Final Technical Report

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Technical Contact:
Rich Schiferl
26391 Curtiss Wright Parkway, Suite 102
Richmond Hts, OH 44143
(216) 261-3644 x211
(216) 261-3887 (fax)
Rich.Schiferl@baldor.abb.com

Recipient Organization:
Baldor Electric
6040 Ponders Court
Greenville, SC 29615

Partners: Stephen D. Umans

Customers & End Users:
(free consultations provided)
Colfax Americas
Duke Energy Carolinas, LLC
DuPont Engineering
Howden / Buffalo Fan
Ameren
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List of Acronyms /Terms

DOL – Direct on Line (full voltage, full frequency, three phase line operation)

LSIPM – Line-Start, Interior Permanent-Magnet (a type of motor which uses a cage winding to allow DOL starting with a pull-in to synchronism at the end of the starting process)

NEMA – National Electrical Manufacturers Association – publisher of motor and generator standards (such as NEMA MG1)

NEMA Design B – A general purpose motor type described (in NEMA MG1) by characteristics including starting torque and starting current

NEMA Premium® Efficient – A level of efficiency described by NEMA MG1 which is the highest efficiency level in this industry standard

NEMA Efficiency Bands – A geometric progression of efficiency levels defined in NEMA MG1. Each higher band represents approximately a 10% reduction in motor losses. See Table IV.

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1.0 Executive Summary

The primary purpose of this project was to combine the ease-of-installation and ease-of-use attributes of industrial induction motors with the low-loss and small size and weight advantages of PM motors to create an ultra-efficient, high power density industrial motor that can be started across-the-line or operated from a standard, Volts/Hertz drive without the need for a rotor position feedback device. PM motor products that are currently available are largely variable speed motors that require a special adjustable speed drive with rotor position feedback. The reduced size and weight helps to offset the magnet cost in order make these motors commercially viable.

The scope of this project covers horsepower ratings from 20 – 500. Prototypes were built and tested at ratings ranging from 30 to 250 HP. Since fans, pumps and compressors make up a large portion of industrial motor applications, the motor characteristics are tailored to those applications. Also, since there is extensive use of adjustable frequency inverters in these applications, there is the opportunity to design for an optimal pole number and operate at other than 60 Hz frequency when inverters are utilized. Designs with four and eight pole configurations were prototyped as part of this work. Four pole motors are the most commonly used configuration in induction motors today.

The results of the prototype design, fabrication, and testing were quite successful. The 50 HP rating met all of the design goals including efficiency and power density. Tested values of motor losses at 50 HP were 30% lower than energy efficient induction motors and the motor weight is 35% lower than the energy efficient induction motor of the same rating. Further, when tested at the 30 HP rating that is normally built in this 286T frame size, the efficiency far exceeds the project design goals with 30 HP efficiency levels indicating a 55% reduction in loss compared to energy efficient motors with a motor weight that is a few percentage points lower than the energy efficient motor. This 30 HP rating full load efficiency corresponds to a 46% reduction in loss compared to a 30 HP NEMA Premium® efficient motor.

The cost goals were to provide a two year or shorter efficiency-based payback of a price premium associated with the magnet cost in these motors. That goal is based on 24/7 operation with a cost of electricity of 10 cents per kW-hr.

Similarly, the 250 HP prototype efficiency testing was quite successful. In this case, the efficiency was maximized with a slightly less aggressive reduction in active material. The measured full load efficiency of 97.6% represents in excess of a 50% loss reduction compared to the equivalent NEMA Premium Efficiency induction motor. The active material weight reduction was a respectable 14.5% figure. This larger rating demonstrated both the scalability of this technology and also the ability to flexibly trade off power density and efficiency.

In terms of starting performance, the 30 – 50 HP prototypes were very extensively tested. The demonstrated capability included the ability to successfully start a load with an inertia of 25 times the motor's own inertia while accelerating against a load torque following a fan profile at the motor's full nameplate power rating. This capability will provide very wide applicability of this motor technology. The 250 HP prototype was also tested for starting characteristics, though without a coupled inertia and load torque. As a result it was not definitively proven that the same 25 times the motor's own inertia could be started and synchronized successfully at 250 HP. Finite element modeling implies that this load could be successfully started, but it has not yet been confirmed by a test.

The conclusions reached as a result of this project include the following.

- The targeted loss reduction of 30% compared to induction motors has been demonstrated to be achievable.

- The active material weight reduction target of 30% can also be achieved.
- The loss reduction and active material weight reductions are not an either/or proposition, but rather both can be simultaneously achieved.
- The starting and synchronization performance demonstrated the ability to successfully start loads of significant inertia.
- The operation of these motors on adjustable frequency inverters is possible without the use of special PM control algorithms nor any shaft position feedback device.
- There are torque pulsations during starting that include torque reversals. These pulsations are of sufficient amplitude that the selection and sizing of couplings needs to account for this behavior.
- The commercial viability of motors using this technology is highly dependent on the cost and availability of powerful permanent magnets.

It is recommended that motor product development should be undertaken to commercialize this technology.

2.0 Introduction

Three phase electric motors are widely used in US industrial applications. Fans, pumps, and compressors are three broad categories of applications operated by electric motors. The primary type of motor used for these applications is a three-phase squirrel-cage induction motor. Induction motors already have better efficiency than many of the devices they drive. They also are much more energy efficient than other prime movers such as internal combustion engines. However, due to the sheer quantity of connected power associated with electric motors, there are still very substantial reductions possible in energy usage. This reduced energy usage then also provides an associated reduction in CO_2 emissions through the power generation process.

The goal of this project was to develop line-start and line-run constant-speed electric motors and simple-to-control electric motors with the goal of obtaining at least a 30% reduction in motor losses as compared to conventional energy-efficient induction motors and a 15% reduction in motor losses as compared to NEMA Premium® efficient induction motors. These ultra-efficient motors will be 30% smaller in volume, 30% lower in weight, and have a higher power factor than energy-efficient or NEMA Premium® induction motors, factors expected to drive rapid market penetration into user and original equipment manufacturer markets.

The technology to enable this simultaneous improvement in both efficiency and power density is dependent on permanent magnets. PM motor products that are currently available are largely variable speed motors that require a special adjustable speed drive with rotor position feedback. These motor systems are applied where rapid motor dynamic response is required and the lower rotor inertia of the high power density PM motor is an advantage when compared to an induction motor. However, there are many applications, such as pumps fans, and compressors, where dynamic response requirements are very low. Pump, fan, and compressor applications utilize over 60% of industrial electric motor energy in the US. In many of these applications constant-speed induction motors that are started across-the-line are the motor of choice. Alternatively, variable speed induction motors, powered from an open-loop (Volts/Hertz control) variable speed drive, are utilized without any rotor position feedback device. Induction motor Volts/Hertz drives are commonplace and available from a large number of drive manufacturers.

The primary objective of this project is to combine the ease-of-installation and ease-of-use attributes of industrial induction motors with the low-loss and small size and weight advantages of

PM motors to create an ultra-efficient, high power density industrial motor that can be started across-the-line or operated from a standard, Volts/Hertz drive without the need for a rotor position feedback device. This will be accomplished by adding a starting cage to the rotor of the PM motor. Computer simulation and design tools will be developed for these ultra-efficient motors in order to predict the starting characteristics and to allow for design optimization. The design tools will be verified with tests on laboratory prototypes (50 hp and 200 hp) that will be designed to meet the requirements of project team members Colfax pump and Howden fan. Project success will be measured by the energy efficiency and power density levels achieved and by the ability to predict the starting and steady state performance of the prototype PM motors based on laboratory testing of both line-start and open-loop-controllable PM motors. The open-loop-controllable PM motors will likely require a less substantial rotor cage thereby allowing more rotor design freedom to maximum efficiency and/or minimize motor volume and weight.

If these "hybrid" motors which combine line-starting of induction machines with excellent efficiency of PM machines can be developed across a wide range of power ratings, the energy savings are substantial. For an individual industrial user, the primary benefit is reduced electricity cost. If the price premium paid for this motor can be recouped (via saved electricity) in two years or less, that typically can drive commercial adoption of a new technology.

3.0 Background

Pumps, fans, and compressors use more than 60% of industrial electric motor energy in the United States. The most widely used motors in these applications are constant-speed motors that are started and run across the line. In some applications, variable-speed motors, powered from an open-loop variable-speed drive, are utilized (without any rotor position feedback device) to achieve more energy-efficient system operation when flow control is desirable. Induction motors are the workhorses of industry and represent nearly the entire installed base of constant-speed and most variable-speed motors. In the United States, induction motor efficiency for new industrial motor sales falls into two categories: energy-efficient motors that meet the requirements of the 1992 U.S. Energy Policy Act, and National Electrical Manufacturers Association (NEMA) Premium® efficient motors that have even higher energy efficiency levels. NEMA Premium® motors are heavier and have more active material than energy-efficient electric motors.

New motor technology is under development that will increase motor efficiency while reducing the size and weight of the motor by reducing the amount of active material used. This technology has become economically viable for some variable-speed motor applications and over a wide horsepower range. However, its ability to be utilized in general-purpose industrial applications has been limited by the need for a variable-speed drive with a rotor position feedback device to allow for stable operation at any speed. This project developed the technology to create a low-loss, high power density industrial motor that is easy to install and use and more efficient, lighter, and smaller than current alternatives, including energy-efficient and NEMA Premium® motors. It will be a general-purpose motor that can replace existing induction motors for a wide range of line-start and variable-speed applications. The motor will have the ability to be started and run across the line or operated from a standard (volts/hertz) drive without the need for a rotor position feedback device.

Fig 1 - Typical NEMA Premium Efficiency Induction Motor

4.0 Results and Discussion

4.1 Technical approach and hypothesis guiding this approach

For this work there was a high degree of dependence on test-correlated finite-element analysis. This is especially the case for the electromagnetic design of the rotor, including the incorporation of both magnets and a significant starting cage.

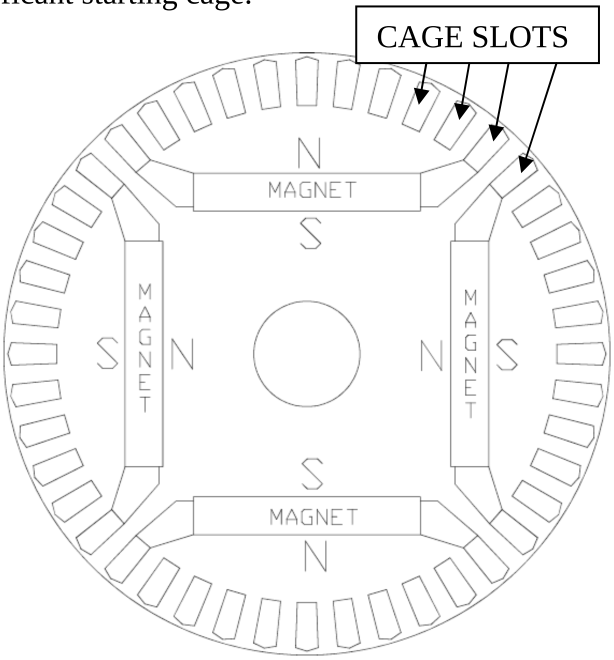


Fig 2 a – Rotor configuration with radial magnetization and uniform cage slot pattern

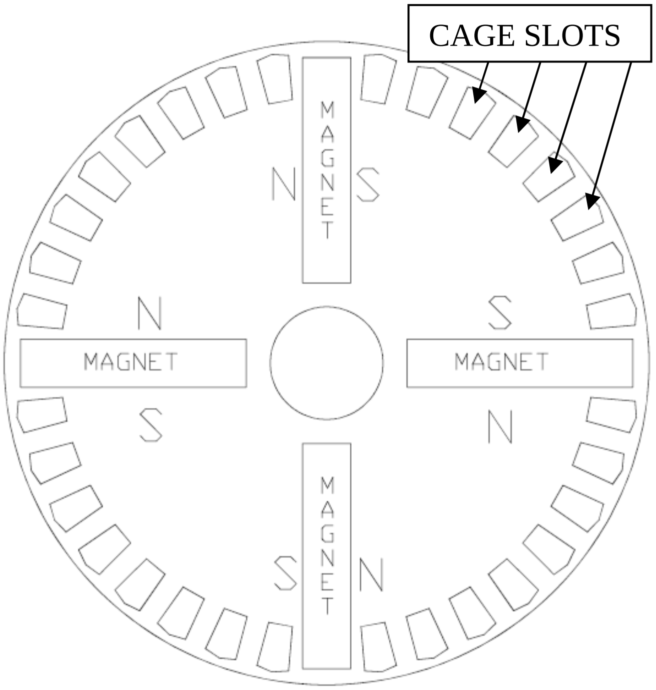


Fig 2 b – Rotor configuration with azimuthal magnetization and cage pattern interrupted by magnets

There is a wide range of possible magnet and cage configurations that can be used in a LSIPM motor. Fig 1 shows two of the configurations previously proposed. In Fig 2a, the magnets are oriented with a radial direction of magnetization. In Fig 2b, in contrast, the direction of magnetization is azimuthal. In addition, in Fig 2a the cage slots are evenly distributed, while in Fig 2b there are "interruptions" in the cage pattern due to the magnets extending nearly to the rotor outer diameter. The motors built and tested as part of the work reported on in this report use the V-shaped magnet configuration as shown in Fig 3. As seen in Fig 3 the starting cage slots are distributed around the rotor periphery – accommodating the space not claimed by the magnets. The work reported on in this report includes rotors made with both cast and fabricated cages, with the fabricated versions made with either aluminum or copper cage construction. The prototypes that were the source of the majority of the test data in this project were made with cast aluminum cages as seen in Fig 5. The rotor die casting process was as shown in Figs 6-8. The prototypes with die cast rotors were built in a NEMA 286T frame size.

In Fig 4, a typical flux plot of an open circuit condition is shown. The pattern of flux created by the V-shaped magnets is apparent. The V-shape provides a measure of flux concentration at the air gap and also provides a means by which cogging torque can be minimized.

The stators used in the construction of the prototypes for testing of this technology were built with common tooling used in induction motor manufacturing (Fig 9).

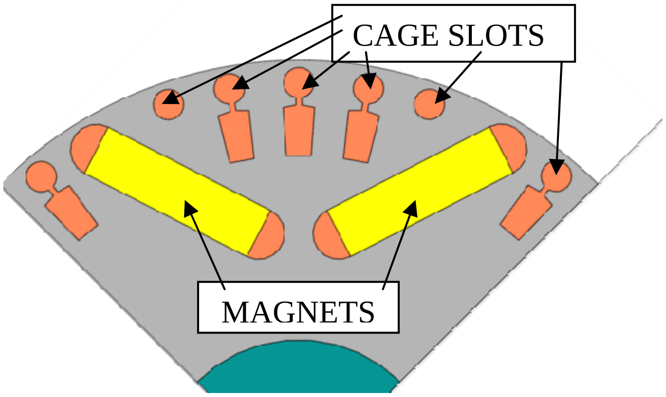


Fig 3 – Rotor magnet and cage pattern for many of the motors tested in this project

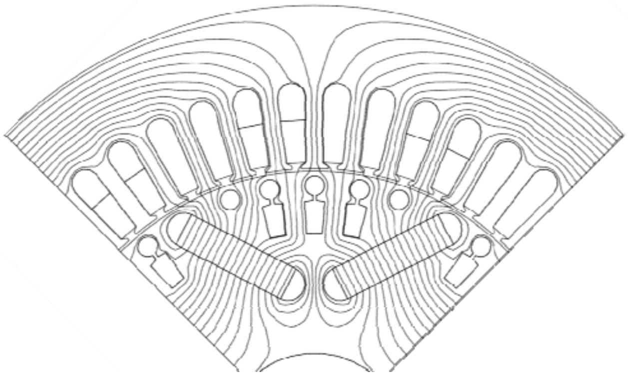


Fig 4 – Open circuit flux pattern for the LSIPM motor of Fig. 3

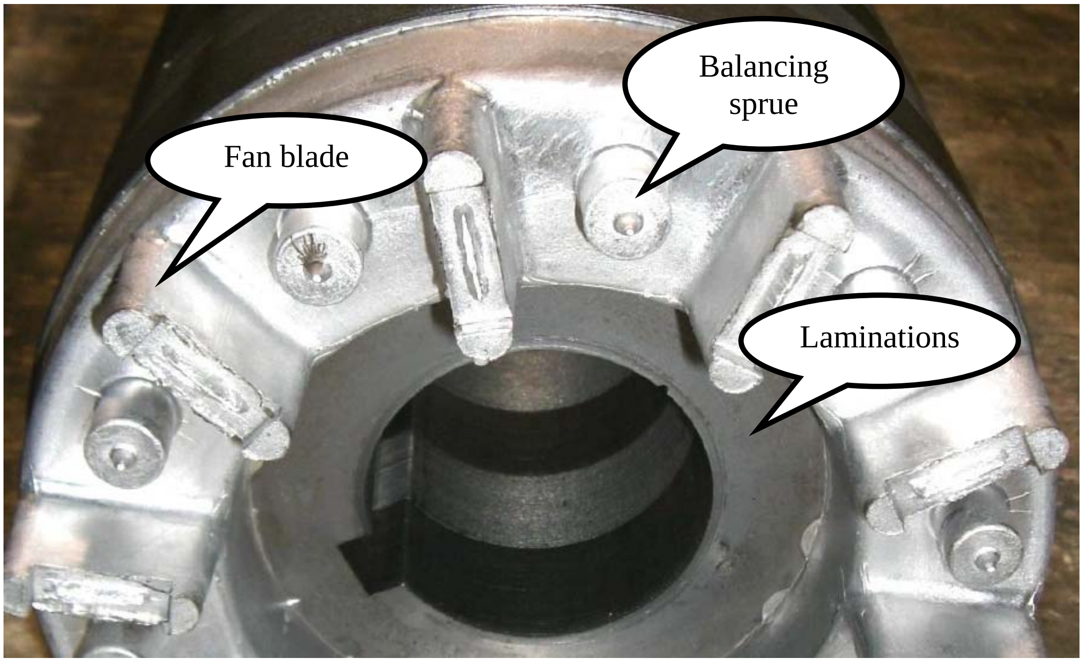


Fig 5 – Rotor showing end ring of die cast cage

Fig 6 – Rotor die casting manufacturing cell

Fig 7 – Rotor core stacked with magnets ready for die casting

Fig 8 - Shaft insertion following die casting of rotor

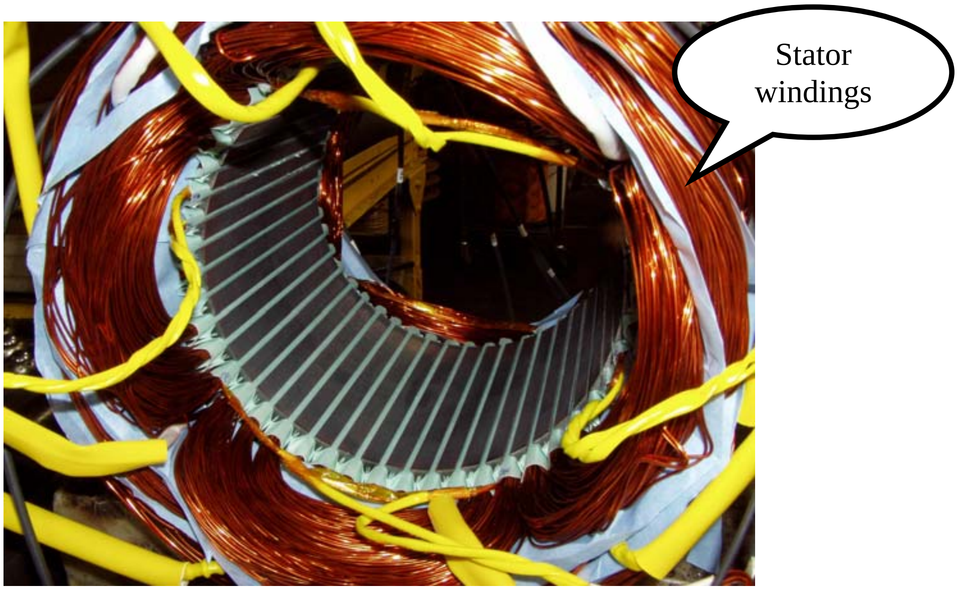


Fig 9 – Wound stator for use in prototype testing

The magnets used in these motor are high-temperature, high-energy-product, rare-earth sintered magnets. A typical second quadrant B-H characteristic is shown in Fig 10. It can be seen that there is a well-known temperature dependence of the magnetic properties of a NdFeB material. The material characterized by Fig 10 can be considered a high-temperature material in that the knees of the recoil lines stay in the third quadrant up to about 170°C. A range of magnet materials were tested in prototype rotors, with the ability to resist demagnetization during hot starts being a key issue. This topic is discussed further in a later section covering starting performance. There are a number of different grades of high-energy-product magnets that can be selected based on the highest expected temperatures

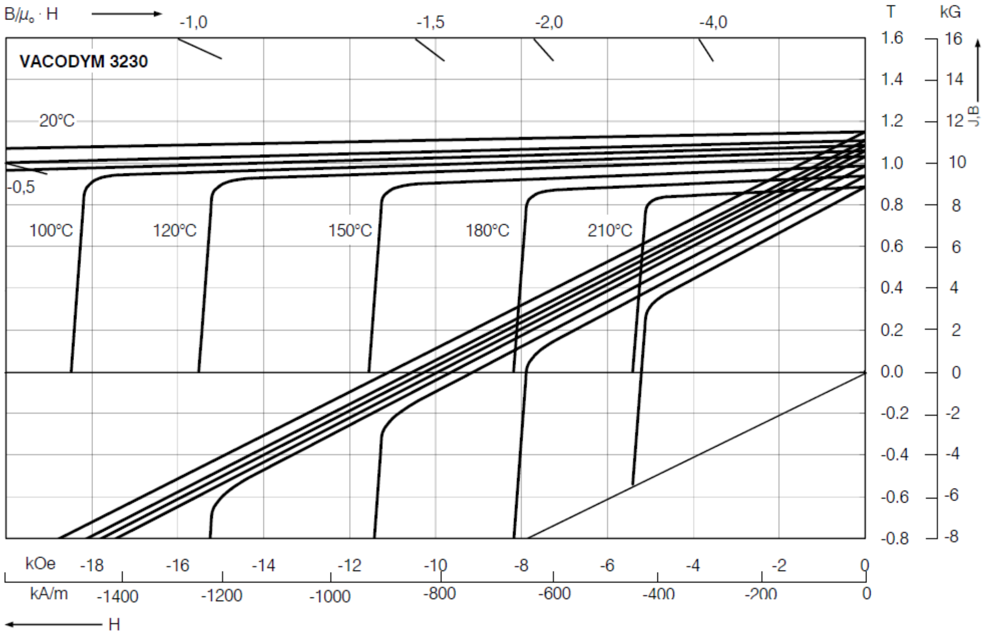


Fig 10 – Typical high-temperature rare-earth magnet second quadrant B-H curves

Fig 11 – Magnetization of a prototype rotor

The magnetization of the smaller prototype rotors was done with a pulse-type magnetizer (Fig 11). For the larger, 250 HP prototype, the magnets were also magnetized with a pulse-type magnetizer, but were done in axial rows before insertion into the rotor assembly.

4.2 Experimental methodology, test procedures, characterization methods

Note: The 30 – 50 HP prototypes are used to explain the testing methodologies employed. In addition, due to a larger number of prototypes built in the 286T frame size, there are more test points reported on as compared to the 250 HP 440 frame prototype.

Steady-State Performance -

The test procedure for steady-state efficiency measurements consisted of the following steps:

- The motor is first synchronized to the 60-Hz source. This can be done either by line-starting the motor from the source or by bringing the motor up to speed using the load motor and "paralleling" it in the fashion of a synchronous machine.
- The motor voltage and load torque are adjusted to the desired level for the test being conducted (Fig 12a).
- Once the test is underway, the motor temperatures are monitored for the purposes of determining when the motor has reached a steady-state operating condition. During this time period, which is typically on the order of 3 hours or more when the motor is started from ambient temperature, it is also often necessary to readjust the applied voltage and the load torque to maintain them precisely at their desired values. Note that the time to reach steady state for an interior permanent-magnet motor may be longer than that of a similarly-rated induction motor because the temperature dependent characteristics of the permanent magnets

(Fig 10) provide a feedback mechanism which can significantly impact the steady-state operating condition. Specifically, as the motor heats up (typically due to I^2R power dissipation in the stator windings and to core loss), the magnets will heat up. This in-turn will reduce their magnetization strength, which will in-turn cause a change in the stator current and hence the stator-winding I^2R loss which will change the magnet temperatures, etc.

- Steady-state operation is considered to have been achieved when there is no noticeable trend in the motor temperatures. For the prototype motors, we monitor the temperatures with a resolution of 0.5^oC and have found steady-state is reached when it is clear that the temperatures are essentially constant for a period of 30 minutes or more. Although this may seem to be a rather stringent requirement, we have determined that it is a requirement to give consistent, reproducible test results. This criterion must typically be tailored to the motor under test; thermal time constants tend to increase with motor size and rating and hence the time period over which to determine that the temperatures are constant will be correspondingly longer for larger machines.
- Once steady-state operation has been achieved, a data acquisition system (Fig 12b) is used to record the motor characteristics at 10 second intervals for a period of 5 minutes or more. These include the motor terminal voltages and currents, the motor temperatures and the electrical input power and the motor torque.
- Immediately following the recording of this steady-state data, the motor is operated open-circuited at its rated speed and the open-circuit voltage is measured. A comparison of this open-circuit voltage with the value measured at ambient can be used as an indirect measurement of the magnet temperature rise.

In order to eliminate noise as well as the effects of small drifts in the motor operating condition, the performance of the motor at any given operating conditions is determined by taking the average of the last 5 minutes of recorded readings (30 data sets). The mechanical output power is calculated from the product of the motor speed in rad/sec (1800 rpm = 60π rad/sec) and the average torque. The efficiency is calculated based upon this value of output power and the average electrical input power.

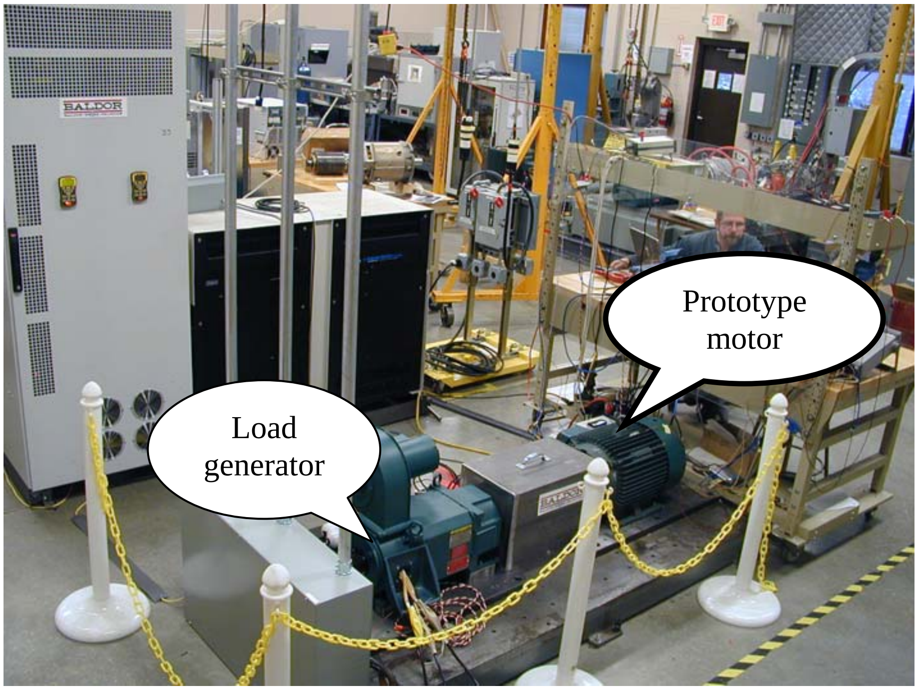


Fig 12a – Dynamometer test setup for 30 – 50 HP steady-state tests

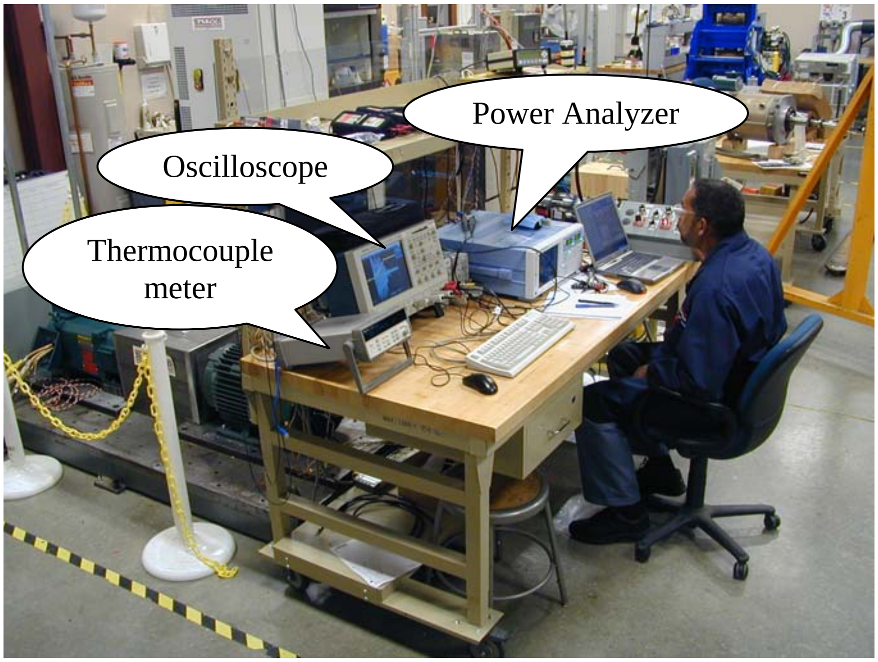


Fig 12b – Data acquisition for steady-state testing

Starting Performance -

For starting performance tests, the equipment used included both changeable inertia wheels and an adjustable load generator as shown in Fig 13.

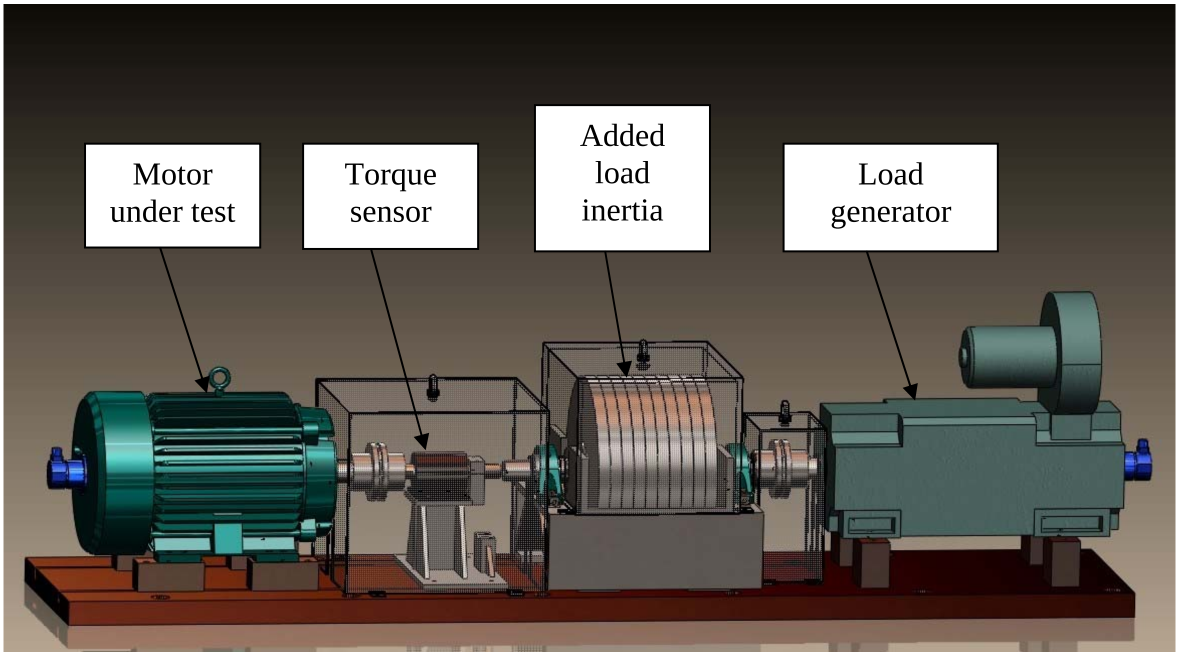


Fig 13 – Test rig for starting and synchronization evaluation

4.3 Presentation and discussion of results

1) Measured steady-state performance of a prototype LSIPM motor at 30-hp: In this section, typical test results are presented. Because this is a prototype motor and because one of the design objectives is to achieve high efficiency, a series of tests at an output power of 30-hp were first conducted to examine the impact of voltage on motor efficiency. The test results are presented in Table I and plotted in Figs. 14-16.

From these test results, we see that it appears that this motor achieves optimal efficiency at a terminal voltage on the order of 380 V. A second set of tests, consisting of a range of loads at 380 V, illustrates another dimension of the performance of the tested prototype. The test results are found in Table II and plotted in Figs. 17-19.

TABLE I

PERFORMANCE OF THE TESTED PROTOTYPE LSIPM MOTOR AT AN OUTPUT POWER OF 30 HP

Voltage	Current [A]	Efficiency [%]	Power factor
340	40.2	95.4	0.995
360	38.0	95.8	0.989
380	36.5	96.0	0.978
400	35.5	95.8	0.952
420	35.7	95.4	0.903
440	37.5	94.2	0.832
460	40.8	92.7	0.744

TABLE II
PERFORMANCE OF THE TESTED PROTOTYPE LSIPM MOTOR AT AN INPUT OF 380 V, 60 HZ

Power [hp]	Current [A]	Efficiency [%]	Power factor
22.6	27.5	95.6	0.975
30.2	36.5	96.0	0.978
37.7	45.9	95.7	0.972
45.0	55.9	95.1	0.960
50.0	63.2	94.6	0.948

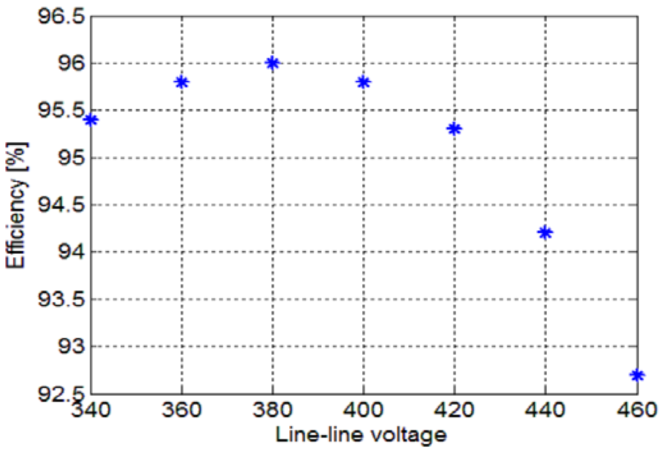


Fig. 14 – 30 hp tests: Efficiency vs voltage

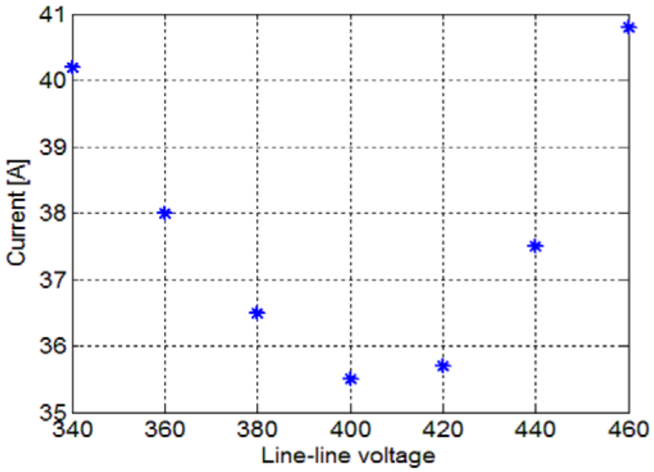


Fig. 15 – 30 hp tests: Current vs voltage

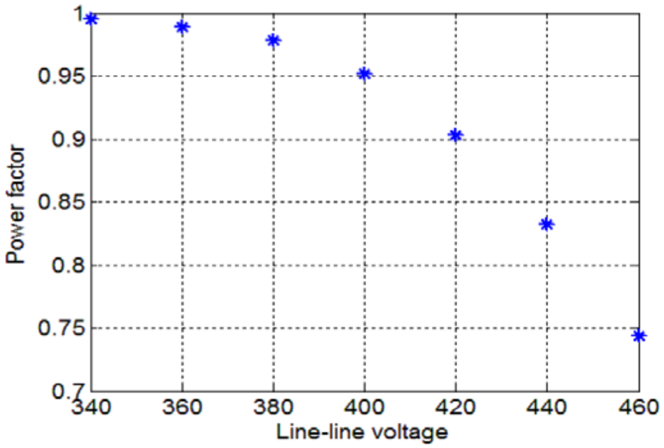


Fig. 16 – 30 hp tests: Power factor vs voltage

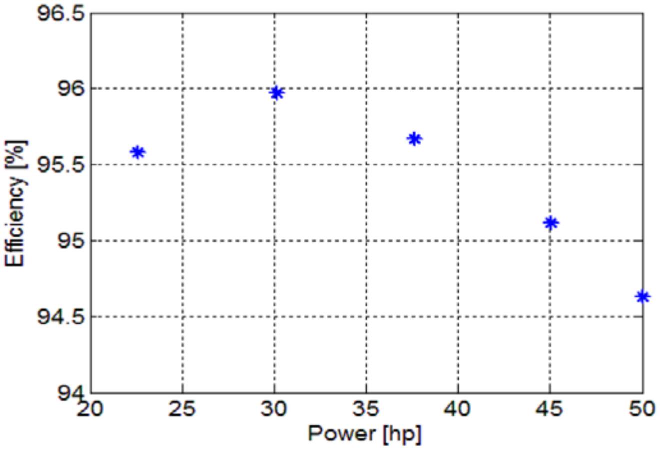


Fig. 17 - 380 V tests: Efficiency vs power

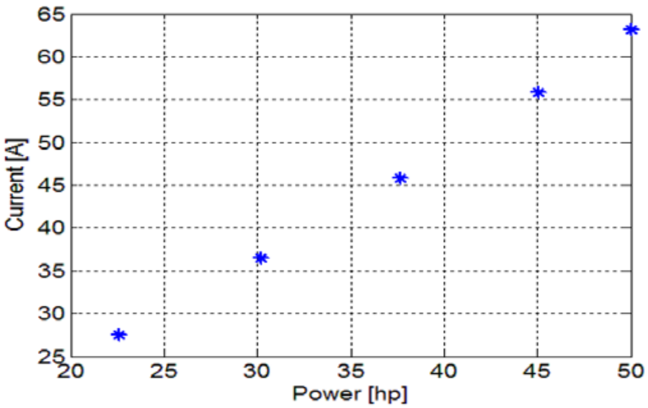


Fig. 18 - 380 V tests: Current vs power

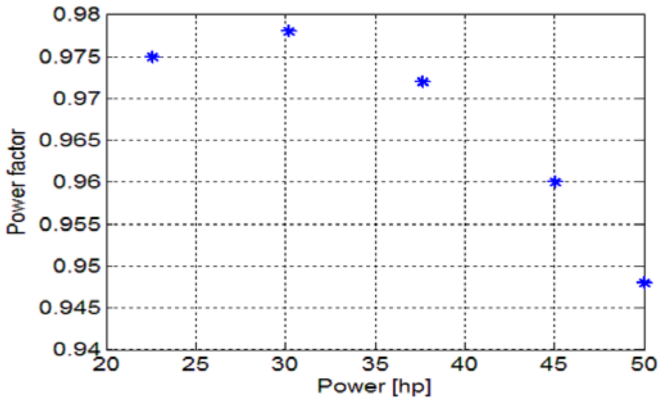


Fig. 19 - 380 V tests: Power factor vs power

The measured steady-state performance of a larger prototype built in a NEMA 440 frame size is shown in Table III.

TABLE III
PERFORMANCE OF THE TESTED NEMA 440 FRAME PROTOTYPE LSIPM MOTOR AT AN INPUT OF 480 V, 60 HZ

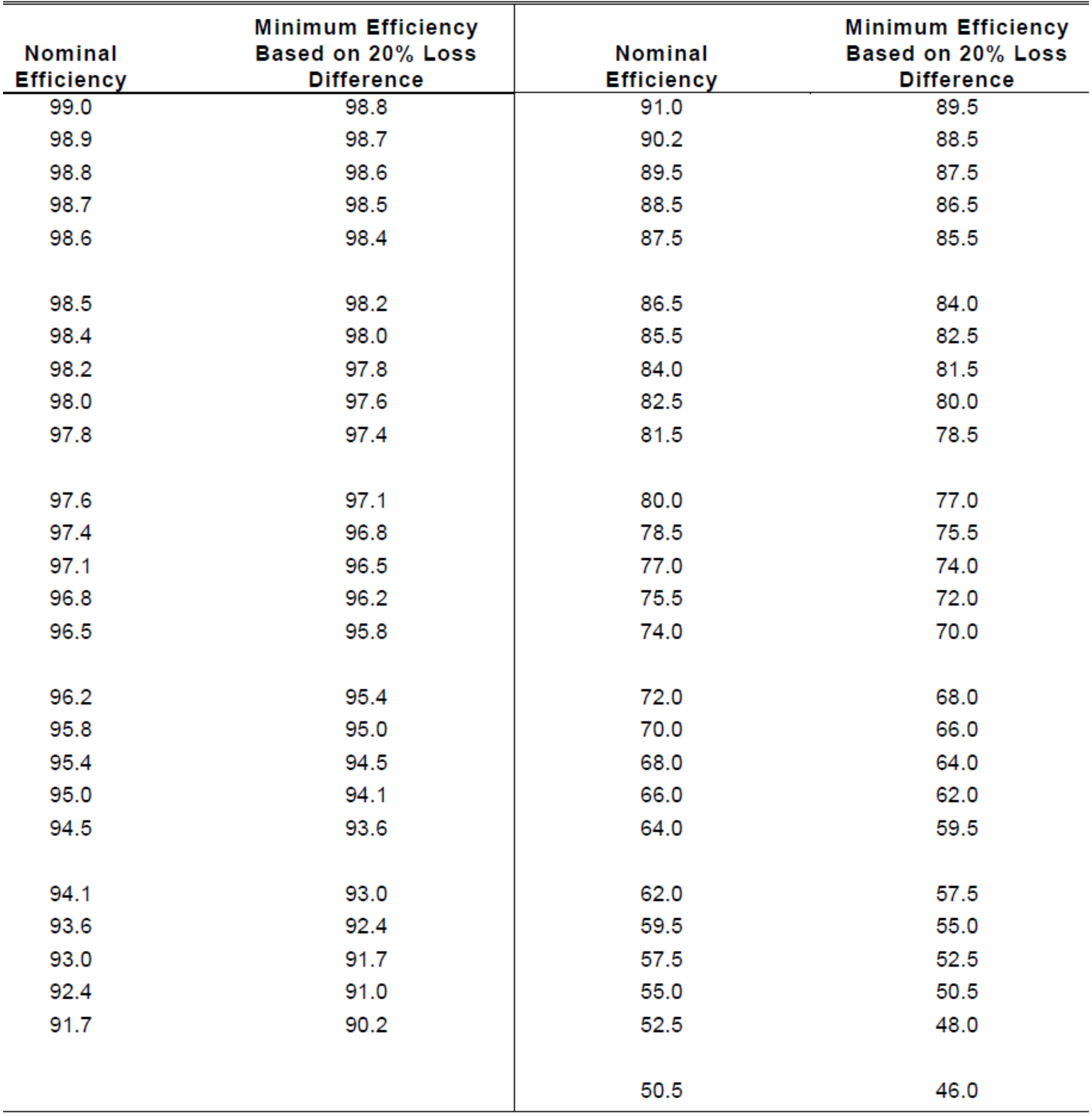
Power [hp]	Current [A]	Efficiency [%]	Power factor
64.9	120	95.0	0.511
125	147	96.9	0.788
192	200	97.5	0.879
250	256	97.6	0.898
279	285	97.5	0.902

The efficiency levels seen in Tables I – III for the 30 and 250 HP prototypes can be put into context by comparing them to NEMA Premium levels. For an 1800 RPM, 30 HP Premium Efficiency motor, the nominal efficiency is 93.6%. For a 900 RPM, 250 HP Premium Efficiency motor, the nominal efficiency is 95.0%. Since NEMA uses a geometric progression of "efficiency bands," it is convenient to state changes of efficiency as a number of "efficiency band jumps." The table of NEMA efficiency bands is shown in Table IV. For the 30 HP prototype, the 96.0% level represents between 5 and 6 bands higher efficiency than NEMA Premium. For the 250 HP rating, the demonstrated 97.6% efficiency is an impressive 8 bands above NEMA Premium.

Starting Performance -

For a direct-on-line (DOL) started motor, it is necessary to demonstrate satisfactory starting performance in addition to the steady-state performance reported above. For a LSIPM motor this includes more than just the starting current and starting torque during the asynchronous period of acceleration as would be the case for an induction motor. The motor also must be able to pull the load into synchronism at the end of the starting process. Both the load torque and the load inertia enter into whether a specific LSIPM motor will be able to successfully start and synchronize a load. Another aspect of the starting behavior of an LSIPM motor involves the fact that the magnet flux and rotor saliency introduce oscillating components of torque at all speeds until the motor is synchronized. While there are oscillatory components of torque during DOL starting of induction motors, rotor saliency and magnet flux create a more significant set of torque oscillations during DOL starting of a LSIPM motor. The rotor saliency feature is created when the magnets are placed in the interior of the rotor laminations. It results in preferred directions for magnetic fields in the rotor. This saliency does not exist in common induction motors, but does exist in many wound-field synchronous motors and generators.

Table IV – NEMA Efficiency Bands



Nominal Efficiency	Minimum Efficiency Based on 20% Loss Difference	Nominal Efficiency	Minimum Efficiency Based on 20% Loss Difference
99.0	98.8	91.0	89.5
98.9	98.7	90.2	88.5
98.8	98.6	89.5	87.5
98.7	98.5	88.5	86.5
98.6	98.4	87.5	85.5
98.5	98.2	86.5	84.0
98.4	98.0	85.5	82.5
98.2	97.8	84.0	81.5
98.0	97.6	82.5	80.0
97.8	97.4	81.5	78.5
97.6	97.1	80.0	77.0
97.4	96.8	78.5	75.5
97.1	96.5	77.0	74.0
96.8	96.2	75.5	72.0
96.5	95.8	74.0	70.0
96.2	95.4	72.0	68.0
95.8	95.0	70.0	66.0
95.4	94.5	68.0	64.0
95.0	94.1	66.0	62.0
94.5	93.6	64.0	59.5
94.1	93.0	62.0	57.5
93.6	92.4	59.5	55.0
93.0	91.7	57.5	52.5
92.4	91.0	55.0	50.5
91.7	90.2	52.5	48.0
		50.5	46.0

Figures 20 – 22 show the motor speed, phase current, and terminal voltage as measured during a line start of the prototype motor discussed in the steady-state section of this report. For this test, the motor was coupled to a load consisting of an inertia of 100 lb-ft^2 and a programmable torque. In this case, the torque was programmed to follow a "fan load" characteristic with the torque being proportional to the square of the speed, reaching 113 Nm at 1800 rpm. The same 380 V condition that was found to be optimal for the steady-state performance was used for this starting test. It can be seen that the voltage seen at the motor terminals experienced the common sag and recovery associated with drawing about 300 amps during the early portions of the start.

The oscillatory behavior seen in the speed signal of Fig 20 can be partly attributed to the torque pulsations due to the combination of rotor saliency and magnet flux during asynchronous operation. In addition, the torsional compliance of the couplings also modify this oscillatory behavior. While the motor's own inertia tends to filter the developed air-gap torque pulsations, there is significant ripple in the shaft torque applied to the load. As a result, care must be taken in the selection and application of couplings.

Since one common point of reference for starting behavior is NEMA Design B, it is instructive to compare the starting performance of this motor on that basis. For a 30 HP 1800 RPM rating, the prescribed minimum locked-rotor torque is 150% of rated. The start shown in Figs 20-22 demonstrated 200% torque at zero speed based on the initial rate of acceleration of the load inertia. The reason for using the initial rate of acceleration as an indicator of the locked-rotor torque is that the torque under truly locked conditions is a strong function of the locked-rotor angular position. This is quite different than would be observed for an induction motor. It is an area that should be explored in terms of industry test standards. In terms of the starting current drawn during the start shown in Fig 21, the current exceeds the NEMA Design B maximum (for this 380 V level) by just under 15%. This higher starting current would be equivalent to that for a NEMA Design A induction motor. Table V summarizes the starting current and starting torque for a 30 HP prototype compared to a 30 HP, 1800 RPM NEMA Design B motor.

Table V – Tested Prototype Data Compared to NEMA Design B Starting Current and Torque

	Test (@ 380 V)	NEMA Design B (@ 380 V)
Starting Current	300 A	263 A max
Starting Torque	200%	150% min

The test documented by Figs 20-22 was run using a fixed-speed alternator as a controllable power source. The hardware used for these starting and synchronization tests is shown in Fig 13. The oscilloscope traces of both the current and voltage were processed into the equivalent rms quantities. The plots of Figs 21, 22 show both the instantaneous signals and these equivalent rms traces. As can be seen in Fig 22, there is a noticeable droop in the terminal voltage due to the voltage drop across the equivalent impedance of the source. Because starting torque is strongly affected by the motor terminal voltage, the source impedance in a given application can significantly affect the ability of a LSIPM motor to accelerate and synchronize a given load.

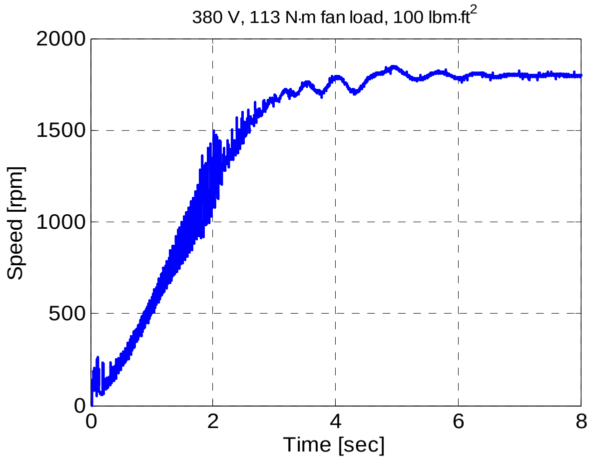
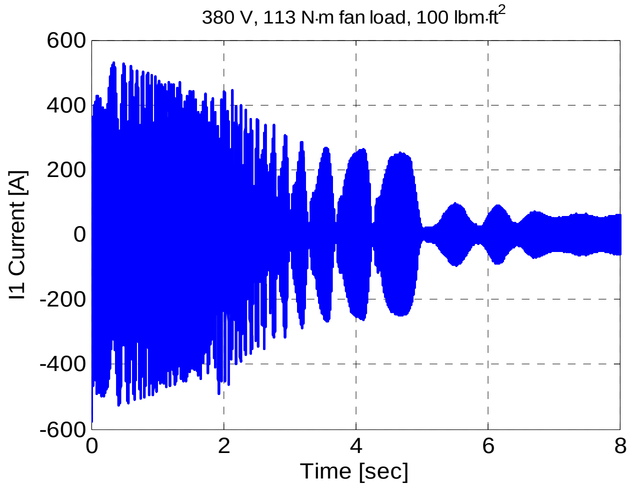
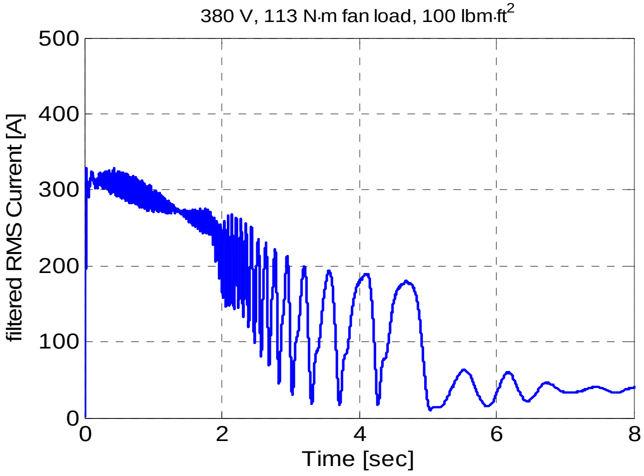


Fig 20 – Speed during DOL starting at 380 V, 60 Hz, 113 Nm load torque, with a coupled load inertia of 100 lb-ft^2

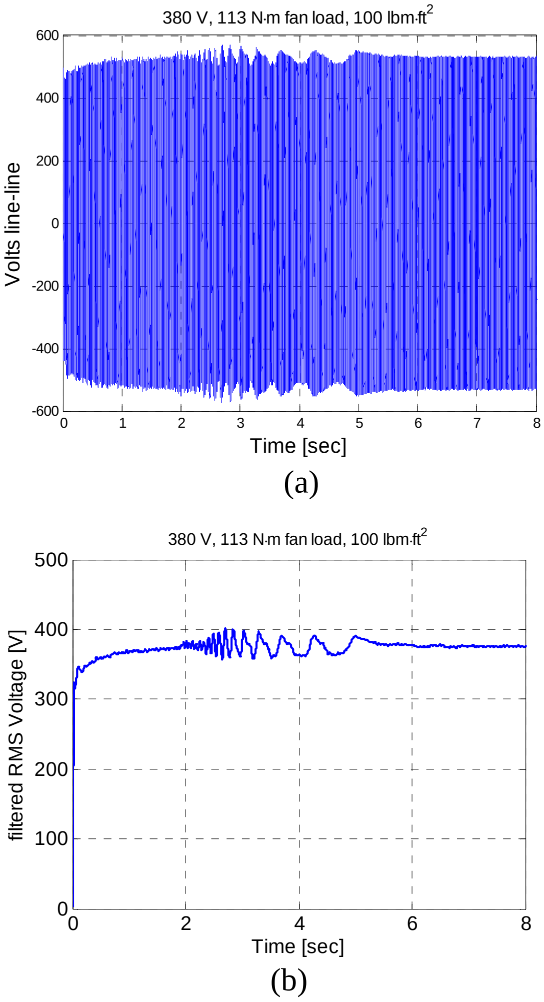


(a)



(b)

Fig 21 – Current during DOL starting at 380 V, 60 Hz, 113 Nm load torque, with a coupled load inertia of 100 lb-ft^2 - (a) Time waveform, (b) rms value of the current waveform of (a)



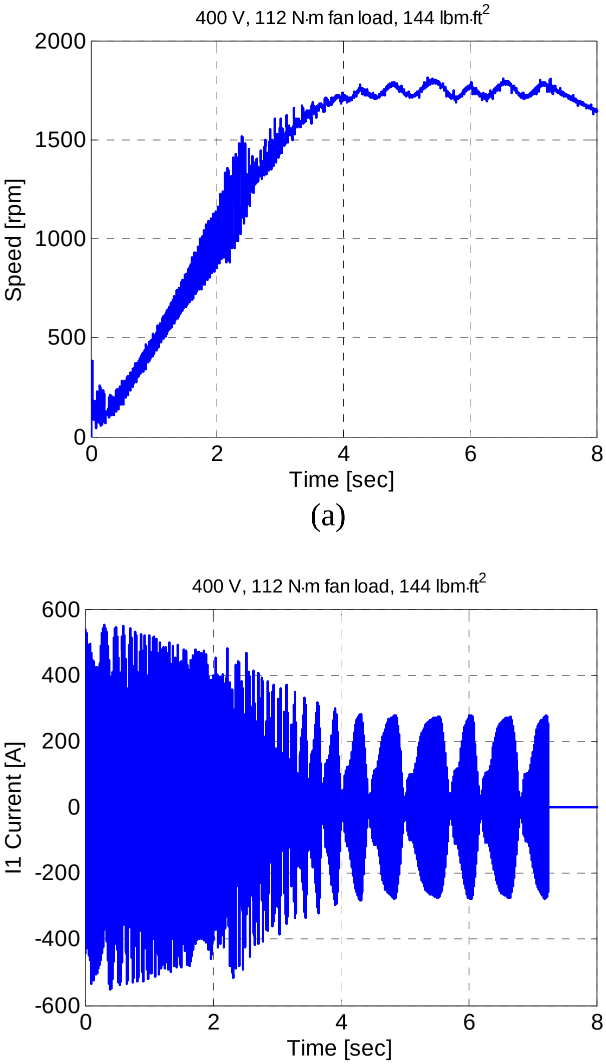
(a)

(b)

Fig 22 – Voltage during DOL starting at 380 V, 60 Hz, 113 Nm load torque, with a coupled load inertia of 100 lb-ft^2 - (a) Time waveform, (b) rms value of the voltage waveform of (a)

In contrast to the start and successful synchronization depicted in Figs 20-22, the speed and current measured during a test with a higher load inertia is shown in Fig 23. It can be seen in Fig 23a that the speed does not synchronize at 1800 rpm, but rather oscillates around a speed slightly below synchronous speed. In this case, the motor is operating asynchronously as an induction motor at an average slip speed with speed variations produced by the torque pulsations produced by the magnet and motor saliency as the rotor slips past the synchronous flux wave of the stator. The electromagnetic models for the starting and synchronization performance of these motors matched well with these test points. This demonstrates that these motors can be applied reliably.

Similarly, instead of the current settling to the nominal load current, it pulsates with a rather high amplitude, again due to the fact that the salient rotor with its fixed magnetic excitation slips past the stator flux wave. After about 7 seconds, when it was apparent that this case would not synchronize, the contactor feeding the LSIPM motor was manually opened. A case such as depicted in Fig 23 would be expected to trip a motor starter. How quickly a particular starter might react to such a situation and take the motor off line is beyond the scope of this work.



(a)

(b)

Fig 23 – Start with failure to synchronize –
(a) Speed, (b) current

Another aspect of starting performance is related to the magnet exposure to potentially demagnetizing fields during the starting process. Due to the asynchronous behavior during starting, the magnets go through a "pole-slipping" process. This means that the high stator currents which flow during DOL starting may expose the magnets to demagnetization depending upon the magnetic characteristics and their operating temperature. The motor design and magnet selection must take account of all possible operating conditions to insure that demagnetization does not occur. It is important to consider the magnet temperature during the starting process, as the ability to resist demagnetization (Fig 10) is significantly temperature-dependent for all viable magnet materials.

While it is true that the starting cage provides somewhat of a "shielding" effect for the magnets in regard to transient fields, there are situations such as the final pole-slip before synchronization that are slow events and therefore the cage provides very little shielding in that case.

Using a fairly high temperature grade (33EH) magnet such as SANVAC 3230, there was no irreversible demagnetization experienced through many tests across a range of conditions. However, with lower temperature grades such as SANVAC 4020 or SANVAC 3625, if a direct-on-line start is performed while the magnets are particularly hot, some demagnetization can occur. Demagnetization is an unacceptable situation, and the selection of the magnet materials and their proper thermal application is required for successful application. The electromagnetic models along with the magnet manufacturer's published data correlated well to the observed test results. This demonstrated that the phenomenon of demagnetization is modeled adequately. While lower temperature magnet grades are less costly, the ability to resist demagnetization is an absolute requirement.

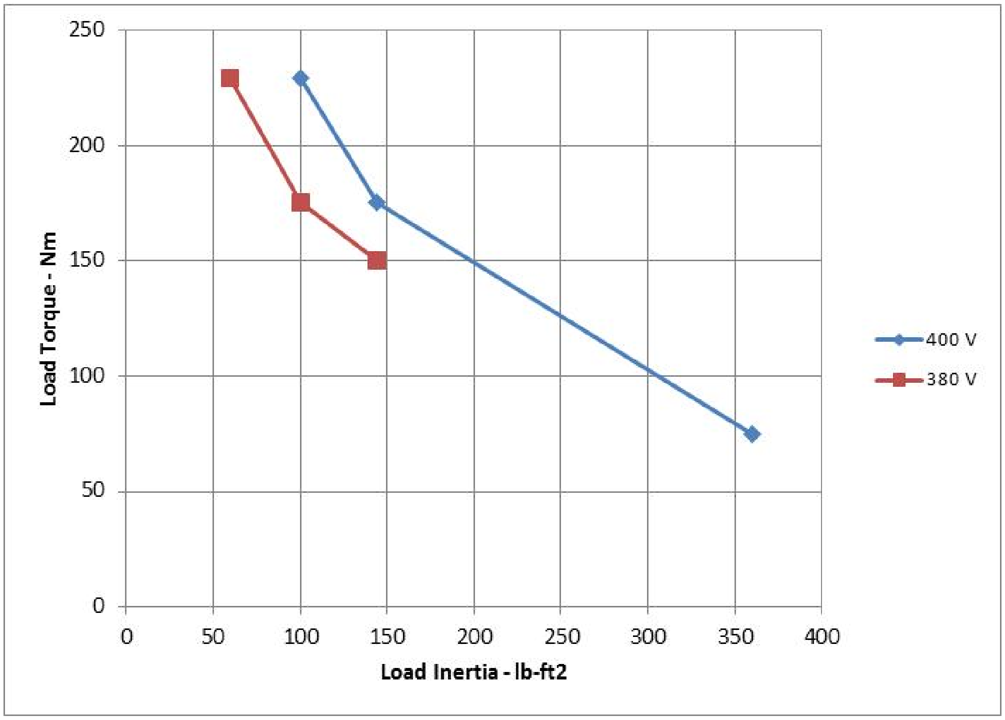


Fig 24 – Limiting cases of synchronization capability of 286T frame prototype

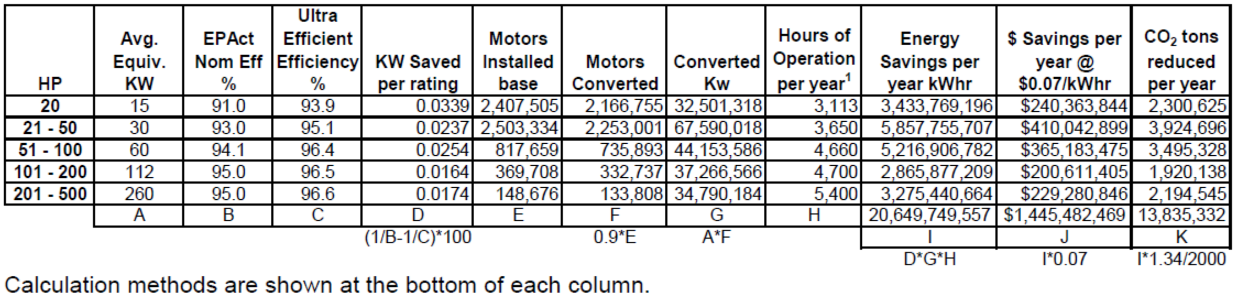
Figure 24 shows the limiting cases of successful starting and synchronization for a 50 HP prototype tested at two different voltages with four different load inertias. Rated torque is 198 Nm, so at 400 V, the inertia which can be synchronized at full load is about 120 lb-ft^2.

5.0 Benefits Assessment

Introduction of ultra-efficient, high power density electric motors will enable US energy savings of over 70 Trillion BTU per year and reduction in CO_2 emissions of over 13 million tons per year. Table VI shows the basis for the energy and emissions reductions. Baldor Electric Company, a leader in the development and marketing of energy efficient electric motors for utility and industrial applications, has developed across-the-line starting and simple-to-control permanent magnet (PM) motor technology with the capability of obtaining at least a 30% reduction in motor losses compared to conventional Energy Efficient induction motors and a 15% reduction in motor losses compared to NEMA Premium Efficient induction motors. (Energy Efficient induction motors are those that meet the requirements of the 1992 US Energy Policy Act). These ultra-efficient PM motors are 30% smaller in volume, 30% lower in weight, and have higher power factor than Energy Efficient or NEMA Premium Efficient induction motors. This will allow rapid market penetration into user and original equipment manufacturer (OEM) markets. The Baldor project team included the leading equipment manufacturers; Colfax Pumps, PeopleFlo, and Howden Fan and energy efficiency conscious end-users: DuPont, Duke Energy, and Ameren Power. These companies provided consultation in regard to the desired characteristics and application of motors built with this technology. The across-the-line starting PM motors have been designed to replace constant speed induction motors and the simple-to-control PM motors are designed to replace variable-speed induction motors. Target applications will be pumps, fans, and compressors with motor ratings from 20 hp to 500 hp. These ultra-efficient, high power density PM motors can enable United States annual energy savings of over $1.4 Billion. The smaller motor size and weight will keep the cost of these PM motors low enough so rapid market penetration will occur in the wide range of US industries that Baldor serves.

Table VI – Annualized Energy Savings and CO_2 Emissions Reductions when 90% of the Installed Base is Converted from Energy Efficient and Premium Efficient to LSPM Ultra Efficient Motors

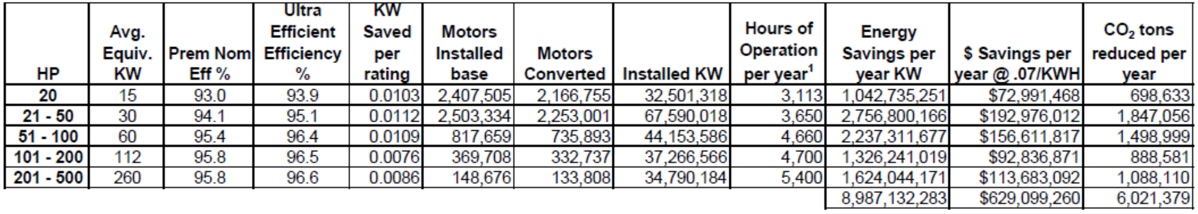
(Energy Efficient to Ultra Efficient Case)



HP	Avg. Equiv. KW	EPAct Nom Eff %	Ultra Efficient Efficiency %	KW Saved per rating	Motors Installed base	Motors Converted	Converted Kw	Hours of Operation per year[1]	Energy Savings per year kWhr	$ Savings per year @ $0.07/kWhr	CO_2 tons reduced per year
20	15	91.0	93.9	0.0339	2,407,505	2,166,755	32,501,318	3,113	3,433,769,196	$240,363,844	2,300,625
21 - 50	30	93.0	95.1	0.0237	2,503,334	2,253,001	67,590,018	3,650	5,857,755,707	$410,042,899	3,924,696
51 - 100	60	94.1	96.4	0.0254	817,659	735,893	44,153,586	4,660	5,216,906,782	$365,183,475	3,495,328
101 - 200	112	95.0	96.5	0.0164	369,708	332,737	37,266,566	4,700	2,865,877,209	$200,611,405	1,920,138
201 - 500	260	95.0	96.6	0.0174	148,676	133,808	34,790,184	5,400	3,275,440,664	$229,280,846	2,194,545
	A	B	C	D	E	F	G	H	20,649,749,557	$1,445,482,469	13,835,332
				(1/B-1/C)*100		0.9*E	A*F		I	J	K
									D*G*H	I*0.07	I*1.34/2000

Calculation methods are shown at the bottom of each column.

(Premium Efficient to Ultra Efficient Case)



HP	Avg. Equiv. KW	Prem Nom Eff %	Ultra Efficient Efficiency %	KW Saved per rating	Motors Installed base	Motors Converted	Installed KW	Hours of Operation per year[1]	Energy Savings per year KW	$ Savings per year @ .07/KWH	CO_2 tons reduced per year
20	15	93.0	93.9	0.0103	2,407,505	2,166,755	32,501,318	3,113	1,042,735,251	$72,991,468	698,633
21 - 50	30	94.1	95.1	0.0112	2,503,334	2,253,001	67,590,018	3,650	2,756,800,166	$192,976,012	1,847,056
51 - 100	60	95.4	96.4	0.0109	817,659	735,893	44,153,586	4,660	2,237,311,677	$156,611,817	1,498,999
101 - 200	112	95.8	96.5	0.0076	369,708	332,737	37,266,566	4,700	1,326,241,019	$92,836,871	888,581
201 - 500	260	95.8	96.6	0.0086	148,676	133,808	34,790,184	5,400	1,624,044,171	$113,683,092	1,088,110
									8,987,132,283	$629,099,260	6,021,379

Source – ACE3 American Council for an Energy-Efficient Economy, June 2007 prepared by R. Neal Elliot, PhD, P.E.

PM motor products that have previously been available are largely variable speed motors that require a special adjustable speed drive with rotor position feedback. These motor systems are applied where rapid motor dynamic response is required and the lower rotor inertia of the high power density PM motor is an advantage when compared to an induction motor. However, there are many applications, such as pumps, fans, and compressors, where dynamic response requirements are very low. Pump, fan, and compressor applications utilize over 60% of industrial electric motor energy in the US. In many of these applications constant-speed induction motors that are started across-the-line are the motor of choice. Alternatively, variable speed induction motors, powered from an open-loop (Volts/Hertz control) variable speed drive, are utilized without any rotor position feedback device. Induction motor Volts/Hertz drives are commonplace and available from a large number of drive manufacturers.

The primary objective of this project was to combine the ease-of-installation and ease-of-use attributes of industrial induction motors with the low-loss and small size and weight advantages of PM motors to create an ultra-efficient, high power density industrial motor that can be started across-the-line or operated from a standard, Volts/Hertz drive without the need for a rotor position feedback device. This was accomplished by adding a starting cage to the rotor of the PM motor. Computer simulation and design tools were developed for these ultra-efficient motors in order to predict the starting characteristics and to allow for design optimization. The design tools were verified with tests on laboratory prototypes (30 - 250 hp) that were designed to meet the requirements of project team members Colfax pump and Howden fan. Project success was measured by the energy efficiency and power density levels achieved and by the ability to predict the starting and steady state performance of the prototype PM motors based on laboratory testing of both line-start and open-loop-controllable PM motors. The open-loop-controllable PM motors require a less substantial rotor cage thereby allowing more rotor design freedom to maximum efficiency and/or minimize motor volume and weight.

6.0 Commercialization

One of the primary motivations for a customer to use motors with this level of energy efficiency is the payback based on lower electricity cost. Figure 25 below shows how gains in motor efficiency can have a fairly quick payback depending on the motor price premium charged for the more efficient motor. This figure is based on an electricity unit cost of 10 cents per kW-hr. It is also based on continuous operation, as might occur on a pump in a process industry such as a refinery. The 50 HP prototype demonstrated in this project had a “4 band jump” in efficiency compared to a NEMA Premium level as an induction motor might have. Even with a $1500 price premium, there could be less than a 2.5 year payback with the 10 cents/kW-hr cost of electricity. For locations such as Hawaii and Italy where the electricity cost is much higher, the payback would be that much quicker.

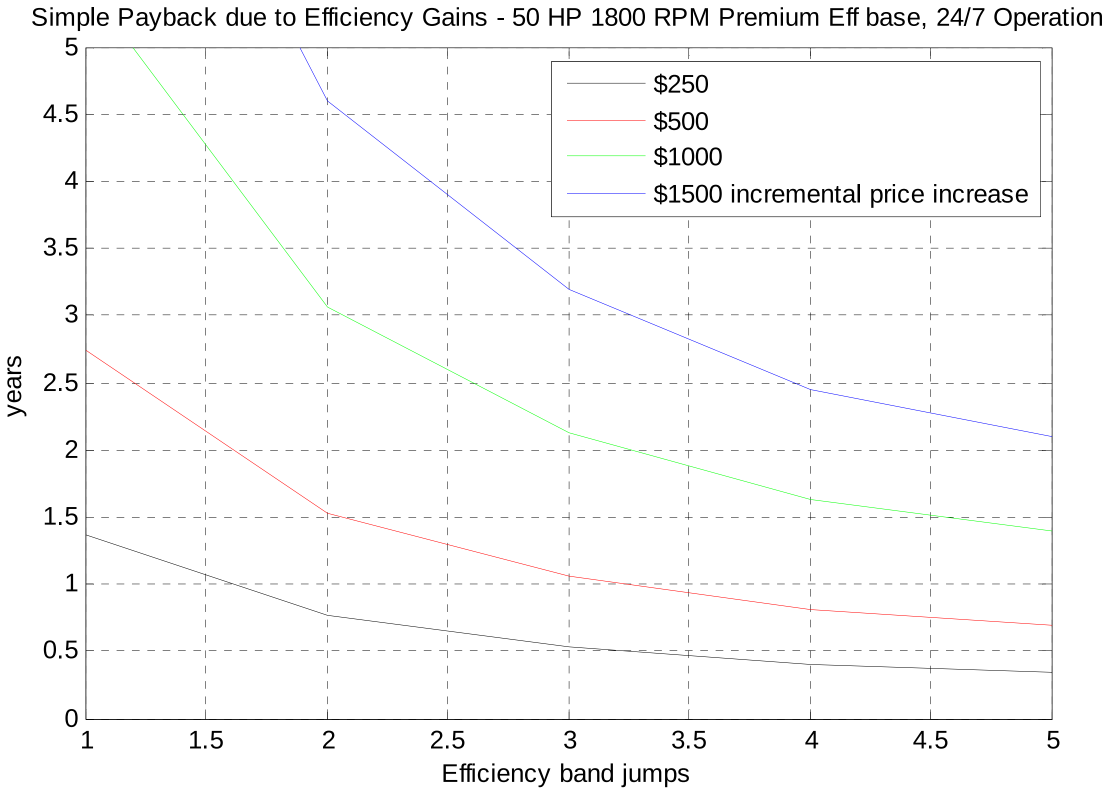


Fig 25 – Simple payback based on electricity savings with 24/7 operation

Of course, with less than a 24/7 operation (for example 4000 hours/year), the payback would be longer as shown in the Fig 26 below. A two shift operation with a 5 day workweek might be a typical 4000 hours per year situation.

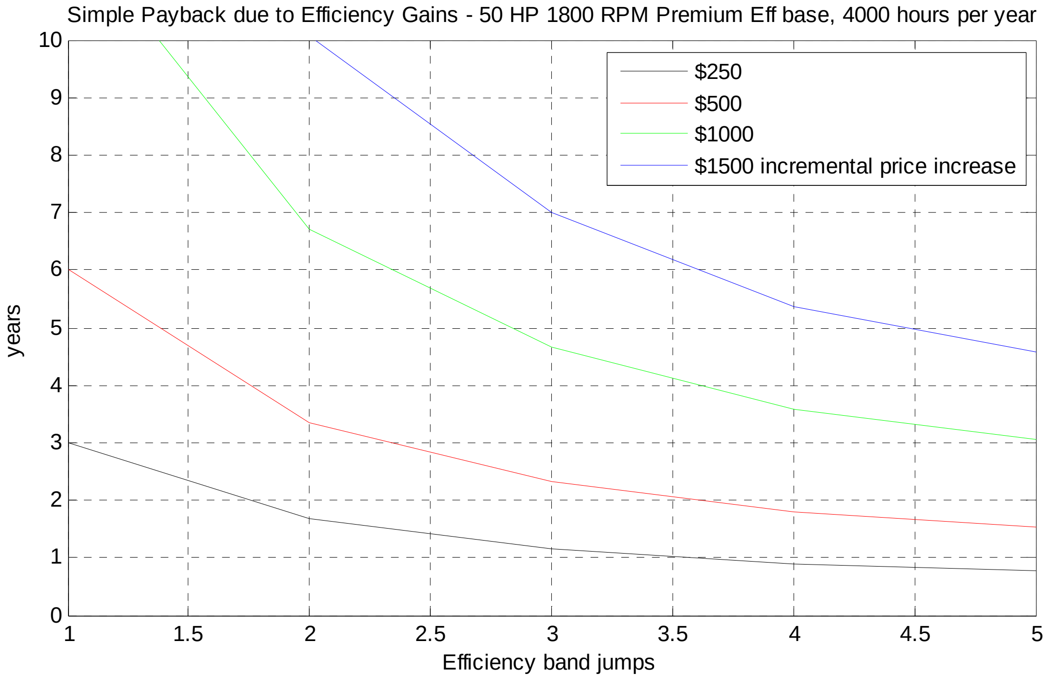


Fig 26 – Simple payback based on electricity savings with 4000 hours/year operation

7.0 Accomplishments

As a result of the success demonstrated in the development of this technology, there is a technical viability to commercialize this technology. Whether there is an economic justification for such a product development is dependent on the availability of permanent magnets at a reasonable cost. During the course of this project work, the cost of magnets has fluctuated by a large amount. That fluctuation is perhaps best generalized by looking at the commodity cost of two of the primary raw materials that are most commonly used in the manufacture of these magnets. Figure 27 below shows that fluctuation in the prices of Neodymium (Nd) and Dysprosium (Dy). At the magnet prices that existed at the start of this project, the economic viability was there. At the peak of the magnet prices, the payback would be longer than the target two year level at 10 cents per kW-hr electricity cost.

Table VII shows the specific efficiency achieved at 30, 50, and 250 HP ratings. These levels are compared to the NEMA Energy Efficient and NEMA Premium Efficient levels prescribed for those ratings in a TEFC enclosure as was used for the prototypes in this project.

Table VII – Energy Efficiency Demonstrated by Test Relative to NEMA Standard Levels

Rating	Tested	NEMA Energy Efficient	NEMA Premium Efficient
30 HP @ 1800 RPM	96.0%	92.4%	93.6%
50 HP @ 1800 RPM	96.2%	93.0%	94.5%
250 HP @ 900 RPM	97.6%	94.5%	95.0%

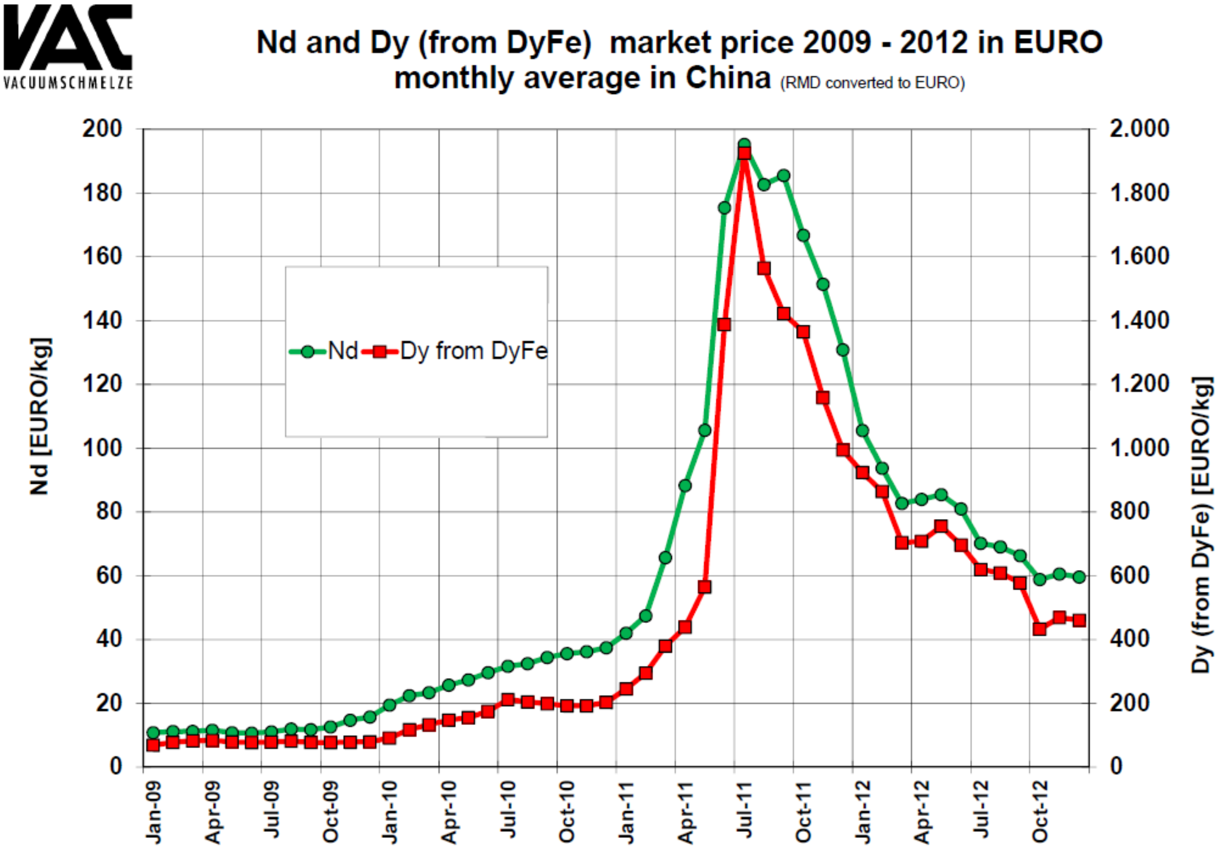


Fig 27 – Price fluctuations of magnet constituent materials over the past four years

Two patent applications were filed and in addition a provisional application was filed as part of this project. Table VIII below shows the titles of these three applications. Figure 28 shows the use of a soft-start coupling to enable synchronization of higher load inertias and torques.

Table VIII – Patent applications submitted during this project

Patent Application Title	Status / Type
Rotor for a Line Start Permanent Magnet Machine	Patent application
System and Method to Allow a Synchronous Motor to Successfully Synchronize with Loads that have High Inertia and/or High Torque	Patent application
Synchronous Motor with Soft Start Element formed between the Motor Rotor and Motor Output Shaft to Successfully Synchronize Loads that have High Inertia and/or High Torque	Provisional patent application

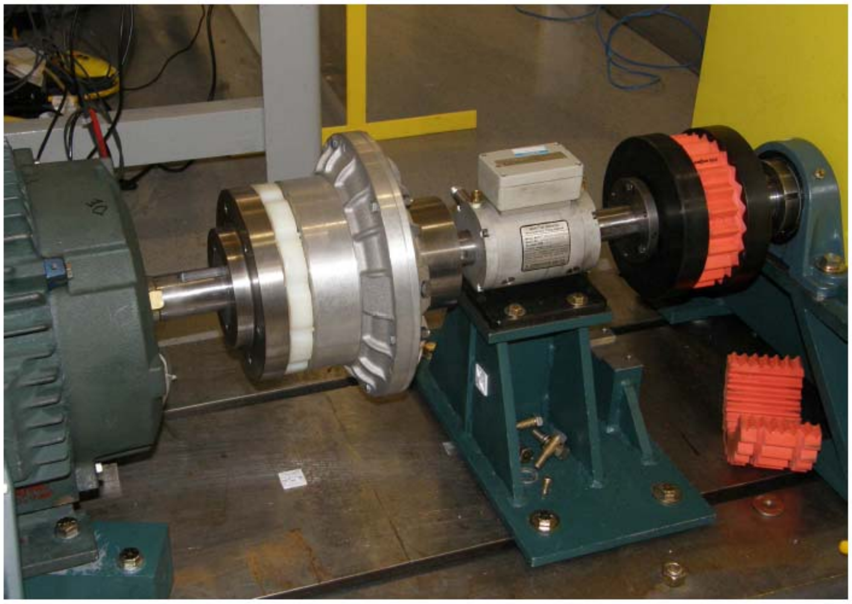


Fig 28 – Soft-Start coupling used to enable synchronization of high torque or high inertia loads

8.0 Conclusions

The technology of LSIPM motors provides an unmatched level of energy efficiency. The ability to improve upon and extend this technology to hundreds of horsepower has been demonstrated in this project.

The design and modeling of these machines adds significant complexity and challenges compared to either induction motors or inverter-fed PM motors. The more complex rotor geometry requires careful finite element analysis in order to both achieve the maximum efficiency and also to have an effective starting cage.

9.0 Recommendations

Based on magnet costs staying in an acceptable range, a product development to commercialize this technology should be pursued. Baldor has initiated a "gate-based" product development process to begin commercialization.

10.0 References

NEMA MG1- 2011

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