August 26, 2025

Validation Analysis of the Power Index Calculation Procedure

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NEMA MG 10011-1

Published by:

National Electrical Manufacturers Association
1812 North Moore Street, Suite 2200
Arlington, VA 22209

www.nema.org

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700 NE Multnomah St, Suite 1300
Portland, OR 97232

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Table of Contents

Figures

Tables

Acknowledgements

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NEMA is the leading U.S. trade group representing nearly 325 electrical equipment manufacturers which make safe, reliable, and efficient products and systems, including companies which produce grid components, distribution transformers, and industrial automation equipment. Collectively, our members provide around 370,000 American manufacturing jobs in more than 6,100 facilities, labor and capacity that is essential for the successful transition to an electrified and cleaner U.S. economy.

For more than 20 years, NEMA has administered the NEMA Premium® License Program to promote highly efficient motors, reduce electrical power consumption and costs, and improve system reliability.[1] NEMA is committed to shaping policies and standards to reflect the latest advancements in the field and to prioritize safety, sustainability, and energy savings.

NEMA has partnered with the Northwest Energy Efficiency Alliance (NEEA) to play a pivotal role in developing efficiency programs for Power-Drive Systems (PDS). NEEA is an alliance of more than 140 utilities and energy efficiency organizations working on behalf of over 14.5 million energy consumers across the four Northwest states.

NEMA and NEEA seek to promote the integration of cutting-edge motor technology with advanced drive systems, delivering unparalleled precision, efficiency, reliability, and energy savings by offering methods to verify and label PDS products. The program will reduce overall energy consumption, lower utility bills, and drive increases to manufacturing demand, productivity, and long-lasting growth. Encouraging the use of PDS supports the broader goal of achieving energy resilience, reducing strain on the power grid, and promoting long-term cost savings for the entire supply chain.

Thank you to the authors and contributors listed below.

Charlie Philips, Advanced Energy Lab
Cory Luker, Resource Innovations
Holly Fallah, Quantum Energy Analytics
Isaac Shultz, Resource Innovations
Kristen Driskell, 2050 Partners
Lily Baldewicz, 2050 Partners
Mary Anderson, Pacific Gas & Electric
Nick Michel, Northwest Energy Efficiency Alliance
Nicky Dunbar, Asarum Consulting
Yao Jung Wen, Energy Solutions

[1] https://www.nema.org/directory/products/nema-premium-motors

Executive Summary

Published in 2024, NEMA's MG 10011-2024 Power Index (PI) Calculation Procedure provides a simplified method to compare motor operations in real-world operating conditions. This procedure is applicable to many motor types and systems and considers average motor load conditions to produce a value that considers how motors are loaded in the field. Research indicates that motors with load control can save a significant amount of energy, but adoption of load control technologies remains low[2]. More than 70% of commercial and industrial motor systems operate at a load factor of 0.75 or below[3], but only a fraction of these installed systems utilizes load control technology. The complexity of motor systems and challenge in evaluating available energy savings is a key barrier to adoption of these technologies. Utilizing the NEMA PI metric, motor systems could be more readily compared to assess opportunities for energy savings and highlight load control technologies for applications where current adoption is infrequent.

The main objective of this research was to verify whether the interpolation calculations yield accurate results. This Validation Analysis compared tested data to interpolated data in 19 different motor and drive systems to verify that interpolation produces similar results to actual test data. Interpolating load points instead of requiring testing in these conditions will allow manufacturers to cost-effectively rate motors using the NEMA PI metric without additional burdensome requirements. Motors were tested according to NEMA MG 10011-2024 at three different independent laboratory facilities, and included induction, synchronous, and start-line permanent magnet motor models. Lab measurements were used to calculate losses for each system, and these losses were then compared to data interpolated from previously reported IEC (International Electrotechnical Commission) test data. Three motors were excluded from the reported results as analysis indicated that these results were outliers or possibly errors in testing. Results indicate strong agreement between interpolated and tested data, with a PI value absolute error of under 0.5 for all motor systems tested.

Other key findings indicate that the presence of a drive has the greatest impact on PI values due to the shift from fixed-speed to variable-speed operation. Additionally, motor losses have a larger influence on the overall PI value than drive losses. At low load points, motors under 50 HP had good agreement between the measured and interpolated power losses, with the most significant variation in induction motors. For all motors, losses were low at this low load point, and impacts from these values had a less significant impact on the overall PI value. At the high load point, overmodulation is a concern for many motors and a correction factor was tested to determine whether motors were overmodulating during the bench test. At this operating condition, errors in drive loss values were more significant, with synchronous and line-start permanent magnet motors more impacted by these error values. In general, induction motors exhibited the largest variability in overall losses, and motor losses made the most impact on resultant PI values for this motor type. Drive losses were more impactful on the overall PI rating of synchronous motors, but overall losses were smaller for this motor group.

Results from this research indicate that the NEMA PI metric is a simple and effective tool for representing real world performance of motor systems operating at part-load conditions. This calculation method will simplify efforts for motor system manufacturers to highlight energy savings opportunities from power drive systems and for users to evaluate the impacts of load control on installed systems. The ability to rank the performance of motor products and systems is an important asset to programs aiming to increase the

[2] Rao, Prakash, et al. "US industrial and commercial motor system market assessment report volume 3: Energy savings opportunity." (2022).
[3] Rao, Prakash, et al. "US industrial and commercial motor system market assessment report volume 3: Energy savings opportunity." (2022).

adoption of energy efficient motor technology and sets a strong foundation for voluntary incentive programs to build resources to advance adoption of these products.

1 Introduction

Electric motor systems are ubiquitous in buildings and facilities, accounting for roughly 29 percent of the total load on the United States (U.S.) electric grid[4]. While improved load control (such as through the use of variable speed drives) offers significant energy savings potential (over 115,000 GWh per year) and could reduce commercial and industrial operating costs by an estimated $13 billion annually, adoption remains limited[5]. Of these motor systems, load control technology is more likely to be installed on larger motor systems and is as of yet still infrequently used in most motor systems. 76 percent of U.S. industrial motor systems and 91 percent of commercial industrial systems are installed with no load control technology, even though more than a third of all industrial and commercial motor systems operate at variable load.

A key barrier to adoption of load control technology has been the ability to easily assess the energy savings and performance of motors with load control installed (compared to systems with no load control). Because each motor system is unique, with assorted load conditions, different motor efficiencies, and with efficiencies of load control technologies also varying, most assessments of energy savings from load control are performed via custom calculation and are not easily comparable between individual motor systems.

This report assesses the performance of 19 motors and drives, collectively referred to as Power Drive Systems (PDS), in accordance with the NEMA MG 10011-2024 Power Index (PI) Calculation Procedure[6]. This standardized calculation procedure evaluates energy performance across multiple motor load points, providing a more comprehensive view of real-world operating conditions compared to traditional full-load efficiency metrics. The NEMA PI procedure generates a standardized number that can be used to compare energy usage between motor products (whether paired with a variable speed drive or not).

This validation analysis was produced to confirm the reliability of the PI value in representing motor efficiency across different products and motor/drive combinations. The analysis centers on two primary objectives. First, it examines the accuracy of the interpolation methods defined in the NEMA PI Calculation Procedure by comparing calculated estimates with measured data. Second, it identifies performance trends among PDSs, investigating how factors such as motor type and motor size influence energy savings. By validating interpolated data, this report aims to make PI ratings more readily available on products without adding additional test burden to manufacturer processes. This effort will allow the comparison of motor products in many applications.

2 PI Calculation Background

The NEMA PI Calculation Procedure is an averaged rating that can apply to induction motors (both direct-on-line and inverter-fed), synchronous motors, and PDSs that incorporate these motors when paired with a drive. Using the PI value, a wide range of motor types and configurations can be assessed on a common platform and their performance compared. Commercially available motors are rated for continuous operation at nameplate rated speed and horsepower, but more than 70% of commercial and industrial

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[4] Rao, Prakash, et al. "US industrial and commercial motor system market assessment report volume 1: Characteristics of the installed base." (2022).
[5] Rao, Prakash, et al. "US industrial and commercial motor system market assessment report volume 3: Energy savings opportunity." (2022).
[6] Power Index Calculation Procedure—Standard Rating Methodology for Power Drive Systems and Complete Drive Modules, https://www.nema.org/standards/view/power-index-calculation-procedure-standard-rating-methodology-for-power-drive-systems-and-complete-drive-modules

motor systems are typically operated at a load factor of 0.75 or below[7]. Motor operation at nameplate rated speed is not indicative of the actual operating speed of any given motor/drive product operating in the field.

In this report, induction, synchronous, and line-start permanent magnet PDSs spanning 3 HP to 75 HP are evaluated. By comparing PI scores, the energy performance of these PDSs at conditions consistent with what motors experience in the field can be ranked. NEMA's MG 10011-2024 Power Index (PI) Calculation Procedure allows manufacturers to rate their products by either directly measuring performance at various part-load conditions or by interpolating data that is gathered from IEC test processes that manufacturers are already required to perform.

Equation 1 expresses the relationship between input power savings achieved (PI) by comparing the tested PDS to a baseline system. For example, a PI score of 35 would indicate that the tested PDS uses 35% less energy than the baseline system. This is determined by the difference between the baseline input power ($P_{in,Base}$) and the tested PDS input power ($P_{in,PDS}$), normalized by the baseline input power:

$$PI = \frac{P_{in,Base} - P_{in,PDS}}{P_{in,Base}} * 100 \quad (1)$$

Equation 2 details how the input power of the evaluated PDS is calculated. The tested input power ($P_{in,PDS}$) is averaged across multiple load points ($P_{in,PDS,i}$), which correspond to typical speed and torque conditions for variable torque equipment[8]. These load points, represented by blue diamonds in Figure 1 and defined in Table 1, are evenly weighted (w_i) to determine the system's average input power:

$$P_{in,PDS} = \sum_i \left(w_i \times P_{in,PDS,i}\right) \quad (2)$$

Equation 3 defines the baseline input power ($P_{in,Base}$). It is calculated using the baseline motor's nominal horsepower (P_{Nom}) and nominal full-load efficiency (η_{Nom}).

$$P_{in,Base} = \frac{P_{Nom}}{\eta_{Nom}} \quad (3)$$

Calculating the PI score requires motor and drive power loss data at specific load points defined in Table 1 and shown as blue diamonds in Figure 1.

Table 1—PI Load Points

PI Load Point	% Speed	% Torque	% Load
PI Low	44%	19%	25%
PI Mid Low	60%	36%	50%
PI Mid High	79%	62%	75%
PI High [9]	100%	100%	100%

This data can be obtained in one of two ways:

1. Directly measured at Table 1 PI load points, or

[7] Rao, Prakash, et al. "US industrial and commercial motor system market assessment report volume 1: Characteristics of the installed base." (2022).

[8] Variable torque equipment, such as centrifugal pumps and fans, require less torque at lower speeds, resulting in significant energy savings when operated with variable frequency drives (VFDs).

[9] PI High is measured at 90% of rated speed at full load torque, then extrapolated to 100% rated speed and full load torque. This is due to additional measurement uncertainty at full load and rated speed for some drives (e.g., overmodulation, where drive supplied voltage exceeds standard line voltage).

2. Interpolated using load points and formulas from IEC 60034-2-3[10] and IEC 61800-9-2[11] standards (orange dots in Figure 1).

By utilizing test data from the IEC standards, the PI Calculation Procedure minimizes additional testing for OEMs as specified by European Union (EU) requirements. Since OEMs already measure PDS performance in accordance with these standards, the procedure enables them to interpolate power loss data at the PI load points using existing measurements, eliminating the need for direct measurements at those specific points. The main objective of this research was to verify whether the interpolation calculations yield accurate results.

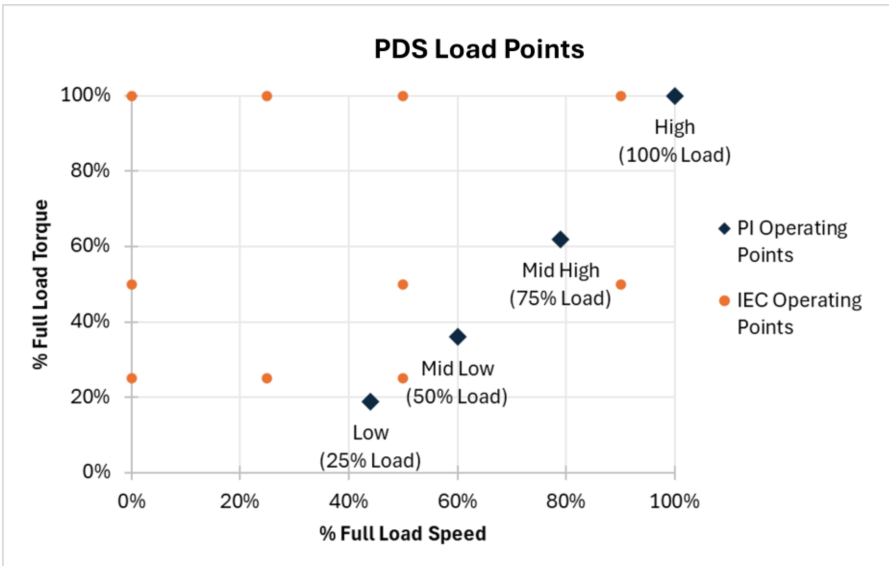

Figure 1—Comparison of Power Drive System (PDS) Load Points

3 Methodology

This report leveraged data collected from four motor testing labs. Table 2 provides a summary of the PDS contributions by lab. In total, 22 PDSs were evaluated, including 14 induction motors (IM), seven synchronous (SYN) motors, and one line-start permanent magnet (LSPM) motor. Of the seven synchronous motors, five were surface permanent magnet (SPM) motors, one was a synchronous reluctance motor (SynRM), and one was a permanent magnet-assisted synchronous reluctance motor (PMaSynRM). Detailed information on each PDS, including nominal horsepower, pole count, and rated RPM is provided in Appendix A.

Lab A tested each PDS twice to assess measurement repeatability, with results from both tests included in the analysis. The three Lab D motor tests were damaged and excluded from the analysis, resulting in 19 total motor systems considered in this dataset.

[10] IEC 60034-2-3:2024 Rotating electrical machines—Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC motors, https://webstore.ansi.org/standards/bsi/bseniec600342024

[11] IEC 61800-9-2:2023: Adjustable speed electrical power drive systems (PDS)—Part 9-2: Ecodesign for motor systems—Energy efficiency determination and classification, https://webstore.ansi.org/standards/bsi/bseniec618002025

Table 2—Summary of Participating Test Lab Contributions

Motor Type	Induction Motors	Synchronous Motors (SYN)			Line-Start Permanent Magnet Motors
Motor Subtype	N/A	SPM	PMaSynRM	SynRM	LSPM
Lab A*	6 (x2)	5 (x2)		1 (x2)	
Lab B	2				1
Lab C	3		1		
Lab D**	3 (damaged)				
Total	14	5	1	1	1

* Lab A tested each PDS two times for measurement repeatability assessments.
** Lab D motor tests were defective and excluded from the report.

All testing adhered to the PI Calculation Procedure, which references the IEC 60034-2-3 and IEC 61800-9-2 standards for measuring motor and system properties. Prior research by Lily Baldewicz and Tim Albers in 2024 identified several factors influencing the repeatability of test methods IEC 60034-2-3 and 61800-9-2[12]. Building on their findings, this study incorporated specific guidelines aimed at improving both accuracy and repeatability. Participating labs were instructed to follow these guidelines throughout the testing process.

Each PDS was tested at both IEC standard and PI-specific load points shown in Figure 1. Testing at both sets of points is necessary to compare measured power losses at PI-specific load points with interpolated losses derived from IEC standard points. For each load point test, three power measurements and two nominal motor parameters were collected, as shown in Table 3.

Table 3—Measured Data for Analysis

Parameter	Description
P_{DI}	Drive input power
$P_{DO} = P_{MI}$	Drive output power = Motor input power
P_{MO}	Motor output power
P_{Nom}	Nominal motor power
η_{Nom}	Baseline motor full-load efficiency

Using this data, motor, drive, and system power losses were calculated at each load point, along with the corresponding PI values, as shown in Table 4.

[12] Baldewicz, Lily and Tim Albers. 2024. Validation Research on IEC 61800-9-2 and 60034-2-3.

Table 4—Derived Values for Analysis

Parameter	Description
$PL_M = P_{MI} - P_{MO}$	Motor power losses
$PL_D = P_{DI} - P_{DO}$	Drive power losses
$PL_{SYS} = PL_M + PL_D$	System power losses
$PI(PL_{SYS}, P_{Nom}, \eta_{Nom})$	Power Index (PI) is function of system power losses at each PI load point, nominal motor power, and baseline motor full-load efficiency. For complete details of how to calculate PI, see NEMA MG 10011.

Interpolated power losses at the PI load points were then calculated using IEC interpolation methods for both motor and drive losses, and these values were then used to calculate interpolated PI scores. The interpolated power losses and PI scores at each load point were compared to the measured values to evaluate the accuracy of the interpolation methods. Appendix B contains a URL link to the complete dataset acquired for the PI validation analysis, including both measured and interpolated data.

4 PI Validation Research

This PI validation assessment reviews measured system performance and compares measured performance to interpolated performance. The analysis addresses the following:

Outlier Assessment:

- Do certain measured power loss values indicate significant deviations from expected trends?

PI Score Analysis:

- How do measured PI scores vary as a function of motor type and motor size?
- Do PI scores based on measurements align with those calculated using interpolation equations?

Load Point Power Losses Analysis:

- How do power loss values vary as a function of motor type and motor size?
- Do measured power loss values align with interpolated values at PI load points?

Outlier Assessment

Of the 19 motors analyzed, the team identified three outliers that were excluded from the analysis. The table below summarizes the outliers and explains why they were classified as such. Additional data for these outliers can be found in Appendix B. A visual representation of measured PI values as well as the absolute error between the measured and interpolated PI scores for all motors, including the outliers, is shown in Figure 2 and Figure 3, respectively.

PDS 5—A 5-HP induction motor test showed approximately 60 percent error in motor losses between measured and interpolated values at the PI MidLow load point, while all other load points showed minimal deviations. Additionally, the measured motor losses at PI MidLow exceeded those at PI MedHigh, which is physically implausible and suggests a user input error. As a result, this PDS was classified as an outlier and excluded from the analysis.

PDS 6—A 7.5-HP synchronous motor exhibited a 38 percent error in measured motor losses at the PI MedHigh load point and a 90 percent error at the PI High point. Notably, the measured motor losses were about twice the interpolated values at PI MedHigh and half the interpolated values at PI High, an unusual pattern that supported classifying PDS #7 as an outlier and excluding it from the analysis.

PDS 8—A 7.5-HP synchronous reluctance motor failed to meet its nameplate efficiency and was not representative of synchronous reluctance technology. After contacting the manufacturer, the issue was traced to a defect in the raw materials. As a result, this motor was classified as defective and excluded from the analysis.

PI Score Analysis

This section begins by assessing the range of measured PI scores. This is followed by a comparison of measured PI scores to interpolated PI scores.

Comparison of Measured PI Scores

Figure 2 illustrates measured PI scores plotted against motor horsepower, with distinct markers for induction motors (IM), synchronous motors (SYN), and line-start permanent magnet (LSPM) motors. PI scores range from around 51 to 56 across all motor types.

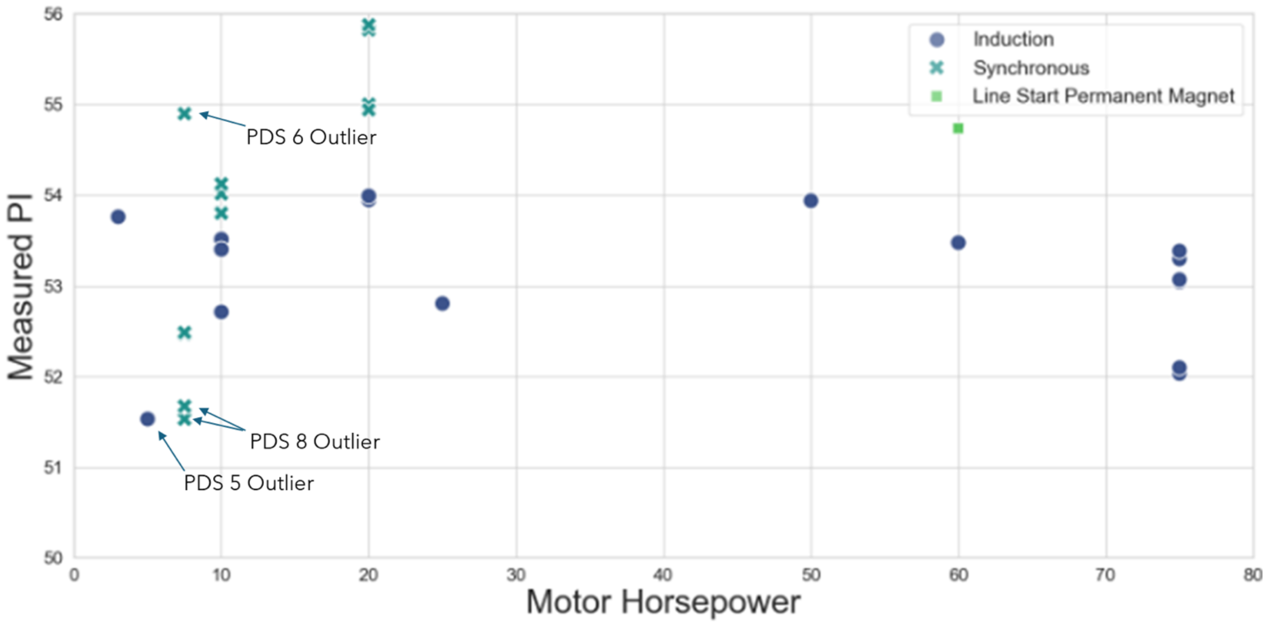

Figure 2—Measured PI Values by Motor Type and HP

Figure 3 compares the measured PI score for induction and synchronous motor types, with outliers removed. Each box represents the interquartile range, where the middle 50% of measured PI scores fall, with the horizontal line inside the box indicating the median value. Induction motors show a relatively narrow distribution, with PI values ranging approximately from 52 to 54, and a median near 53.5. In contrast, synchronous motors exhibit a wider distribution of measured PI values, ranging from about 52.5 to 56, and a slightly higher median near 54.0. The broader spread for synchronous motors suggests greater variability in performance, but higher maximum efficiency than induction motors.

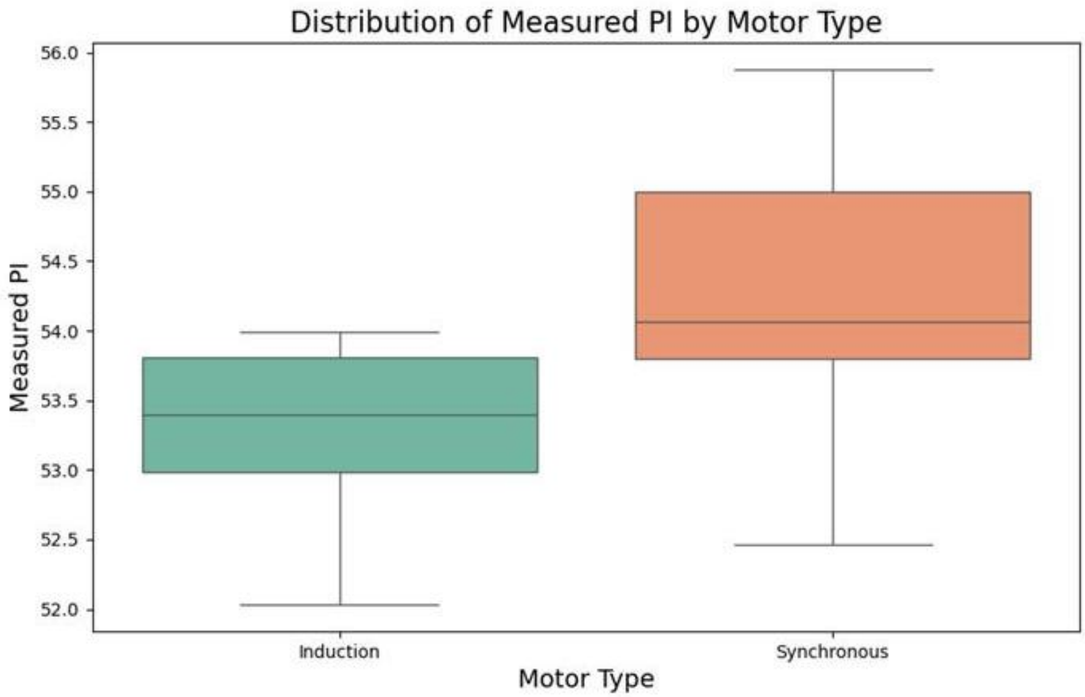

Figure 3—Distribution of Measured PI Scores by Motor Type

While these initial comparisons offer useful insights, the sample sizes for each motor type remain limited. Additional testing is needed to confirm these trends and more accurately define typical PI score ranges by motor type.

PI Score Error Analysis

Figure 4 illustrates the absolute errors between measured and interpolated PI score as a function of motor horsepower. Positive values indicate that the measured PI score was higher than the interpolated PI score. Absolute error is calculated as:

$$Absolute\ Error = Measured\ PI - Interpolated\ PI \quad (4)$$

Figure 4 illustrates that the average absolute PI errors are small across all motor types and motor sizes, demonstrating the strong agreement between measured and interpolated PI values. Excluding the PDS outliers, all absolute errors between measured PI and interpolated PI are below 0.5.

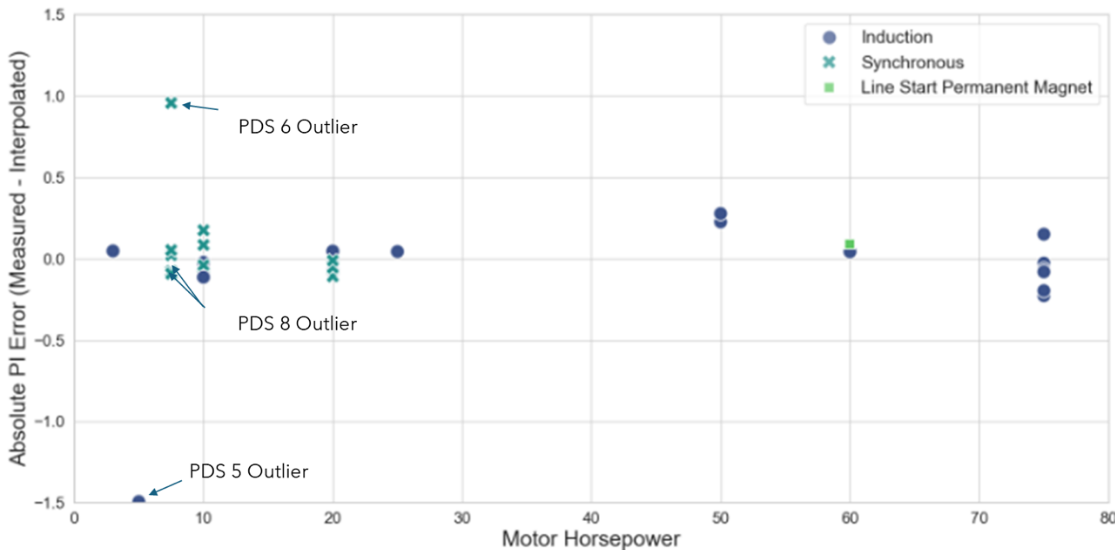

Figure 4—PI Absolute Error by Motor Type and HP

Table 5 presents PI absolute error statistics by motor type with outliers removed. The results reinforce the core finding that variation between measured and interpolated PI values are negligible.

Table 5—PI Absolute Error Statistics by Motor Type (Outliers Removed)

Motor Type	Average PI Error	Sample Size	Min PI Score	Max PI Score	Standard Deviation
Induction	–0.003	16	52.03	53.99	0.61
Synchronous	–0.013	10	53.80	55.88	1.15
Line Start Permanent Magnet	0.09	1	52.46	55.88	NA

Load Point Power Loss Analysis

This previous section assessed PI scores, this section assesses power losses at each PI load point, originally defined in Table 1. This section begins by assessing the range of measured motor and drive losses at various PI points. It then compares measured versus interpolated motor and drive losses at each PI load point. Examining the discrepancies in losses at each PI load point provides a clearer understanding of the sources of interpolation errors and their impact on the PI calculation. Outliers described above have been removed from this analysis.

This analysis uses percent error, as calculated in Equation 5, rather than absolute error because the magnitude of error can vary depending on motor size and load. Percent error normalizes the error relative to the motor's size and load, providing a consistent measure of error across motor sizes and load points, allowing for a more meaningful comparison.

$$Percent\ Error = \frac{Measured\ Loss - Interpolated\ Loss}{Measured\ Loss} \quad (5)$$

Comparison of Measured Motor and Drive Losses

Figure 5 illustrates measured motor losses (top panel) and measured drive losses (bottom panel) as a function of motor horsepower and PI load point. Losses are calculated as the difference between the input power and the output power.

Key Observations:

- **Motor losses exceed drive losses**: Across all PI points and motor sizes, motor losses are significantly higher than drive losses, typically by an order of magnitude. As a result, motor losses have a greater influence on the PI score than drive losses.
- **Losses increase with motor load**: For all motor sizes, both motor and drive losses are highest at the PI High load point and lowest at the PI Low load point. This pattern holds consistently for both motor and drive losses, making PI High losses the most influential on the PI score and PI Low losses the least influential.

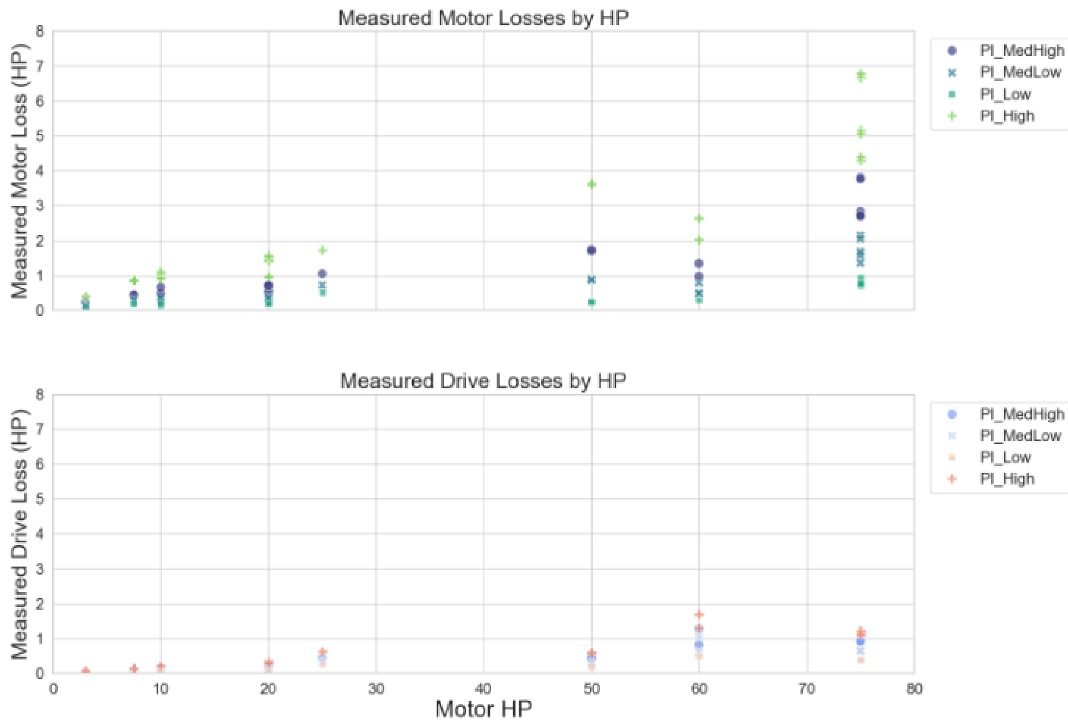

Figure 5—Measured Motor and Drive Losses by Motor Horsepower

PI Low Load Point Error Analysis

PI Load Point	% Speed	% Torque	% Load
PI Low	44%	19%	25%

At low-load load points like PI Low, variable speed-controlled induction motors commonly employ flux optimization controls such as voltage boosts and phase angle adjustments to improve efficiency. In contrast, synchronous motors inherently optimize phase angle for smooth and consistent operation. Since the interpolation method relies on linear V/Hz control, discrepancies between measured and interpolated power losses were anticipated at this load point, particularly for induction motors.

Figure 5 illustrates the percent error in measured versus interpolated losses at the PI Low load point, plotted as a function of motor horsepower and motor type.

Key Observations:

- **Good agreement for motors <50 HP:** The percent error between measured and interpolated losses for motors less than 50 HP is less than 20%. Synchronous motors exhibit closer agreement than induction motors.

- **High percent errors at PI Low for ≥50 HP induction motors:** Induction motors 50 HP and larger exhibit larger discrepancies at PI Low. The team attributes this to variations in flux optimization controls at low loads, which are not accounted for in the linear interpolation method.
- **Limited impact on PI value:** Despite notable percent errors at PI Low for some larger induction motors, its contribution to the overall PI calculation is minor due to the low loss magnitude at this load point.

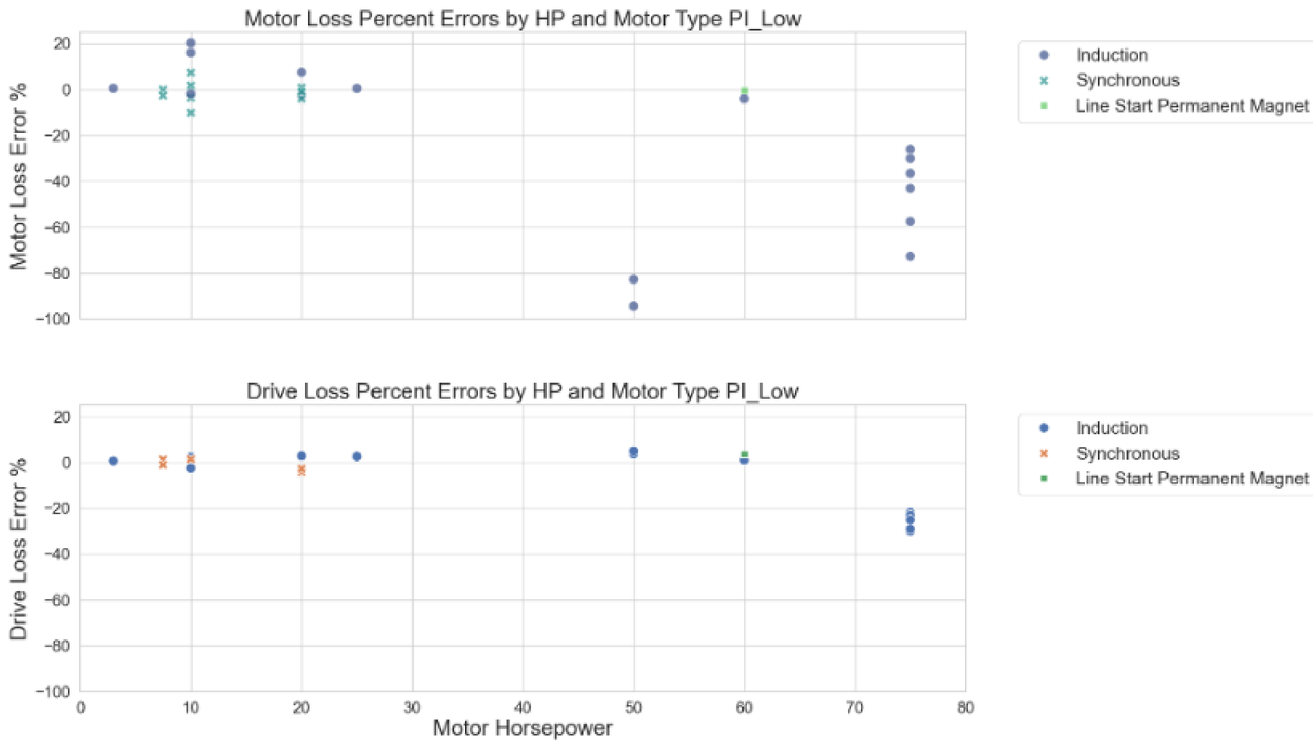

Figure 6—Motor and Drive Loss Percent Errors at PI Low

PI Mid Low Load Point Error Analysis

PI Load Point	% Speed	% Torque	% Load
PI Mid Low	60%	36%	50%

Figure 7 illustrates the percent error in measured versus interpolated losses at the PI Mid Low load point, plotted as a function of motor horsepower and motor type.

Key Observations:

- **Good agreement at PI Mid Low:** Measured and interpolated motor and drive losses align well at the PI Mid Low load point, with most percent errors within 10%. Some larger discrepancies were observed at higher horsepower, but all percent errors remained under 20%.

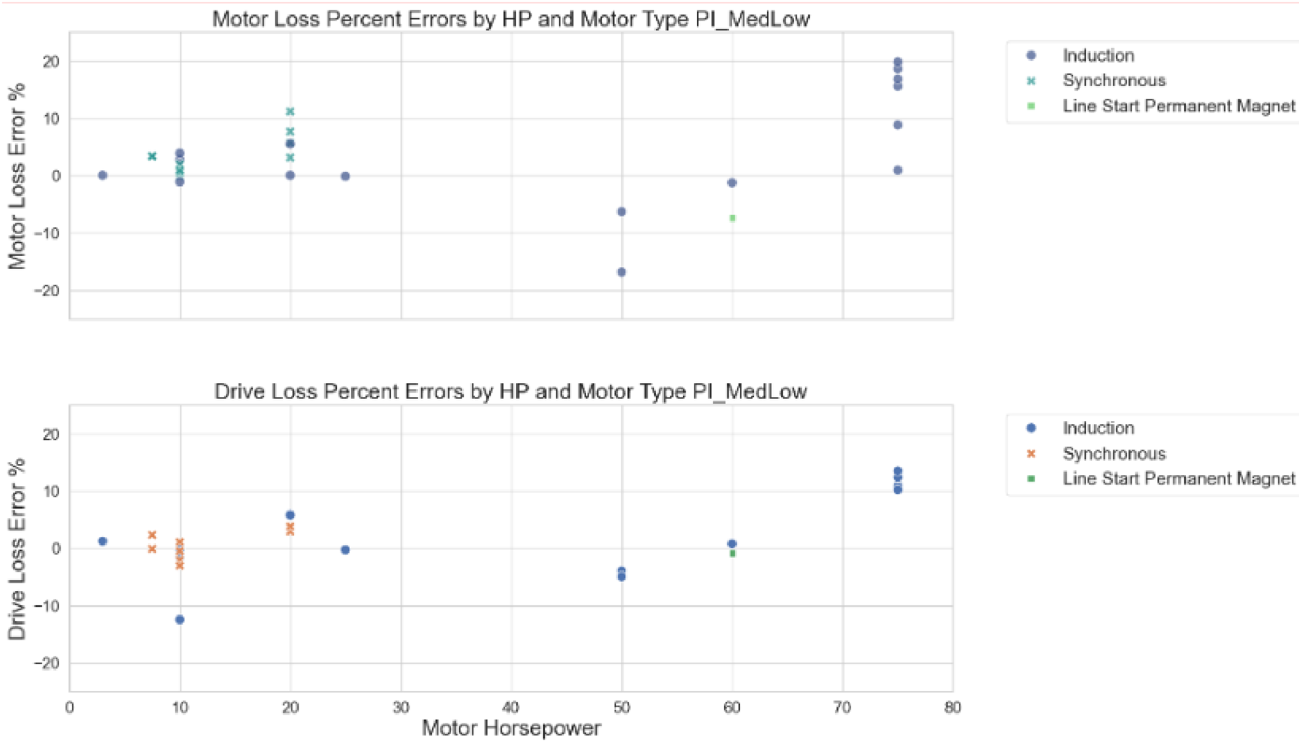

Figure 7—Motor and Drive Loss Percent Errors at PI MidLow

PI Mid High Load Point Error Analysis

PI Load Point	% Speed	% Torque	% Load
PI Mid High	79%	62%	75%

Figure 8 shows the percent error in measured versus interpolated losses at the PI MidHigh load point, plotted as a function of motor horsepower and motor type.

Key Observations:

— **Good agreement at PI MidHigh:** In most cases, the measured and interpolated motor and drive losses at PI MidHigh agree within 10%. There are some larger discrepancies at higher horsepower, but all percent errors are around 20%.

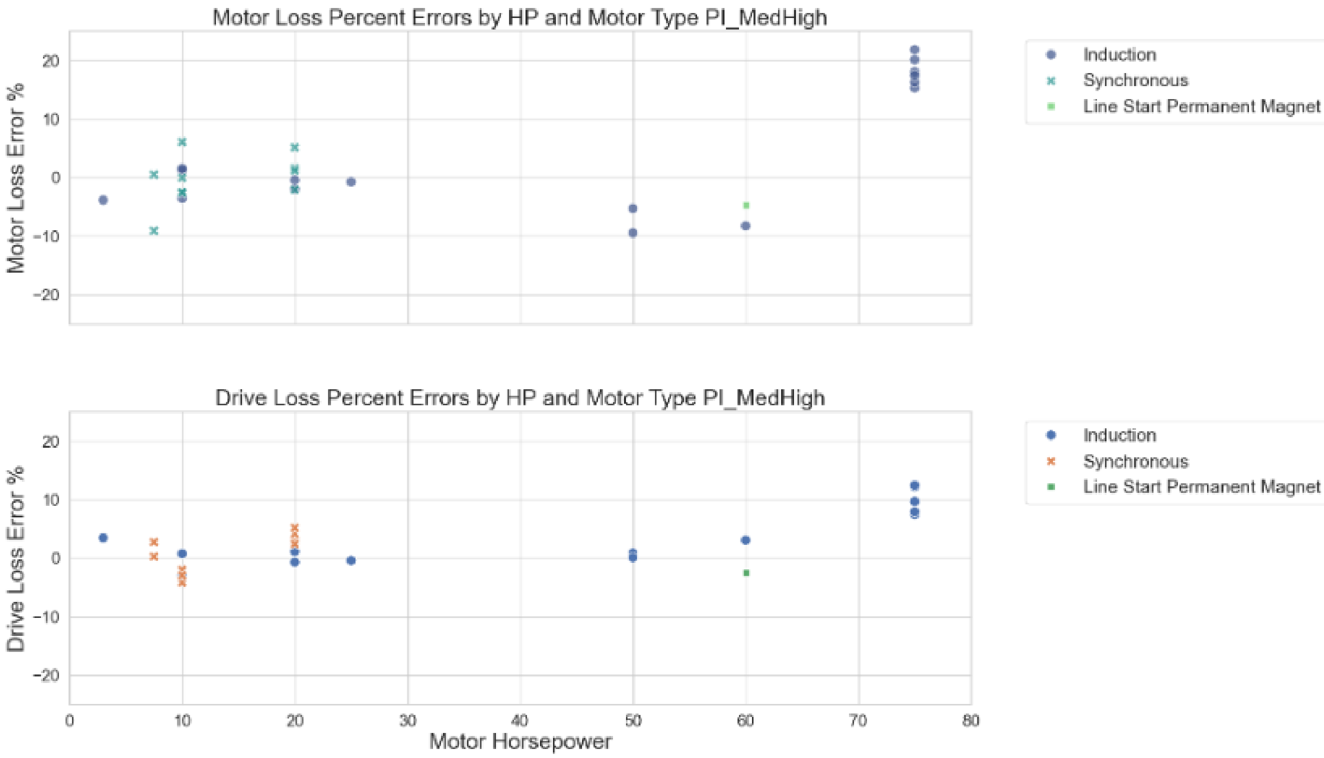

Figure 8—Motor and Drive Loss Percent Errors at PI MedHigh

PI High Load Point Error Analysis

PI Load Point	% Speed	% Torque	% Load
PI High[13]	100%	100%	100%

At PI High, the full load operating condition, variable speed-controlled induction motors frequently operate in overmodulation mode. Overmodulation occurs when the drive exceeds the modulation index, in that it is attempting to deliver more voltage to the motor than the DC bus voltage can support. This leads to distorted output voltage waveforms, increased harmonic content, and reduced system efficiency. Overmodulation primarily impacts high load points, as these conditions demand higher motor voltage to sustain torque and power output. At lower loads, the voltage requirement typically remains within the drive's capabilities, minimizing the likelihood of overmodulation. As such, overmodulation is a critical factor in accurately assessing motor and drive performance at PI High.

The team evaluated whether each system was overmodulating by applying an overmodulation factor of 1.11 to the interpolated PI High load point motor loss values, as shown in Equation 6. If applying this factor reduced the percent error between measured and interpolated values, the system was assumed to be overmodulating, and the factor was retained. Conversely, if the error increased, the factor was removed, and the system was considered not to be overmodulating. While this method provides a preliminary assessment, it is relatively crude. The team is actively developing more sophisticated methods, such as analyzing harmonic distortions in waveforms, to better identify and assess overmodulation. Figure 9 shows

[13] *PI High* is measured at 90% of rated speed at full load torque, then extrapolated to 100% rated speed and full load torque. This is due to additional measurement uncertainty at full load and rated speed for some drives (e.g., overmodulation, where drive supplied voltage exceeds standard line voltage).

the percent errors in motor and drive power losses at the PI High load point, plotted as a function of motor horsepower and differentiated by motor type.

Key Observations:

- **Strong agreement at PI High:** After applying the overmodulation factor to PDSs identified as likely overmodulating, agreement between measured and interpolated motor loss values is within 10% for all tested PDSs.
- **Higher drive loss percent errors:** Unlike at the other three PI load points, the drive loss percent errors are higher than the motor loss percent errors at PI High.

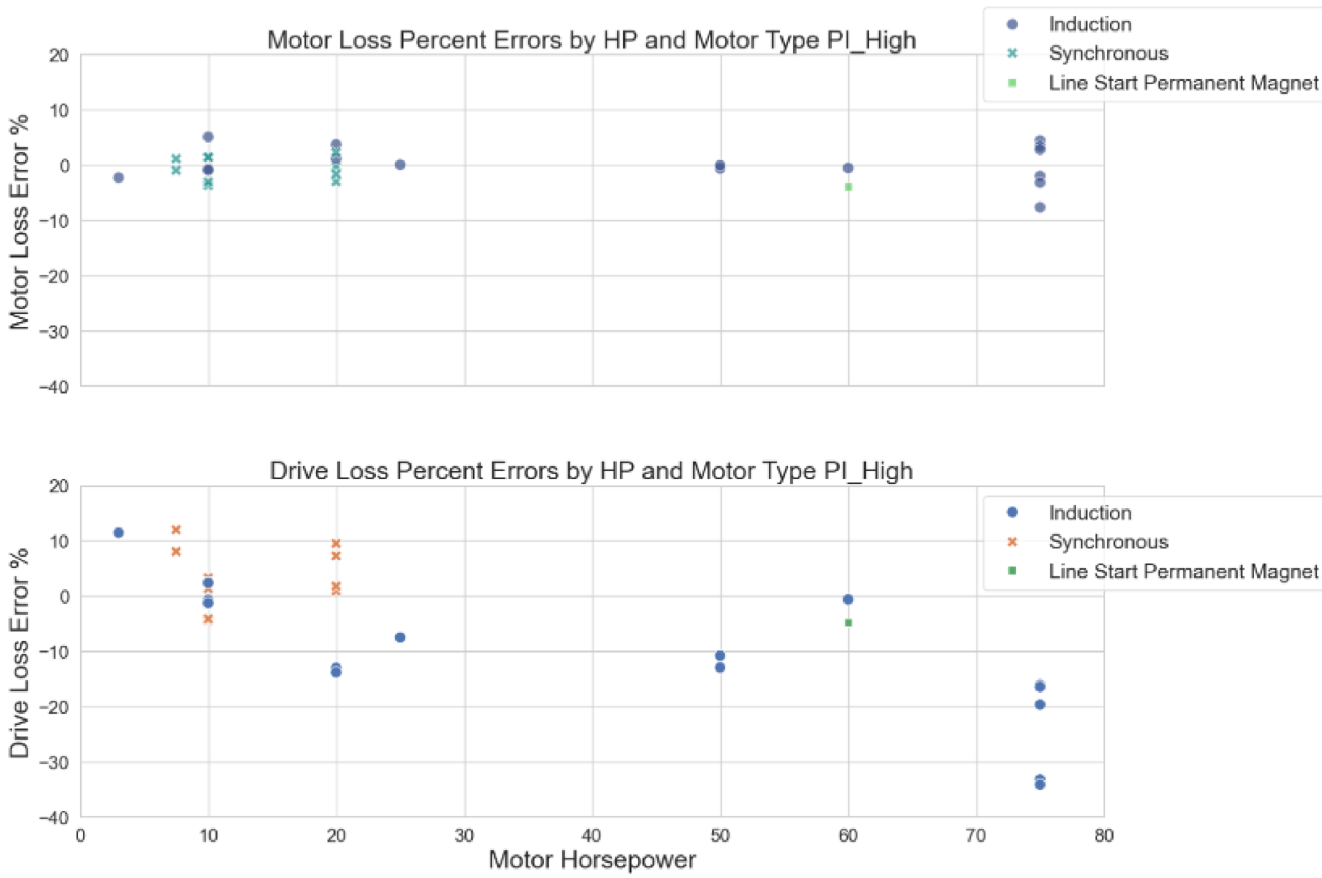

Figure 9—Motor and Drive Loss Percent Errors at PI High

Figure 10 shows the same plot as Figure 9, but in this case, overmodulating motors are excluded from receiving the overmodulation factor, while non-overmodulating motors are assigned the factor. This represents a worst-case scenario for the sensitivity analysis. This causes motor loss percent error to expand to range closer to 10% and 20%.

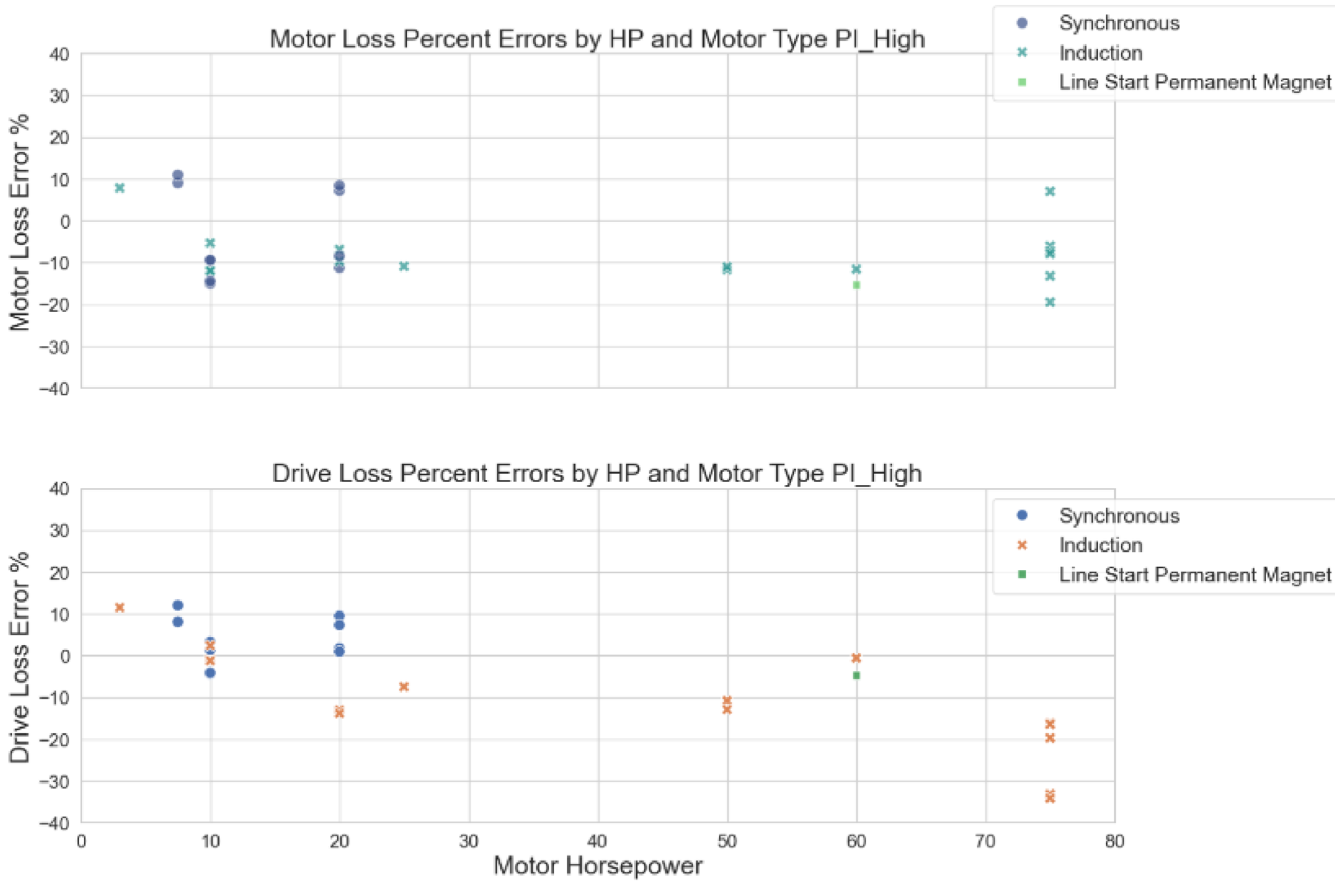

Figure 10—Motor and Drive Loss Percent Error PI High (Worst Case Scenario)

Table 6 presents the average absolute value of the percent error in PI High motor losses for the three motor types—Induction, Synchronous, and Line Start Permanent Magnet—under both best-case and worst-case scenarios. Induction motors, which exhibit a low average percent error in the best-case scenario (2.4%), see this error rise substantially to 9.9% in the worst-case scenario. Synchronous motors show a more pronounced sensitivity, with their average percent error rising from 3.9% in the best case to 15.3% in the worst case. Line Start Permanent Magnet (LSPM) motors experience the highest error rates in both scenarios, with their average percent error increasing from 8.8% to 17.8%. Appendix B includes a standalone data table showing PI High motor losses for both the best-case and the worst-case scenarios, as well as the impact on PI scores.

Table 6—High Load Point Error Statistic by Motor Type

Motor Type	Average PI High Percent Error (Best Case)	Average PI High Percent Error (Worst Case)
Induction	2.4%	9.9%
Synchronous	1.9%	10.4%
Line Start Permanent Magnet	3.9%	15.3%

Overall, these findings from Table 6, paired with Figure 10, illustrate the importance of accurately accounting for overmodulation when calculating PI metrics.

Summary of Load Point Loss Errors

Figure 111 is a boxplot showing the variation in motor and drive loss percent error across the four PI Points, grouped by motor type. Each box represents the distribution of power loss percent errors for a specific motor type at each load point.

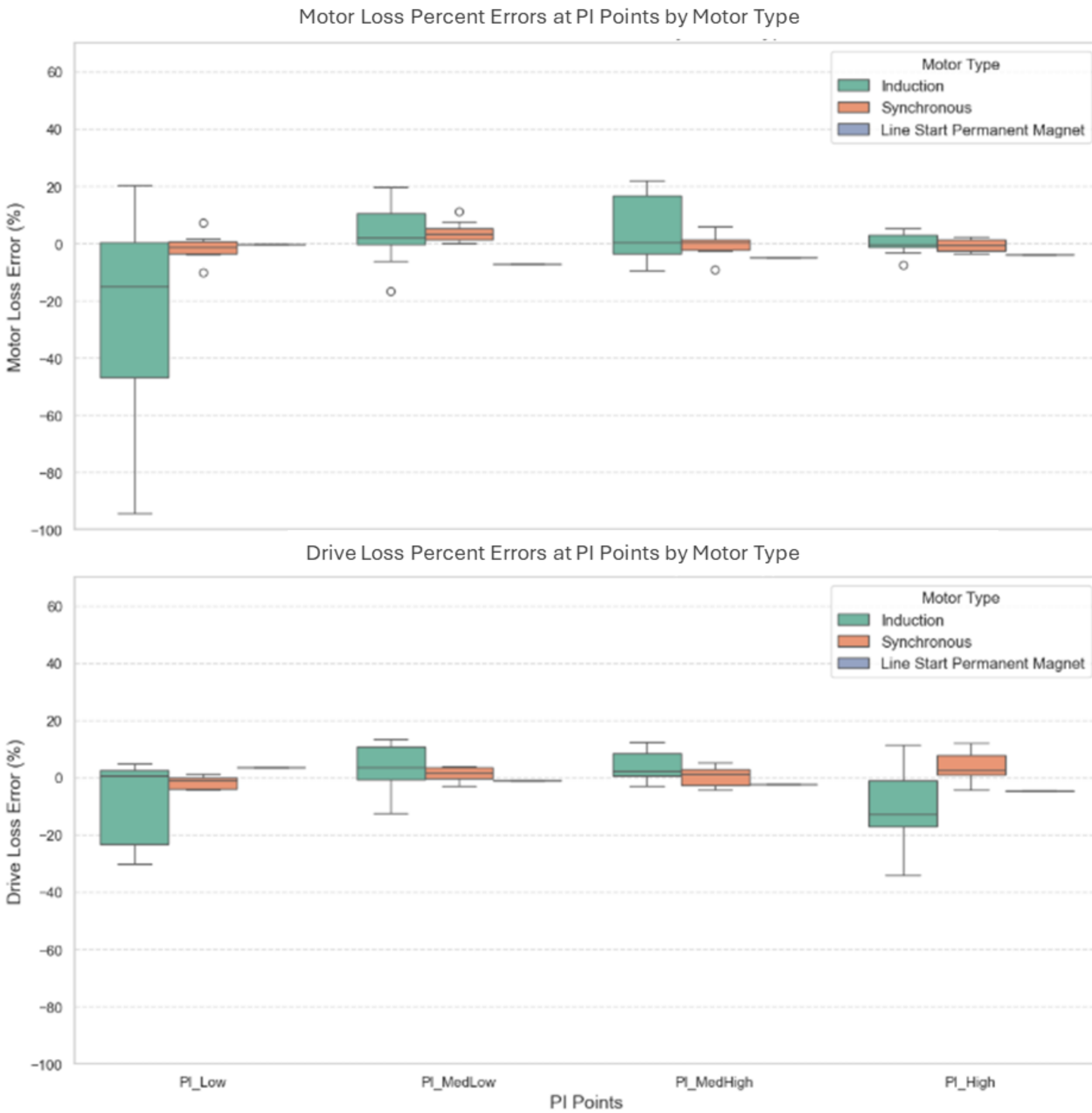

Figure 11—Motor and Drive Loss Percent Errors by PI Point and Motor Type

Key Observations: Induction Motors

- Average motor errors at all four PI points are near zero, but there is variability at some PI points, especially PI Low, with significant negative errors. Variability decreases at higher motor loading, but errors remain larger compared to synchronous motors.
- Average drive errors at all four PI points are near zero, but there is variability at some PI points, especially PI High and PI Low.
- Induction motors exhibit the largest variability in both motor and drive losses.

Key Observations: Synchronous Motors

- Motor losses are less variable than induction motors and center around zero.
- Drive loss errors are moderate and consistent compared to induction motors, although variability is present, particularly at PI High.
- Synchronous motors perform better than induction motors in terms of minimizing variability in both motor and drive losses.

Key Observations: Line-Start Permanent Magnet Motors

- Only one LSPM motor was tested, and it exhibited consistent performance across all PI points, with errors staying close to zero.

5 Conclusions

This analysis validates the accuracy and reliability of the PI Calculation Procedure, NEMA 10011-2025 Appendix B, for assessing the energy performance of PDSs across a range of motor types and motor sizes. The results demonstrate that the interpolation methods defined in the procedure produce PI scores that closely align with measured data, with average absolute PI errors across all motor types and load points remaining below 0.5%. This indicates that the calculation procedure effectively reflects real-world motor and drive performance under typical load conditions.

The analysis of load point power losses further supports the validity of the interpolation methods. While induction motors at PI Low showed some deviation due to the interpolation method's limited ability to account for flux optimization controls, these discrepancies had a negligible impact on overall PI values. Strong agreement at PI MidLow, PI MidHigh, and PI High load points, with most errors within 10%, underscores the interpolation procedure's effectiveness aligning with real world performance data.

Overall, the PI Calculation Procedure, which leverages existing IEC 60034-2-3 and IEC 61800-9-2 test data and interpolation methods from the EU requirements, reduces the testing burden for OEMs without compromising the accuracy and reliability of the PI scores. The procedure's ability to produce valid PI values across a wide range of motor types and sizes makes it a valuable tool for standardizing energy performance assessments in the electric motor industry.

The PI metric offers a strong foundation for voluntary energy efficiency programs aimed at improving motor and drive performance. Unlike traditional full-load efficiency metrics, PI reflects performance across multiple load points, providing a more comprehensive measure of real-world efficiency. This makes PI particularly useful for utility incentive programs, where rewards can be aligned with actual energy savings under variable operating conditions. The ability to consistently rank a wide range of motors and PDSs using PI could help manufacturers and end-users identify high-efficiency products more effectively.

6 References

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Appendix A

PDS Sample Summary and Specifications

Table A.1 contains the specifications for each of the 19 PDS evaluated in this study, including motor type, nominal horsepower, number of poles, and rated RPM. In cases where a PDS is listed with two numbers (e.g., PDS 11/12), this indicates that the same system was tested twice, with results corresponding to reports 11 and 12 in Appendix B.

Table A.1—Specifications for Tested PDS

Lab	PDS	Motor Type	Sub-Type	HP	POLES	RATED RPM
Lab B	PDS 1	Induction	(n/a)	25	4	1780
Lab A	PDS 11/12	Induction	(n/a)	10	4	1800
Lab A	PDS 13/14	Synchronous	SPM	10	10	1800
Lab A	PDS 17/18	Induction	(n/a)	20	4	1800
Lab B	PDS 2	Induction	(n/a)	60	4	1785
Lab A	PDS 21/22	Induction	(n/a)	50	4	1800
Lab A	PDS 23/24	Induction	(n/a)	75	4	1800
Lab A	PDS 28/33	Induction	(n/a)	75	4	1800
Lab B	PDS 3	Line Start Permanent Magnet	SPM	60	4	1800
Lab A	PDS 31/32	Synchronous	SPM	10	4	1800
Lab C	PDS 6	Induction	(n/a)	5	4	1750
Lab C	PDS 7	Synchronous	PMaSynRM	7.5	4	1800
Lab C	PDS 8	Induction	(n/a)	10	6	1180
Lab A	PDS 9/10	Synchronous	SynRM	7.5	4	3600
Lab A	PDS 15/16	Synchronous	SPM	20	8	1800
Lab A	PDS 19/20	Synchronous	SPM	20	6	1800
Lab A	PDS 25/26	Induction	(n/a)	75	4	1800
Lab A	PDS 29/30	Synchronous	SPM	7.5	10	1800
Lab C	PDS 5	Induction	(n/a)	3	2	3500

Appendix B

PI Validation Analysis Test Results

The Appendix B[14] workbook contains the complete dataset used in the PI validation analysis. For each PDS test, it includes measured power loss values at PI-specific operating points as well as the interpolated power loss values calculated based on IEC standard operating points. This dataset forms the basis for evaluating the accuracy of interpolation methods and supports a detailed assessment of motor, drive, and system performance under varying load conditions.

- Columns M through P contain measured and interpolated motor and drive power loss values for each PI point.
- Columns Q and R contain PI scores based on measured and interpolated values. There is only one PI score for each PDS, so PI score repeats across the four PI operating points.
- Columns S and T shows the selected overmodulation classification.
- Column U shows what the PI scores would be if incorrect assumptions for overmodulation were applied.
- Columns V and W show the percent error between measured and interpolated power losses at PI high, depending on whether the overmodulation factor is applied or not.

§

[14] NEMA 10011-1 Appendix B - PI Validation Analysis Test Results.xlsx