robin tests. In a round robin test a single motor is sent to different manufacturers or different testing labs in order to verify that the different test facilities will achieve similar test results when testing the same motor. NEMA members first performed a round robin test and determined IEEE 112 method B [11] (residual loss method) and CSA C390-10 [12] (residual loss method) to be most accurate and consistent test procedure. IEC Technical Committee 2 (TC 2) Working Group 28 (WG 28) later performed their own round robin test and verified that IEC 60034–2–1 [13] method B1 (residual loss method) to be the most consistent. Today there are three test procedures that follow a similar test method and can be used to verify the efficiency of three-phase Induction Motors and can used interchangeably unless local regulation does not permit.

-IEEE 112 method B [11]
-CSA C390-10 [14]
-IEC 60034-2-1 B1 [13]

Efficiencies levels in North America and Europe have over the years increased multiple times. They started with levels that were lower than what was defined in NEMA MG 1 Table 12-11 [2], which are similar to IEC IE2 class defined in IEC 60034-30-1 [4]. Levels were first increased to NEMA energy-efficient levels NEMA MG 1 Table 12-11 (again similar to IEC IE2 class) and then more recently up to premium efficiency levels per NEMA MG 1 table 12-12 [2] which is similar to IEC IE3 levels. After this there is very little potential for significant energy savings through additional induction motor regulation. Since energy conservation is still important, we must find new ways to encourage energy conservation. System Energy conservation is believed to be the next step in the evolution.

TABLE 3
TESTING FOR ENERGY CONSERVATION AND EFFICIENCY

Product Scope				Efficiency Testing
Motor		Motor		IEEE 112 CSA 390-10 IEC 60034-2-1
Motor Driven By ASD		Motor		IEC 60034-2-3
ASD	ASD			IEC 61800-9-2
Motor & ASD (PDS)	ASD	Motor		IEC 61800-9-2 NEMA MG 10011
Motor + ASD+ Application	ASD	Motor	Pump Fan Compressor	IEC 61800-9-1

B. Efficiency of ASD Motors:

Though the energy savings from higher IE class ASD motors is minimal, it is still important that we understand the levels of energy consumption achieved and have a test method for product verification. NEMA is supporting the development of the IEC standards for ASD type motors, systems testing and efficiency levels and does not plan to develop a separate North American standard.

The ASD motors can be split into two categories, the first is a motor that can run either across the line or also on an ASD defined, in IEC 60034-25 in 2022 [10], as “Converter Capable Motor” and a second type of motor specifically designed to run only an ASD defined as a Converter Duty Motor. A Converter Duty Motor may not be capable of being tested without an ASD. In either case you need a process to determine the motor losses in order to understand and verify the savings potential.

IEC 60034–2–3 [14] establishes a test procedure to determine losses for motors that must run on an ASD. There is a choice of test methods for induction motors. It can either be tested in the same way as found in IEC 60034–2–1 [11] and then adding additional losses for the harmonic components coming from the drive or by testing on a standardized drive that provides the harmonic output, in accordance with IEC 60034-2-3. This is covered in detail in IEC60034–2–3. For those motors that must run on an ASD, testing per IEC 60034-2-3 is the only option when they cannot run without a drive.

IEC 60034-30-2 [5] establishes IE classes for motors running on an ASD. It is important to understand that the IE classes for these motors do not line up with the IE classes of motors covered in 60034-30-1. Motors covered by IEC 60034-30-2 will include the additional losses resulting from the harmonic content coming from the drive. This standard assumes an additional loss for motors running on an ASD of 15% up to 37 kW and 25% above 37 kW. These losses at all the load points are needed for precise PDS energy consumption evaluation.

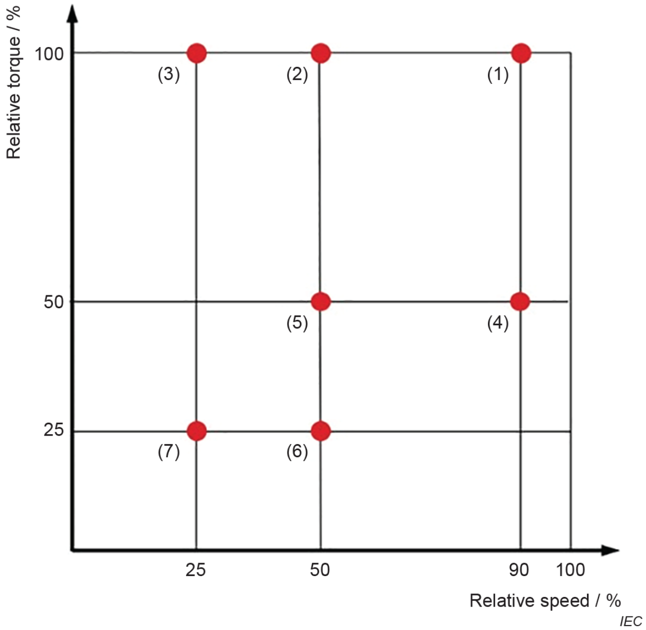

Fig. 1 Seven standardized operating points from IEC 60034-2-3.
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Motors can have the losses directly determined at any load point by test or by the Alternate Efficiency Determination Method (AEDM). Equation (1) can be used to determine the losses at any operating point from 0-100% speed and 0-100% torque. To use this formula the losses will need to be determined at the seven defined operating points shown in Fig. 1. The coefficients (c_{L1}, c_{L2}, ..., c_{L7}.) needed for equation (1) can be calculated from the seven load points (P_{L1}, P_{L2}, ..., P_{L7}), as defined in 60034-2-3 [14]. An Excel spread sheet, provided with the purchase IEC 60034-31 [15], can provide typical losses of induction motors direct-on-line or when running on typical ASDs. This can be used as an estimate when exact data is not available. Precise data from the manufacturers would improve the accuracy and may be required by regulators or end-users but component losses is likely insignificant as compared to the total PDS energy conservation savings potential. The motor and frequency converter data as well as the interpolation formulas are from IEC 60034-2-3:2020 [14]and IEC 61800-9-2:2017 [9].

Losses at any load point can be calculated from equation (1) as follows:

$$P_L(n,T) = c_{L1} + c_{L2} \cdot n + c_{L3} \cdot n^2 + c_{L4} \cdot n \cdot T^2 + c_{L5} \cdot n^2 \cdot T^2 + c_{L6} \cdot T + c_{L7} \cdot T^2 \qquad (1)$$

Where:

(c_{L1}, c_{L2}, ..., c_{L7}.).are calculated per 60034-2-3 from the losses (P_{L1}, P_{L2}, ..., P_{L7}), at seven load points

n = Speed

T= Torque

C. *ASD Energy Lost Determination*

IEC TC 22 working group 18 has developed in IEC 61800–9–2 a methods of loss determination and a series of tests for ASDs or PDSs. NEMA is supporting this work and is adopting these standards. Since loss determination methods or test procedures did not previously exist for testing of ASDs this is an important new addition. Like motors, it is not practical to test every ASD therefore the standard establishes a method of loss determination that does not require testing. It is important that when test verification is required that a method is available, and its uncertainty be understood.

Using IEC 61800-2 will provide a precise determination of component energy consumption, but it is complicated and focused on defining IE classes at a full load point.

D. *The Extended Product Approach (EPA):*

The Extended Product Approach (EPA) is defined in IEC 61800-9-1 and shown in Fig. 2. The authors of NEMA MG 10011 2022 [17] PDS document believe that the method described in IEC 61800-9-1 for defining the energy consumption is accurate, but not all the required data easily accessible. Since the energy savings when using a PDS far outweigh the losses of the individual components, a more complex calculation of all the individual component losses is not necessary to identify a potential savings or create an incentive for adding an ASD to the system. An alternate approach will be discussed later in this paper. Though less complicated it will still need many of the procedures that were previously discussed. Note in figure 2, a Complete Drive Module (CDM) is defined. It includes the ASD and other required accessories.

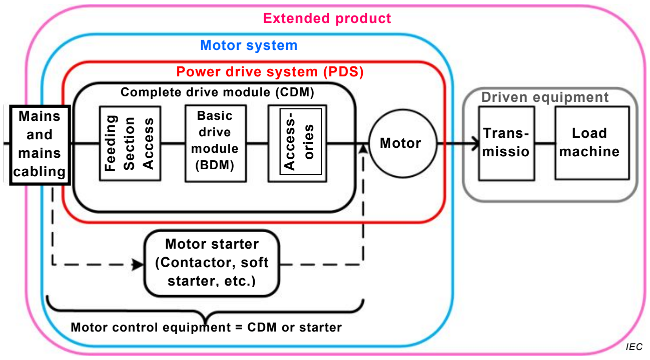

Fig. 2 Extended Product and embedded Components as defined in IEC 61800-9.
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IEC 61800-9-2 defines eight standardized operating points for which the energy component should be provided. With the losses at the eight operating load points (shown in Figure 3) and by using the interpolation procedure included in the standard, the precise total power usage can be determined from zero speed and load to 100 percent speed and load. With this and the defined duty cycle, the total energy consumption can be determined. For this to work, manufacturers must provide the loss information at these points.

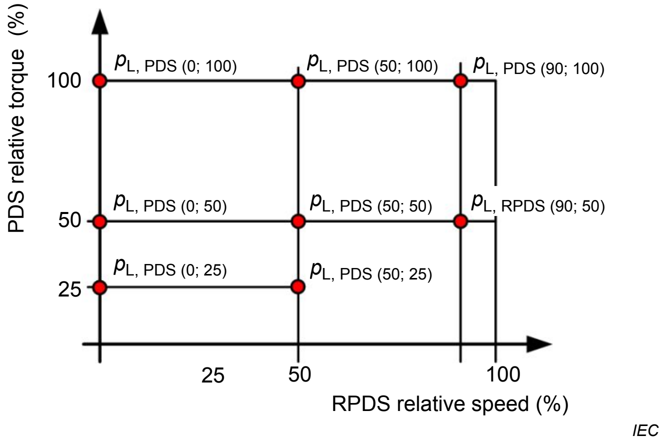

Fig. 3 Illustration of the operating points (shaft speed, torque) for determination of relative losses of the power drive system (PDS)

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With this information energy consumption of one system can be compared to another systems and process control to determine which is the best for energy savings. It can also be compared to that of the fixed speed motor without an ASD.

It is not the intent of IEC 61800-9-1 to evaluate the energy efficiency of the driven equipment (e.g., fan, pump, or compressor). There are other standards developed between the DOE and pump, fan, and compressor manufacturers to regulate the driven equipment. In this work, we are focusing on the energy consumption and savings potential of a PDS realized by the introduction of a ASD and smart process control to the system.

E. Future Loss Determination Activities

There has been identified a need to be able to extrapolate the losses determined in IEC 60034-2-3 to higher speeds. The next revision of IEC 60034-2-3 will likely have interpolation procedures to calculate the losses at any operating point between standstill and twice the rated speed and between no-load and twice the rated torque.

IV. POWER DRIVE SYSTEM ENERGY METRICS

Adjustable speed drives are by no means new but offer a prime example of moving beyond component efficiency and instead looking at optimized process management.

A. ASD Savings Basics

By controlling the speed of a motor with an ASD, the power consumption can be reduced. This is especially true for equipment like centrifugal fans, pumps, and compressors. This equipment generally follows the affinity laws: input power requirements are roughly proportional to the cube of speed. The idealized relationship between power and speed for centrifugal systems is shown in Fig.4. If the speed is reduced to 80% of full speed, the electrical power required is reduced to 51%.

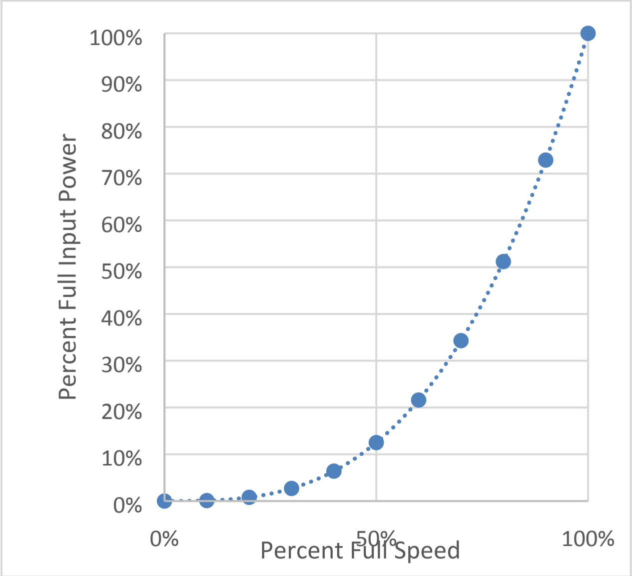

Fig. 4 Affinity Law: Ideal Power/Speed Relationship for Centrifugal Systems

Yet ASDs can be beneficial for both variable load systems (see Fig. 5) and constant load systems (Fig. 6) For variable load systems, where the required flow and torque varies with time (e.g., a pump serving a heating coil, or an oil pipeline), an ASD can increase or decrease the speed of the motor to provide the needs of the system. The savings potential varies, depending on speed, but is the accumulation of power reduction at each speed and how long it operates at that speed. As stated previously, the MSMA found that 94% of Petroleum and 64% of Chemical variable load systems do not have an ASD or any form of load control.

Recent research by NEEA and the Cadeo Group has shown that there is also potential savings for constant-load systems (e.g., constant-flow recirculation). These types of loads, which often use oversized motors, typically use a throttling device to obtain the design flow. But an ASD can be used instead of a throttling device and achieve significant savings. This is shown in Fig. 7. The difference between the upper curve (throttling valve on a pump) and the lower curve (ASD) is the power savings. If a motor is oversized by 20 percent, the power input is reduced from 94% to 58% of full-flow power.

One of the big questions is “how much savings is available by adding an ASD?” Up until now, engineers have had to perform site-specific energy calculations to determine savings. NEMA recently collaborated with NEEA and the Cadeo Group to develop the Power Index (PI) rating system that allows a streamlined method to evaluate the reduction in

\power, and associated energy savings, by controlling motor speed with an ASD.

Power Index gives an estimate of the savings available by adding an ASD to both variable load and constant load applications. PI is a balance between engineering rigor and broad, data-driven assumptions that can be applied over a wide variety of motors. While it does not calculate exact savings for a particular application, PI gives an estimate of savings, similar to the mpg ratings for cars. Like the "city/highway" mileage ratings, PI has separate ratings for variable ($PI,_{VL}$) and constant loads ($PI,_{CL}$). This will allow utility companies to calculate savings without having to perform costly measurements at each installation.

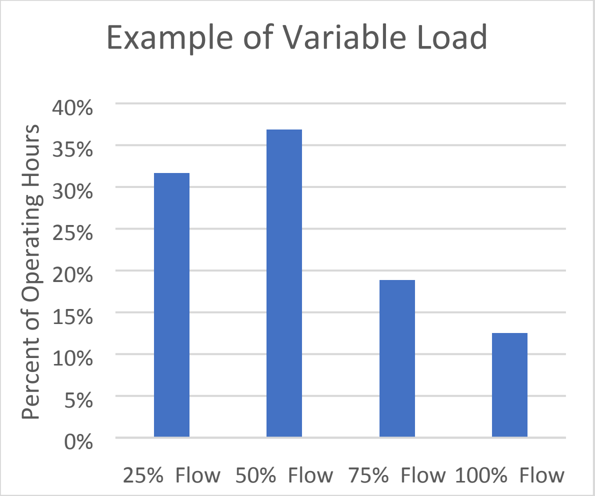

Fig. 5 Example of a Variable Load Profile

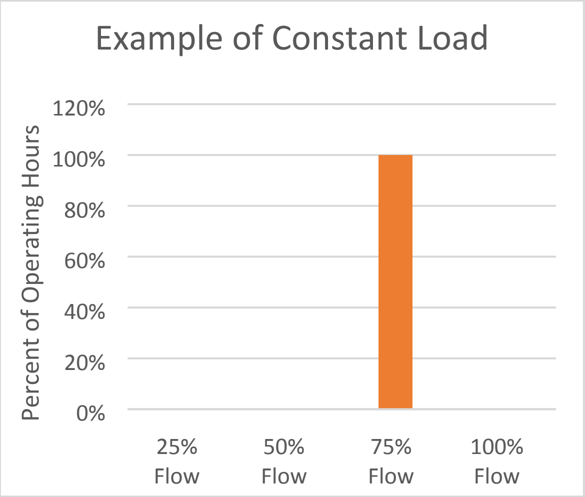

Fig. 6 Example of a Constant Load Profile. Driven equipment may run at an operating point different than 100%.

A. ASD Savings Potential

PI builds upon the data from the IEC 61800-9-2 standard but is different than the metrics from that test procedure in a few important ways. While IEC 61800-9-2 gives a rating based on 100% load, PI ratings use data at several load points over the spectrum of speeds. PI also provides a way to compare the savings of adding a drive to a full-speed motor, while 61800 only allows comparison of the improvements in drive and PDS efficiencies.

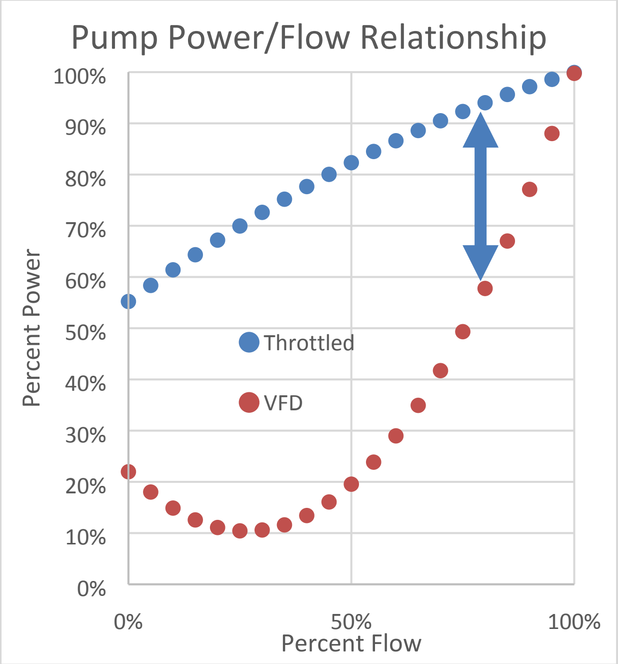

Fig. 7 Typical Power Input Required for Pump Control Methods (Throttle vs. ASD)

The simplicity of PI will allow utilities to estimate savings without having to determine application specifics (e.g., hourly load profiles). This enables incentives based on industry average data, like those found in the 2021 MSMA. This is especially valuable for smaller motors, where the cost of data collection would deplete the cost savings. While PI provides for a simplified calculation, the load points and weightings used are based on rigorous engineering analyses. Authors of PI used data from the MSMA, DOE rulemakings, utility company data, and NEEA research to triangulate typical load profiles and load points. All data was vetted with NEMA industry experts.

B. Power Index: How to Use

One of the big benefits of PI is how user-friendly the ratings are. PI is calculated as a whole number between 0-100. Higher numbers mean higher savings and present a rough percentage of expected savings. For instance, a $PI,_{VL}$ of 45 indicates a user could expect a 45% savings by adding a drive to a variable load system. A $PI,_{CL}$ of 25 indicates a user could expect a 25% savings by adding a drive to a constant load system.

Any centrifugal pump, fan, or compressor with a varying load, and any constant load system with an oversized motor is expected to save energy.

There are also a variety of non-energy benefits of adding drives to equipment: soft-start capabilities of ASDs will reduce wear and increase life of motors, speed control provides better control of feedstock and management of processes, reduced downtime, and reduced demand charges.

With all of the benefits of ASDs, combined with the size of motors in industry, petrochemical manufacturers have a huge potential for savings.

V. CONCLUSIONS

The population of electric motors and usage of ASDs across many industries was identified in the 2021 MSMA. Standards that can measure the efficiency of Power Drive Systems are available from IEC and NEMA. A power index to compare a motor-driven load to one that uses a PDS has been developed and studied by a regional utility coalition. The next steps are to introduce the power index to a wider group of utilities so they may use this as a prescriptive method for rebates for drives used on variable torque applications instead of the measurement and verification method required today. This rebate could be issued at point of sale like what was done for premium efficiency motors in the past. We hope this will be available within the upcoming year. Electric utilities collect $8-9 billion annually that can be used for these for these rebate programs.

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VII. REFERENCES

[1] Rao, P., Sheaffer, P., Chen, Y., Goldberg, M., Jones, B., Cropp, J., and J. Hester. 2021. U.S. Industrial and Commercial Motor System Market Assessment Report Volume 1: Characteristics of the Installed Base. Lawrence Berkeley National Laboratory.

[2] NEMA Standards Publication MG1-2016 (2018 rev), *Motors and Generators, National Electrical Manufacturers Association, 1300 N 17th Street, Suite 1752, Roslyn, VA*

[3] NEMA MG 10011-2022, *Power Index Calculation Procedure – Standard Rating Methodology for Power Drive Systems and Complete Drive Modules*

[4] IEC 60034-30-1, *Rotating electrical machines – Part 30-1: Efficiency classes of line operated AC motors (IE code)*

[5] IEC TS 60034-30-2, *Rotating electrical machines – Part 30-2: Efficiency classes of variable speed AC motors (IE-code)*

[6] North American Industrial Classification System (NAICS) at the three digit-level, https://www.census.gov/naics/

[7] EN 50598-2*, Ecodesign for power drive systems, motor starters, power electronics & their driven applications – Part 2: Energy efficiency indicators for power*

[8] IEC 61800-9-1, Adjustable speed electrical power drive systems – Part 9-1*: Ecodesign for power drive systems, motor starters, power electronics and their driven applications – General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA) and semi analytic model (SAM)*

[9] IEC 61800-9-2:2017, *Adjustable speed electrical power drive systems – Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications – Energy efficiency indicators for power drive systems and motor starters*

[10] IEC TS 60034-25*,* Part 25: 2022 AC electrical machines used in power drive systems – Application guide

[11] IEEE 112-2017 - *IEEE Standard Test Procedure for Polyphase Induction Motors and Generators*

[12] CSA C390-10 *Test Methods, Marking Requirements,*

And Energy Efficiency Levels For Three-Phase Induction Motors

[13] IEC 60034-2-1*, Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from*

[14] IEC 60034-2-3:2020*, Rotating electrical machines – Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC motors*

[15] IEC TS 60034-31:*2021 provides a guideline of technical and economical aspects for the application of energy-efficient electric AC motors.*

VIII. VITAE

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