Permanent Magnet Motor with Tested Efficiency Beyond Ultra-Premium/ IE5 Levels

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ABSTRACT

This paper presents the design and tested performance of a permanent magnet AC motor suitable for comparison to National Electrical Manufacturers Association's Premium Efficiency, Super-Premium Efficiency (future) and Ultra-Premium Efficiency (contemplated) 4-pole induction motor standards, and the equivalent motor standards using the European International Electrotechnical Commission's IE3, IE4, and IE5 efficiency standards, respectively. A 15hp (11kW), 1800 rpm combination was chosen as representative of industrial-sized motors in wide use, well developed, and with efficiencies that are well documented. The motor described here is a proven example of a new class of extremely efficient motors. It is a radial flux, surface permanent magnet alternating current motor, configured for 3-phase, sinusoidal current supply from variable frequency pulse-width-modulated, voltage-source inverters. Efficiency comparison is made with and without the additional motor losses due to the variable frequency drive. A test procedure to measure the performance in a manner suitable for direct comparison to published induction motor efficiencies is included. The results show that the tested efficiency of the PM motor is significantly higher than the best efficiency now available for induction motors, and even higher than the contemplated future Ultra Premium / IE5 values.

Introduction

The design and development of permanent magnet alternating current (PMAC) motors has evolved significantly over the last 25 years as a result of several enabling technologies. These include more energy-dense permanent magnets, new electromagnetic topologies for three-phase permanent magnet motors, availability of lower-loss electrical sheet steels, improved inverter control algorithms in commercial off-the-shelf variable frequency drives (VFDs), improved thermal management materials and systems, and the improved performance and packaging of semiconductor switching devices for the inverters.

Electric motor energy efficiency has been the subject of research and development for many years (Buschart 1979). The ubiquitous induction motor (IM) has been the primary focus of this work, and work continues in this field (Bonnett 1993; Bonnett 1994). In addition, regulatory programs, most notably by the U.S. Department of Energy, in concert with the new standards of the National Electrical Manufacturers Association (NEMA) and the European International Electrotechnical Commission (IEC), have forced forward efficiency improvements that might not otherwise have been implemented (EPAct 1992, EPAct 2005; EISA 2007; IEC 2014, DOE Amended IHP Rule 2014).

The NEMA Motor-Generator standard, MG-1-2016, calls for the 15 hp, 1800 rpm NEMA Premium® Efficient motor (equivalent to IEC's standard IE3) to have a nominal efficiency of 92.4% (NEMA MG-1). The nominal efficiencies for Super-Premium® (equivalent to IE4) and Ultra-Premium (contemplated, equivalent to IE5) efficient motors are not yet published in the requirements of this important standard. However, a recently published NEMA standard does provide NEMA Super Premium® values matching the IEC's published IE4 values for integral horsepower motors, with the 15 hp/1800rpm motor having a nominal efficiency of 93.6% (NEMA MG-10-2017). The proposed Ultra Premium / IE5 efficiency level for 15 hp, 1800 rpm would be 94.8%. Most high efficiency IMs currently available and used in USA are the NEMA Premium® (IE3) motors.

Some discussion has suggested that efficiency improvements for the IM may be near the limit (Boglietti, et al. 2005; Carlsmith, et al. 1990; Nailen 2013), and that PMAC machines hold the better promise to achieve even higher efficiencies (Fang, et al. 2008; Sone, et al. 2014). One paper mentions using a double-layer interior permanent magnet motor to increase reluctance torque, but the efficiency is still less than 93% (Fang, et al. 2008). A special axial flux rotor structure has been proposed to increase the efficiency to 95.6% (Sone, et al. 2014). However, it is not clear that the test was at thermally stable conditions, the manufacturing process appears very costly, and the power density is not significantly increased. Similarly, many special cases of high efficiency motors can be found in the literature, such as high speed switched reluctance motors for traction drives, but close review seems to always show they are not an equivalent comparison for robust industrial applications at this power rating and speed. Sizing and scaling laws quickly show their limitations.

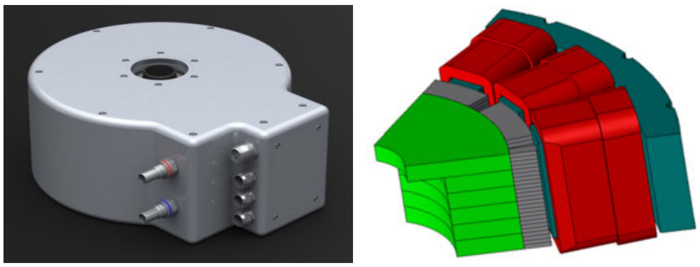
The PMAC motor described here introduces a new class of electric motors with extremely high efficiency and uses state-of-the-art technologies to achieve that efficiency in a robust PMAC motor suited for low cost manufacturing. The design and tested performance of this example, a 15hp (11 kW), 1800 rpm permanent magnet motor, is suitable for comparison to NEMA Premium®/IE3 efficiency IMs, and NEMA Super-Premium/IE4 efficiency IMs. The Ultra-Premium/IE5 standard remains a hopeful proposal only, and no motor data for such IMs is available. The prototype PMAC motor has been developed to be suitable for use in a wide range of applications requiring high efficiency, such as continuous duty industrial pumps, manufacturing processes, fans and blowers, etc. Additionally, contrary to all expectations for high efficiency motors, this motor is significantly smaller and lighter weight than the IMs it is compared to. The large improvement in efficiency is especially noteworthy since IM efficiency has been incrementally improved for more than 30 years, where every 0.1% improvement has been a hard fought achievement by the manufacturers.

A PMAC motor typically requires use of an inverter, or VFD, to reliably get started. Additional losses are created in all inverter-driven motors due to the inverter function itself, which creates high frequency components in the current, commonly referred to as current ripple or current harmonics. The current ripple creates additional losses in coil conductors, and due to the high frequency components of magnetic fields it creates, adds losses in the core steel and in the magnets. Still, even with inverter caused losses, both the IM and PM motor can realize significant energy savings with proper application of VFDs, although the PM motor energy savings is nearly always better than the IM energy savings. The PM motor described here is able to operate without a VFD position feedback system, so cost is lowered, and reliability is increased compared to many previous PM motor installations. The higher purchase cost of the industrial PMAC, usually attributed to low production volume and magnet cost, remains a barrier to widespread utilization.

Motor Design

The subject PMAC motor is a radial flux, surface permanent magnet AC motor. It has modular design of both stator and rotor components, and uses less than half the copper and less than half the core material of equivalent IMs. It is a 12-pole, 18 slot, concentrated coil, fractional-slot machine, with 0.5 slots per pole per phase. The motor was configured for a nominal voltage of 460 V (rms) and a phase current under 18 Amps (rms). This 15hp (11 kW), 1800 rpm is an industrial-sized motor that is comparable to IMs of the same speed and power, and which are very widely used, is very well developed, and has efficiencies well documented by many manufacturers, universities, test laboratories, and users.

The author's company was engaged to advise the motor design team on the electromagnetic design, the mechanical design, the prototype development, the sourcing of parts, materials and services, and the performance testing. To achieve the remarkable results reported here, many designs were modeled, and several were built as prototypes. 3D Finite Element Analysis (FEA) simulations were used and updated to match test data, and the current design was finally derived, as shown in Fig. 1 and Fig. 2. Table I lists the key features of the motor.



(1a). Overview of (1b). FEA 3D model
Fig.1 High efficiency PM motor`s

Fig. 2 T-shaped lamination

Table I. Key specifications of the PMAC motor

Parameter	Specification
Continuous Power	15 HP (11kW) @ 1800rpm
Continuous Torque	59.4 N-m 43.8 Lb-Ft
Efficiency Target	96.0%
Frame Length	150 mm (5.75 inches)
Frame Diameter	330 mm (13 inches)
Mass	53 kg (117 Lbs)
Cooling	TENV,TEFC, or Liquid cooled, as required
Cogging Torque	< 3%

Efficiency can usually be improved by decreasing the factors contributing to losses, namely flux density, current density, temperature and operating frequency. This is done by using more core material for the same flux, and more copper material for the same current, and reduction of harmonic frequencies in currents and magnetic fields. However, this adds cost and weight, with diminishing benefit.

To achieve high copper slot fill, the stator has T-shaped segmented laminations, each a single tooth section and an arc section of back-iron, or yoke material, Fig. 2. The core material is high permeability, low loss, thin gauge, non-grain-oriented electrical sheet steel. The copper wire is rectangular, high-purity copper with 200C heavy film insulation coating, and is compactly layer-wound onto insulated tooth segments to form a tooth/yoke/coil module. With a single coil mounted onto it, the module allows easy assembly and low cost manufacturing despite the high slot fill, with tongue and groove joints used to decrease the flux density crossing the yoke joint.

The rotor is a surface-magnet type, with the magnets mounted on laminated back iron and retained using sleeves with high tensile strength. The permanent magnets are rare-earth Neodymium-Iron-Boron high energy magnets. The magnets are semi-step-skewed to minimize cogging torque, and each magnet pole is segmented axially to minimize eddy current losses. For dimensions of magnet segments, laminations and wire, the ac skin effect due to both fundamental and harmonic magnetic fields needs to be evaluated using 3D FEA. An analytic calculation, as an indicator, is made using Eq. (1). The magnet and lamination maximum axial dimension should be less than twice the skin depth of the material, 2δ**,** which is based on the material properties and the frequency of the impinging magnetic field. A maximum axial dimension of less than one-half skin depth is preferred. Table II lists the skin depth of the relevant materials at an operating frequency of 180 Hz, and the normalized values of dimensions used in the motor.

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \qquad (1)$$

where δ is skin depth (m), ρ is resistivity (Ohm-m), ω is frequency (rad/sec) and μ is permeability (H/m).

Table II. Skin depth of materials and dimensions used, at 180Hz

Materials	Skin depth (180Hz)	Normalized to δ
Copper wire	4.92 mm	0.3 δ x 0.8 δ
NdFeB magnet	32.7 mm	0.1 δ
Stator laminations	0.2 mm	1.0 δ

Equation (2) is used for the efficiency calculation. Total losses must include stator copper loss, stator core loss, rotor core loss, magnet and retainer loss, and windage and friction loss. It is extremely important to calculate and predict each of the terms as accurately as possible, and only FEA is able to achieve the accuracy needed. Still, variations in materials, manufacture, and assumptions make accurate prediction exceedingly difficult to obtain. Calibration against some form of test data will lead to a reliably accurate prediction of efficiency.

$$eff = \frac{P_{out}}{P_{out} + (P_{scu}+P_{score}+P_{mag}+P_{rcore}+P_{wf})} \times 100\% = \frac{P_{out}}{P_{out} + (P_{losses})} \times 100\% \qquad (2)$$

where *eff* is efficiency, P_{out} is net shaft output power, P_{scu} is stator winding loss, P_{score} is stator core loss, P_{mag} is magnet and retainer loss, P_{rcore} is rotor core loss and P_{wf} is windage and friction loss.

Through the many iterations of innovation and development, the designed and built PMAC motor is unique among industrial PM motors, and the manufacturer, Zero E Technologies (Wheat Ridge, CO), refers to the product as the ZEUS Motor™. It represents a new class of extremely high efficiency motors that may be abundantly available from many manufacturers in the future. It has a particularly unique thermal management system, and the motor can be configured for totally enclosed liquid cooling (TELC), forced air fan cooling (TEFC or TEBV), or non-ventilated, natural convection cooling (TENV). One feature used to achieve the thermal and heat transfer requirements is a completely encapsulated stator. This also makes the motor very robust against environmental contamination, improves the dielectric durability, reduces audible noise, and creates excellent mechanical integrity for high reliability. The combination of benefits made for a justifiable cost in a very efficient and very dependable motor intended for demanding and hostile industrial applications.

It has been suggested that the goal of a new level of the IEC's efficiency class is to reduce the losses of the previous level by 20% (Doppelbauer, 2012). Taking this 20% reduction rule and extending it to future standards, some not yet conceived or proposed, we would have the required efficiency of 15hp (11kW) motors set at: IE5 (proposed, not implemented) = 94.8%; IE6 (conceptual only) = 95.8%; and IE7 (conceptual only) = 96.7%. As shown below, this motor, and any other motor with its level of efficiency, is a new class of extremely efficient motors at the conceptual IE7 efficiency level, and we will refer them here generically as IE7-equivalent motors.

Motor Modeling and Testing

In this section, the method for simulation and testing to determine the PMAC motor efficiency, with and without the effect on motor losses due to the VFD, is presented.

FEA Simulations and Model Prediction of Efficiency

Extensive 2D modeling and 3D FEA simulations of the prototypes were performed using the advanced engineering software programs SPEED (by CD-Adpaco Div of Siemens, Melville, NY) and JMAG Designer (by JSOL Corp, Tokyo Japan). The models and simulations were used to calculate power, torque, flux density, core and joule losses, efficiency, etc. The peak flux density is 1.5T in the stator teeth, and 0.9T in the stator back-iron, as shown in Fig. 3. The magnetic flux space harmonics due to the stator teeth cause parasitic eddy current losses in the magnets. The peak eddy current density in the magnet was limited to 0.7-0.9 A/mm^2 to keep losses low and to decrease heating. The flux density of the rotor back-iron is 0.9T, and the eddy current density is $2A/mm^2$, as shown in Fig. 4. The loss distribution was calculated in FEA, and is shown in Table III for full load operation. The predicted efficiency is 96.1%.

Another necessary part of the design was to determine the Back Electromotive Force (BEMF) of the PMAC motor. Too high BEMF compared to the DC bus voltage would prevent full speed or full torque capability, and too-low BEMF leads to low Torque per Ampere, and high current ripple. The simulation predicted about 10% DC voltage overhead margin for the specified conditions. This ensures high performance operation over the speed and torque range.

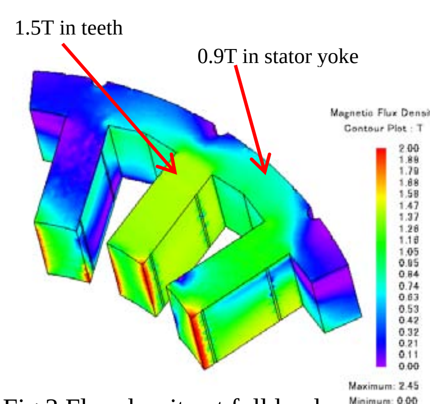


Fig.3 Flux density at full load

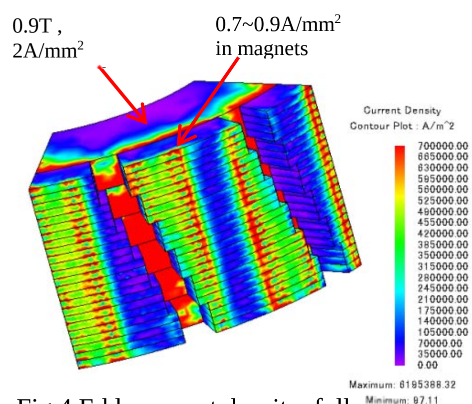


Fig.4 Eddy current density, full load

Table III. Loss and efficiency by FEA

Output Power	Stator winding loss	Stator core loss	Magnet loss	Rotor core loss	Windage and friction loss	Efficiency
11470 W	97.2 W	238 W	40 W	37 W	50 W	96.1%

Testing for Efficiency with VFD as Power Supply

A prototype motor was built and extensively tested at the manufacturer's facility with the author as observer. It was then tested independently and its performance certified by Advanced Energy (Raleigh NC), an accredited NIST NVLAP laboratory. All tests were run until temperatures stabilized, demonstrating continuous performance. While many VFDs are now able to run a PMAC motor, in this case an Allen Bradley PowerFlex 755 VFD controller was used. In the testing by Advanced Energy, the PM motor was operated as a TENV motor, with no fan nor liquid cooling. Data was collected at many torque and speed operating points to provide the data needed for a representative efficiency map (Advanced Energy 2016). In Fig. 5, IE7-equivalent prototype motor is shown on the Advanced Energy test bench set-up during testing.

NEMA Premium® IMs are thoroughly tested by accredited NIST NVLAP laboratories to IEEE Standard 112 Method B, per NEMA MG-1 standard, and the nominal efficiency is provided by the manufacturer. However, this does not include additional losses created by VFDs, which lowers the motor efficiency. To realistically compare the IE7-equivalent motor test results, using a VFD, to a high efficiency IM, the IM should be tested with a VFD. Therefore, a 15 hp NEMA Premium® /IE3 IM was also tested by Advanced Energy using exactly the same test bench configuration, and using the same VFD with the same settings, to the extent possible.

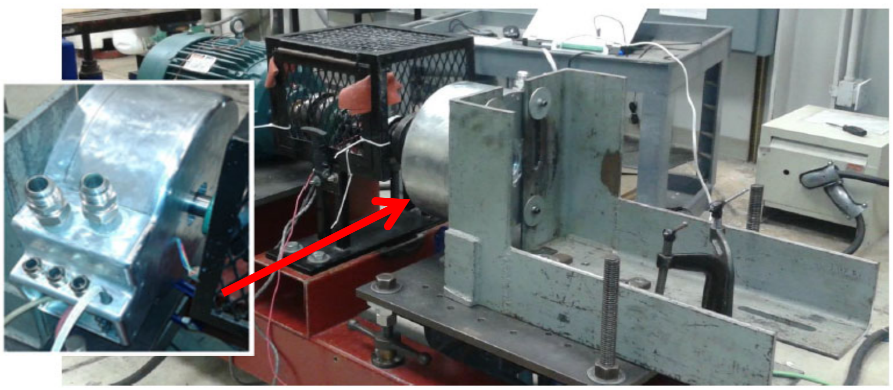


Fig. 5 ZEUS Motor™ under test; TENV cooling, liquid cooling

Figs. 6 and 7 show the Advanced Energy test results comparing the IE7-equivalent prototype motor with the NEMA Premium® IM. The IE7-equivalent motor efficiency was 95.5%. The NEMA Premium® IM efficiency under VFD operation was just 91.2%. This indicates that the total losses of the IE7-equivalent PMAC motor are about one-half the losses of the high efficiency IM, i.e., 4.5% of PMAC output, compared to 8.8% of the IM. The efficiency advantage of the IE7-equivalent PMAC motor is significant, exceeding 4% near rated torque and full speed. Furthermore, it is seen that the IE7-equivalent motor efficiency exceeds the highest efficiency of the IM (91.2%) for all speeds when the torque is above about 35% of rated torque,.

An additional method to compare the PMAC motor to the IM is to calculate the difference between the two efficiency maps. This shows the efficiency advantage of this IE7-equivalent motor over the NEMA Premium® IM for the full range of the Speed-Torque curve, Fig. 8. The IE7-equivalent PMAC motor advantage is everywhere positive, and increases significantly for low speed, high torque operation.

With no active cooling, temperature rise is higher than with air or liquid cooling. This leads to a known increase in winding resistance, and increase in I^2R, or joule, losses. However, this increase in losses is more than offset when the losses of the shaft-driven fan, blower motor, or the coolant pump is eliminated. Although the IE7-equivalent prototype motor temperature rise is increased compared to active cooling, the total losses are lower, and a higher efficiency results. Additionally, the elimination of the shaft driven fan and its fan cover also reduces cost, reduces audible noise, and removes a very common source of maintenance, repair and motor downtime.

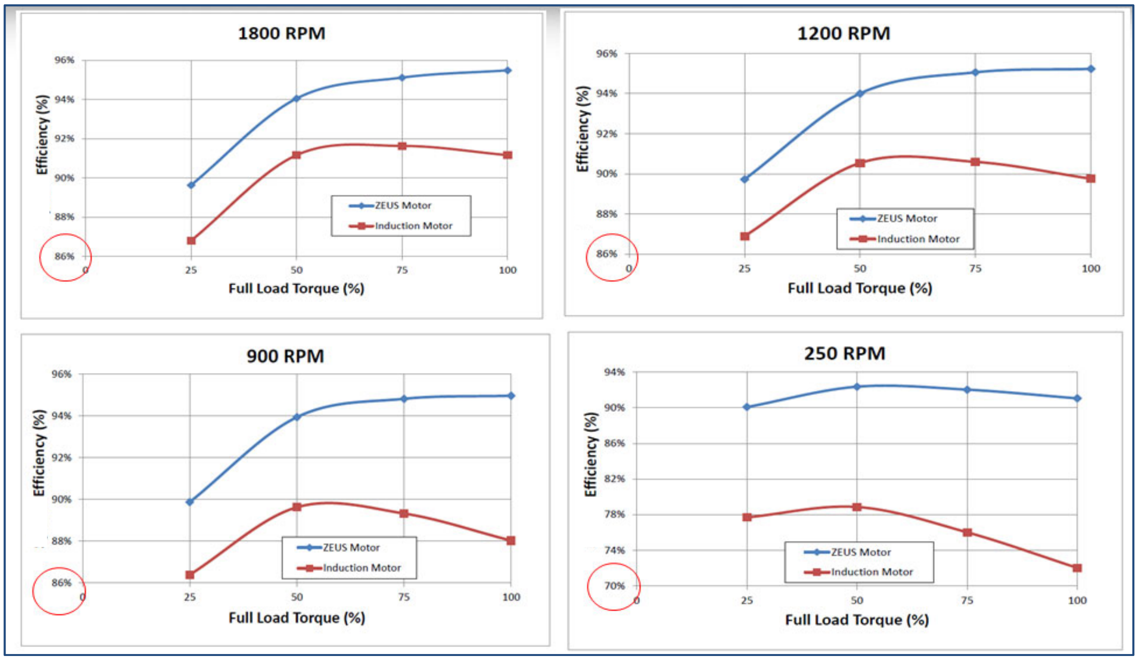


Fig. 6 Motor Efficiency, with VFD

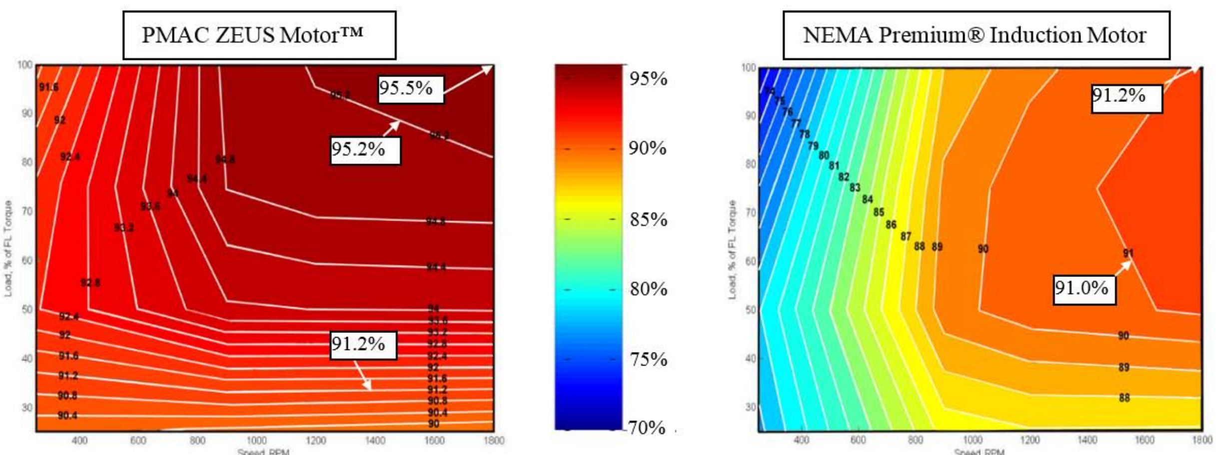


Fig. 7 Motor Efficiency Maps with VFD

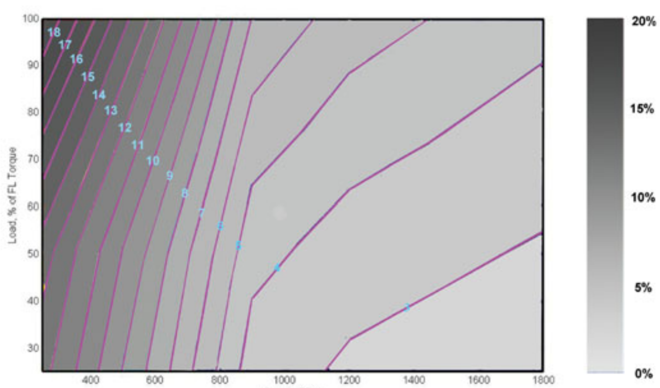


Fig. 8: Efficiency Advantage of PMAC ZEUS Motor™ over NEMA Premium Induction Motor

The same IE7-equivalent prototype motor was tested again with a smaller controller by Allen Bradley, the PowerFlex 525 VFD. With the new controller, the motor efficiency is about 96.1% (uncertified). Thus, the efficiency using a different controller is 4.9% higher than NEMA Premium® IM, and is about 0.6% higher than with the controller PowerFlex 755 VFD. This emphasizes that VFD design, operation and settings will affect the in-situ motor operating efficiency, even among different models by the same manufacturer. However, for the same drive, the higher efficiency of the PMAC motor over the IM can be expected to be consistent.

Method for Determining Efficiency without Effects of Inverter-caused Losses

PMAC machine efficiency can be directly compared to the nameplate nominal efficiency of IMs and other line-start motors, if the VFD-created losses in the PMAC machine are not included. Ideally, the best comparison would be to test the PMAC motor while synchronized to a 3-phase power supply of proper sinusoidal voltage and frequency. The availability of a balanced 3-phase high frequency sinusoidal power supply is one obstacle to such a test. Additionally, the PMAC motor is not self-starting, so a start-up and synchronization procedure with sinusoidal power supply is required, which involves significant added complication and cost.

An alternative is to test the PMAC motor in the generating mode, as a PM alternator. Measurable motor-caused losses under rated conditions, without inverter-caused losses, require no power electronics at the terminals, and data at exactly the same speed and current as when motoring. To avoid power electronics at the terminals, the alternator can be loaded with a 3-phase resistive load. Also, the resistance load ensures no feedback signal errors are introduced.

When the same PMAC machine is used as an alternator, either the input power or output power will be different than while motoring. This is because when driven as an alternator at the rated speed and with rated current, the torque and shaft input power will be the same, but the output voltage and output power, will be lower than the input voltage and input power as a motor. For the same output power, the PM alternator current must be increased, but then the joule losses are not the same. Thus, the alternator efficiency itself, whether with the same output power or same input power, is not the proper comparison to the IM efficiency with no VFD supply.

To use the alternator test to determine motor efficiency without VFD-caused losses, the alternator losses under rated conditions need to be determined, while loaded by resistance. The machine-only losses can be determined as the difference of PM alternator input and output power during a dynamometer test. Then these machine-only losses are added to the output power of the motor, per Eq. (2), and an accurate motor efficiency is calculated based on the measured value of losses. This gives, in a simple dynamometer test, the closest correlation for PMAC motors to published NEMA and IEC nominal efficiencies for IMs, which do not include VFD losses.

This alternator testing was performed by Advanced Energy. The data obtained while running as a PM Alternator showed that the motor-only losses in the PMAC motor, at rated speed and rated current, were 353 Watts. Using this for the losses of a 15 hp (11 kW) motor, the actual intrinsic IE7-equivalent prototype motor efficiency, *with no VFD losses present*, is 96.9%. This is the appropriate value to compare to the NEMA Premium® nameplate value of 92.4%, a 4.5% difference in operating efficiency. For both machines, the effect of the VFD was to reduce the efficiency of the motor by approximately 1.3%.

Future Trends

As stated in the Introduction, the 15 hp, 1800 rpm NEMA Premium® efficient motor is equivalent to IEC's efficiency standard IE3, and must have a nominal efficiency of at least 92.4%. By far, most high efficiency IMs currently sold and used in USA are the NEMA Premium (IE3) motors. The future Super-Premium efficient NEMA values are equivalent to IEC's IE4 standard, and must have a nominal efficiency of at least 93.6%. The Super-Premium (IE4) motors presently have limited availability and use in North America at this time (2017), but their presence will increase in the future. The proposed Ultra Premium values are equivalent to IEC's IE5 efficiency level, which for the 15 hp, 1800 rpm motor is 94.8%, but there is doubt whether IMs that meet NEMA MG-1 requirements can achieve those levels (Doppelbauer 2012).

Now, a new class of motors is proven and becoming available, at an IE7-equivalemnt level. A comparison of measured data for the IE7-equivalent prototype motor and published data for the high efficiency IMs is provided in Fig. 9 and Table IV. The IE7-equivalent prototype motor already significantly exceeds the efficiency of the proposed Ultra-Premium/ IE5 motors.

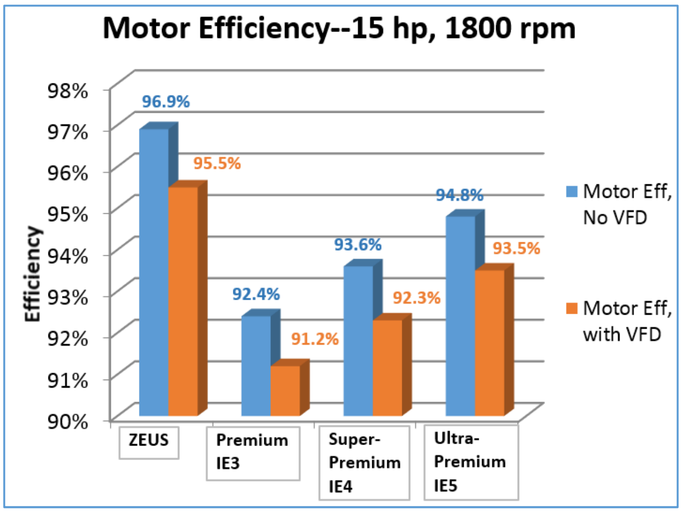


Fig. 9: Efficiency Comparison Summary

Table IV. Comparison, data nearest available TEFC, with estimated -1.3% effect of VFD supply if not measured

Power (continuous)		IE7 equiv. PMAC	Mfr 1 --NEMA "Premium Efficiency/IE3"	Mfr 2 --NEMA "Super-Premium Efficiency/IE4"	"Ultra-Premium Efficiency/IE5" -- not available
15 HP, 1800 rpm	**no VFD**	**96.9%** Measured	**92.4%** Published	**93.6%** Published	**94.8%** Proposed
	w/VFD	**95.5%** Measured	**91.2%** Measured	**92.3%** Published	**94.5%** Proposed
	Housing	Aluminum	Cast Iron	Cast Iron	**TBD**
	Weight	117 Lbs	299 Lbs	280 Lbs	**TBD**

In today's competitive markets, a large increase in efficiency, providing significant cost savings for the user, can be the competitive market differentiation OEMs need to remain viable in the future. Hopefully, more and more motor manufacturers will be able to produce extremely high efficiency class of electric motors at an IE7-equivalent level in the near future. OEMs, system integrators, and motor users can use these motors on a global basis to improve their product offering, and achieve sustainable energy savings not previously anticipated.

Economic Analysis

Generally, the purchase price of an industrial electric motor is about 1.0% of total life cycle costs, the maintenance cost is about 1%, and the energy cost is about 98%. Therefore, the motor efficiency has a very important impact on the long term operational energy cost. To determine the benefit of using a more energy efficient motor in a given application, the following equation (3) is used to calculate the annual differential cost, dC, of the energy based on different motor efficiencies (Andreas, 1982).

$$dC = (0.746 \times HP) \times Ce \times t \times (\frac{100}{eff_1} - \frac{100}{eff_2}) \qquad (3)$$

where, *HP* is HP power of the motor, *Ce* is the energy cost per kWh, *t* is hours per year, eff_2 and eff_1 are efficiencies of the old and new motors, respectively.

We assume a representative USA energy cost after taxes and fees, *Ce*, of USD $0.114 per kWh, annual full-load operating hours of 7000 hours with 80% duty cycle, and an IE7-equivalent motor with 4.0% to 4.5% higher efficiency than the NEMA Premium efficiency induction motor. Then, the energy cost difference per year is calculated as shown in Table V.

For this 15hp power motor, the annual energy savings will be about $360 per year, by choosing the IE7-equivalent motor instead of the NEMA Premium induction motor. If the motor life is 20 years, the life cycle energy savings will be $7,200, not including the time value of money, nor increases in energy cost. The high efficiency motor saves, with every 1% efficiency improvement, about $100 per year. This calculation does not include additional losses due to a VFD power supply, which are present, and about the same, for both motors.

Table V. Energy cost savings per year

Power	5hp	10hp	15hp	20hp	25hp	30hp
Eff_{hp1} (NEMA premium efficiency/IE3)	89.5%	91.7%	92.4%	93%	93.6%	93.6%
Eff_{hp2} (+4.0-4.5%)	94%	96.2%	96.9%	97.2%	97.6%	97.6%
Annual Energy cost savings (USD $)	$130	$240	$360	$440	$520	$625

This analysis indicates that if the price for purchasing the an IE7-equivalent motor is less than about 25% higher than the price of the NEMA Premium induction motor, the payback is 1 year or less. Similarly, based on the cost savings, replacing an *existing and operable* NEMA Premium Efficient induction motor with the more efficient IE7-equivalent motor, the payback is about 4-5 years, assuming no value for the operable motor removed. Certainly, this analysis varies directly with actual energy cost, $/kWh, operation hours, duty cycle and purchase cost for motors (Andreas, 1982).

The above analysis gets better with incentive programs that give rebates for the use of high efficiency motors. There are a wide range of such programs, and they do not all treat extreme energy savings the same. Two examples:

The utility company AEP Ohio offers a rebate of $0.08 per kWh of savings in the first year due to a retrofit with a higher efficiency motor, but this is limited to 50% of the incremental cost. But if an IE7-equivalent motor (with half the copper, and half the core steel) is priced the same as NEMA Premium/IE3 induction motor, there is no incentive! This program discourages low prices for very high efficiency motors, and relies solely on energy savings as the incentive.

The utility company Xcel Energy in Colorado offers a rebate for motors with 1% efficiency improvement-- $160 for a new 15 HP motor, or $710 for an early retirement motor, However, there is no additional rebate if the motor is replaced with an IE7-equivalent motor that is 4.5% more efficient than a NEMA Premium induction motor. With the availability of extremely high efficiency motors at the IE7-equivalent level much more energy could be saved if there was an incentive that is based on the incremental efficiency improvement above IE3.

Summary and Conclusion

A unique and extremely high efficiency IE7-equivalent PMAC motor has been designed, built and tested. It is a proven example of a new class of extremely efficient motors. Rated for 15hp (11kW), 1800 rpm, the measured losses and efficiency were better than predicted, essentially are in close agreement with the FEA simulation results, and about one-half of the losses of an equivalent NEMA Premium/IE3 motor.

With a VFD, the additional motor losses reduced efficiency about 1.3%. Using an inverter, the IE7-equivalent prototype motor achieved a measured efficiency of 95.5%. A new NEMA Premium Efficiency induction motor tested with the same VFD had a measured efficiency of only 91.2%. The efficiency of this PMAC motor, with VFD, already exceeds projected Super-Premium /IE4 efficiency with VFD, (92.3%), and the contemplated Ultra Premium/ IE5 motors with VFD (93.3%).

Testing as a PM alternator allowed determination of the motor-only losses, and calculation of intrinsic motor efficiency. Once the VFD losses are extracted to arrive at motor-only efficiency, the IE7-equivalent prototype motor efficiency is an extraordinary 96.9%, exceeding Super-Premium /IE4 efficiency with no VFD, (93.6%), and exceeding the proposed efficiency of Ultra Premium/ IE5 motors with no VFD (94.8%), and exceeding a conceptual IE7 level of efficiency (96.7%).

This prototype achieved a major efficiency improvement in a smaller, lighter, robust package. The constraints of standard NEMA and IEC frequencies, starting requirements, and dimensions hamper achievement of increased efficiency in IMs, but with the use of a VFD, this IE7-equivalent PMAC motor is compatible with the standard NEMA 254T and 254TC frames and operating requirements of 15hp (11kW), 4-pole motors.

Economic analysis shows the payback interval is very attractive. However, incentive programs by utilities and government agencies need to be adjusted to accommodate and encourage deployment of motors with large improvements in efficiency and energy savings, which are now available.

References

Buschart, R. 1979. "Motor Efficiency." *IEEE Trans on Industry Applications* 18 (5): 507 – 10.

Bonnett, A. 1993. "Understanding the Changing Requirements and Opportunities for Improvement of Operating Efficiency of AC Motors." *IEEE Transactions on Industry Applications* 29 (3): 600 – 10.

Bonnett, A. 1994. "An Update on AC Induction Motor Efficiency." *IEEE Transactions on Industry Applications* 30 (5): 1362 – 72.

"(EPAct) Energy Policy Act of 1992." 1992. *U.S. Public Law 102–486*: 357 pgs.

"(EPAct) Energy Policy Act of 2005." 2005. *U.S. Public Law 109–58*: 551 pgs.

"(EISA) Energy Independence and Security Act of 2007." 2007. *U.S. Public Law 110-140:* 331 pgs.

(IEC) International Electrotechnical Commission. 2014. "60034-30-1:2014 Rotating Electrical Machines - Part 30-1: Efficiency Classes of Line Operated AC Motors (IE code)." 50 pgs.

(U.S. DOE Amended IHP Rule 2014) 2014. *10 CFR Part 431* (Docket EERE-2010-BT-STD-0027), "Energy Conservation Standards for Commercial and Industrial Electric Motors"

(NEMA) National Electrical Manufacturers Association. 2016, MG-1-2016*: Motors and Generators Standard*, Rosslyn, VA: NEMA, 711 pages

(NEMA) National Electrical Manufacturers Association. 2017, MG-10-2017 *Energy Management Guide for Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors,* Rosslyn, VA: NEMA, 28 pages

Boglietti A., A. Cavagnino, L. Ferraris, M. Lazzari, and G. Luparia. 2005. "No Tooling Cost Process for Induction Motors Energy Efficiency Improvements." *IEEE Transactions on Industry Applications* 41 (3): 808-16.

Carlsmith, R., W. Chandler, J. McMahon, and D. Santini. 1990 . "Energy Efficiency: How Far Can We Go?" *Oak Ridge National Laboratory TM-11441*. 73pgs.

Nailen, R. 2013. "Is higher motor efficiency possible?" *Electrical Apparatus* 66 (4): 21-27

Fang, L., J-W. Jung, J-P. Hong,and J-H. Lee. 2008. "Study on High-Efficiency Performance in Interior Permanent-Magnet Synchronous Motor With Double-Layer PM Design" *IEEE Transactions on Magnetics* 44 (11): 4393-96

Sone, K., M. Takemoto, S. Osgasawara, K. Takezaki, and W. Hino. 2014. "Examination for the Higher Efficiency in a Ferrite Permanent Magnet 10kW I-Wheel Axial-Gap Motor with Coreless Rotor Structure." *Conference Record of IEEE 2014 Energy Conversion Congress and Exposition (ECCE) 5885-92.*

Doppelbauer, M., 2012, "IEC Motor Efficiency Classes from IE1 to IE5", Presentation at Motor Summit 2012 Conference, Zurich, Switzerland

Advanced Energy. 2016. "Zero E Technologies 15hp ZEUS® Motor™ Testing." 17 pgs

Lipo, T. 2011. *Introduction to AC Machine Design*. 3rd Edition. Ch 6. Madison, WI: University of Wisconsin

Andreas, J., 1982, *Energy Efficient Electric Motors*, Ch 7. New York, NY: Marcel Dekker,