Permanent Magnet Motors for Energy Savings in Industrial Applications

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Abstract - The present and future market for motors places high value on operating efficiency, reliability, variable speed operation, low running temperature, quiet operation, and low cost. Permanent magnet (PM) motors are now able to meet these market expectations across an increasing range of ratings. Compared to the prolific induction motor, PM motors provide the attributes of efficiency, reliability, etc, plus have the additional advantages of higher power density, superior power factor (low current), low rotor temperature, and synchronous operation. Advancement in magnet technologies allows operation at higher temperatures without permanent magnetization loss. The economic viability of PM motors is increasing with additional sources offering rare-earth magnets such as Neodymium Iron Boron at lower prices. Performance comparisons between induction motors, Surface Permanent Magnet, and Salient Pole Permanent Magnet motors are presented in this paper.

Index Terms — Permanent Magnet, Efficiency, Motor

I. INTRODUCTION

Three phase induction motors have been widely recognized as the workhorse of industrial applications, including the petrochemical industry. Over the past 30 years, there have been clear trends in motor utilization that demand higher energy efficiency and reduced Total Cost of Ownership (TCO). Induction motors have been able to incrementally improve energy efficiency to satisfy the past requirements. Both mandated (legislated) efficiency [1] (EPACT) and voluntary levels [2] (NEMA Premium®) have been provided using products derived from general purpose induction motors. Another method considered for enhanced induction motor efficiency is through the use of cast copper rotors in place of aluminum for medium size ratings [3].

As further improvements to energy efficiency are desired, along with lower noise and variable speed operating capability, other technologies beyond simple induction motors should be considered. Due to dramatic improvements in magnetic and thermal properties of permanent magnet (PM) materials over the past 20 years, along with considerable cost reduction, synchronous PM motors represent viable alternatives. PM motors have long been recognized as providing higher efficiency than induction motors, but limitations in terms of motor control, as well as magnet material limitations (performance and cost) have severely restricted their use. It is anticipated that PM motor availability will soon expand to cover a significant portion of medium HP applications in the petrochemical industry.

This paper compares induction motor technology with that of PM synchronous motors, including various configurations of PM machines. Section IIA gives a brief review of candidate PM materials with their salient characteristics as applied to motors. Section IIB outlines some of the primary electromagnetic configurations of PM motors, highlighting the strengths and weaknesses of each. Section IIC covers some of the system implications of utilizing PM motors, including control strategies, and safety. Section III reviews induction and PM motor performance including efficiency and power factor for a range of ratings in specific configurations. Section IV shows test data for unique prototyped ratings.

II. PERMANENT MAGNET MOTOR TECHNOLOGY

A. Permanent Magnet Materials

Permanent magnets have been widely utilized in motion control motors for many years. Over the past 35 years, the magnet materials have gone through substantial changes in regard to everything from basic chemistry to cost. Today, there are materials available to allow much more power dense, lower cost, higher efficiency PM motors.

In the 1940's – 1960's motor design was primarily done with either Alnico or Ceramic / Ferrite magnet materials. While ceramic magnets are quite economical, the motor air gap flux densities which can be achieved with these magnets do not come close to the levels commonly achieved with induction motors. While Alnico magnets can achieve higher flux densities, their poor resistance to demagnetization limits their use in motors. Figs. 1(a)-1(e) show some comparative properties [4] of these magnets, and relative motor air gap flux densities that can be typically achieved.

The "maximum energy product" data shown in Fig. 1(a) is typically used as a figure of merit for PM materials because it combines both the flux density and the coercivity (resistance to demagnetization) of the magnet. Residual flux density (Fig. 1(b)) is effectively proportional to the flux level that can be achieved in a PM motor. The thermal reversible flux loss shown in Fig. 1(c) shows how the motor flux level (and therefore torque per amp) can change as the magnet temperature changes from cold to hot conditions.

The rare earth PM materials were introduced first with Samarium Cobalt products, both $SmCo_5$ and Sm_2Co_{17} types. These were available starting around 1970, and provided the

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first opportunity to achieve motor air gap flux levels comparable to induction motors. These magnets have outstanding thermal capabilities, both in terms of minimal variation in flux with temperature and in regard to maximum temperature capability. However, the cost has remained high, limiting their use to niche applications.

The introduction of Neodymium Iron Boron ($Nd_2Fe_{14}B$) magnets in the 1980's provided the promise of substantially lower cost compared to Samarium Cobalt magnets. The initial $Nd_2Fe_{14}B$ magnet materials had very limited temperature capabilities, with high susceptibility to demagnetization above 120°C. Over the course of the past 15 years, the material properties have been improved such that some grades can be utilized to 180°C (Fig. 1(d)). In addition, the magnetic field capabilities have been further advanced, and equally important the magnet costs have come down significantly. Furthermore, magnets have been developed that can be either injection or compression molded in place, allowing substantial rotor lamination design freedom.

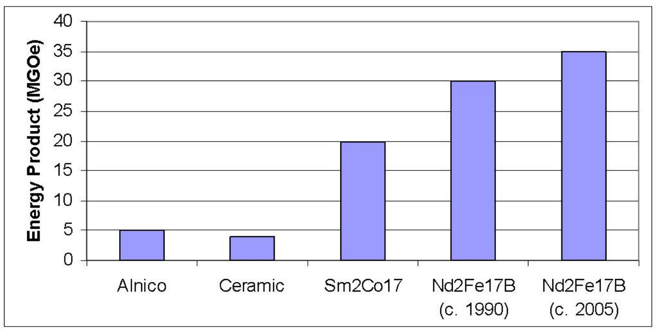

Fig. 1(a) Maximum Energy Product of Various Permanent Magnet Materials

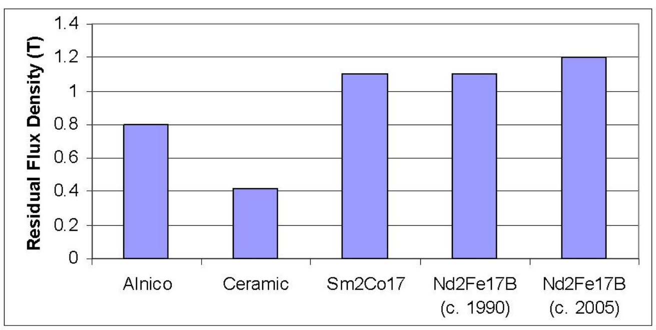

Fig. 1(b) Magnet Residual Flux Density

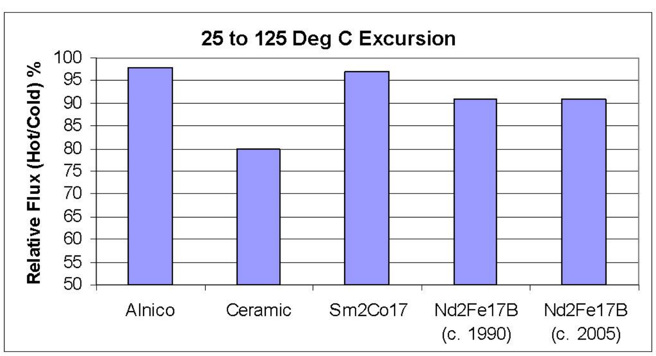

Fig. 1(c) Temperature Impact on Reversible Flux Loss

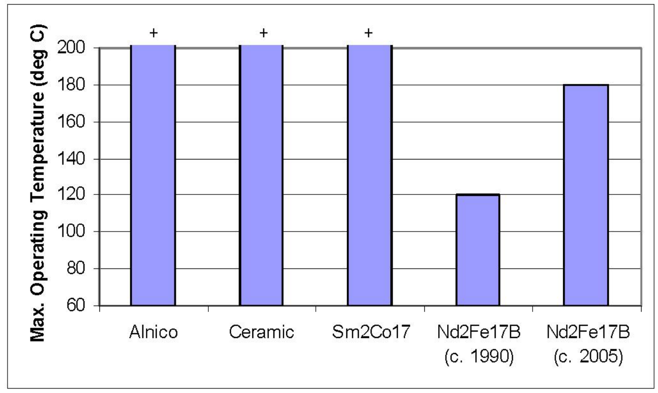

Fig. 1(d) Maximum Magnet Operating Temperature

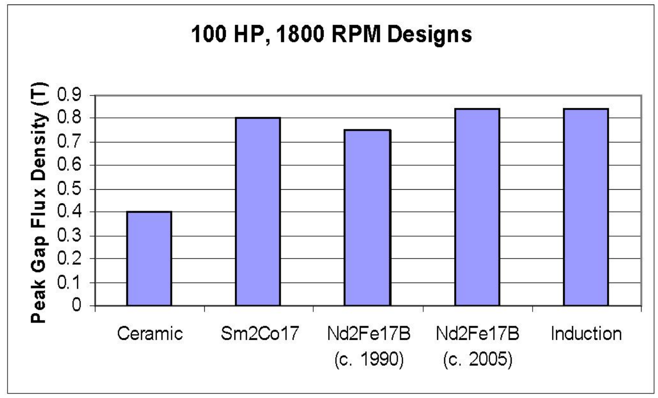

Fig. 1(e) Peak Motor Air Gap Flux Density

B. Permanent Magnet Motor Primary Electromagnetic Configurations

There are many possible rotor configurations for permanent magnet motors. All are synchronously operating machines, but with various other characteristics. Possible across the line starting, or the development of saliency-based torque (in addition to the magnet torque) are examples of some of the possible characteristics.

Figs. 2 – 7 show typical electromagnetic (lamination) configurations for PM motors as well as a typical induction motor. As can be seen, there are a wide range of possible configurations that can be employed in the design of PM motors, with the ultimate selection often being dependent on systems issues and manufacturing preferences.

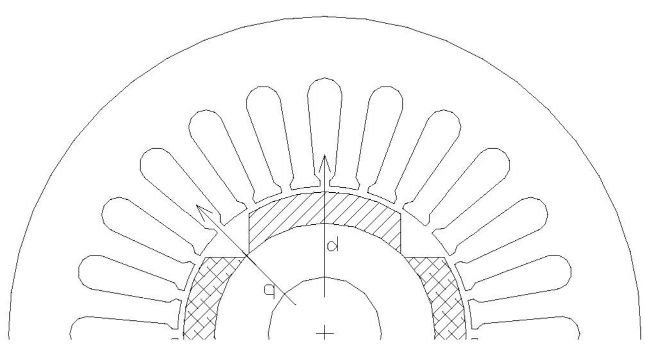

Fig. 2 Surface PM Motor with No Rotor Saliency

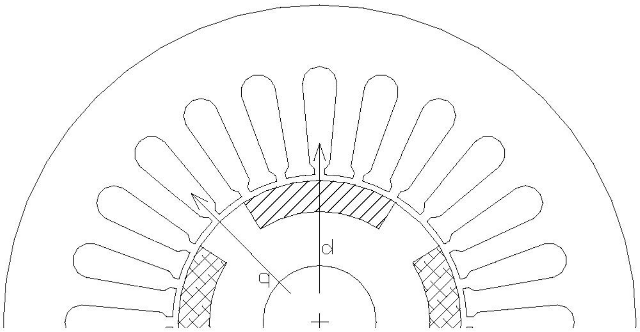

Fig. 3 Surface PM Motor with Teeth Between Magnets to Create Rotor Saliency

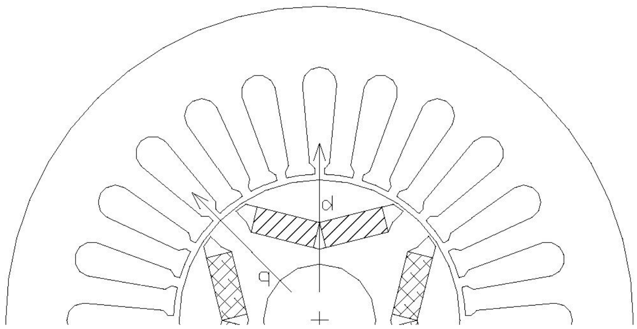

Fig. 4 Interior PM Motor with Rotor Saliency via a Single Flux Barrier

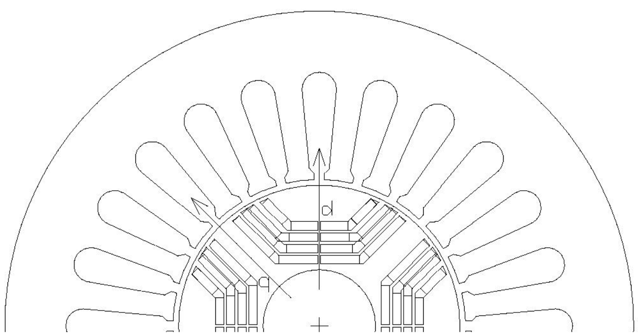

Fig. 5 Interior PM Motor with Multiple Flux Barrier Rotor Saliency

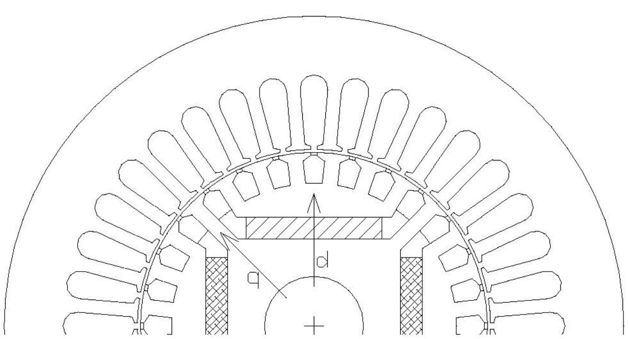

Fig. 6 Interior PM Motor with Rotor Saliency via a Single Flux Barrier – and a Squirrel Cage Winding for Line Starting

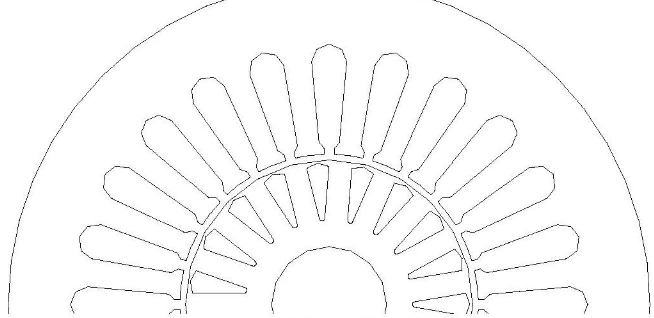

Fig. 7 Induction Motor

In Fig. 2 the rotor can be seen to have magnets on the outer surface of the rotor. Inboard of the magnets is a rotor magnetic structure that has circumferential symmetry. Due to this symmetry, this rotor can be said to have no saliency – meaning there is no preferred / easy direction of magnetization. All motor torque is produced due to the interaction of stator current with magnet flux.

In contrast to Fig. 2, it can be seen in Fig. 3 that while the magnets are still located at the rotor outer diameter (OD), the “teeth” which are in between each adjacent magnet create a circumferential dissymmetry or saliency. This saliency allows this motor to produce a torque component (reluctance torque) due to the same mechanism as employed in a synchronous reluctance motor. Also due to the rotor saliency, the inductance of the stator has a different value as aligned with the rotor quadrature (q) axis, compared to that of the direct (d) axis. The ratio of the q-axis inductance (L_q) to the d-axis inductance (L_d) is called the saliency ratio and is one figure of merit for salient rotor PM machines. It can be especially important for applications with operation above base speed.

With the rotor construction seen in Fig. 4, the magnets have been placed in the interior of the rotor magnetic structure. This again results in rotor saliency and a ratio of L_q to L_d that is greater than one. This configuration also provides the opportunity to use simple rectangular block magnets, which would be lower cost than the arc segment magnets seen in Figs. 2, 3. The rotor assembly process is also simplified.

The rotor of Fig. 5 takes the single layer, single flux barrier, interior PM design of Fig. 4 and extends it to multiple layers. Doing so can provide a means to create higher saliency ratios than the single layer design. However, if constructed from magnet blocks, the rotor assembly can be unusually complex. Another option is to use either compression molded or injection molded magnets for a multilayer assembly such as that shown in Fig. 5.

Fig. 6 shows another single layer interior PM design, but this time with a squirrel cage rotor winding built into the rotor. This provides a means to do a full frequency line start of this type of motor, allowing it to be run across the line, rather than just on inverter power.

Finally, Fig. 7 shows an induction motor cross section. The rotor does not have a specific direct and quadrature axis that is fixed relative to the rotor. Rather, the flux actually rotates at slip frequency within the rotor. If one were to consider a specific instant in time, there would not be substantial saliency in this rotor. There are rotor constructions with a combination of saliency and a squirrel cage (synchronous reluctance motors), but those are not considered here.

C. Permanent Magnet Motor System Implications

An obvious difference between PM motors and induction occurs in that the magnetic field is always present for the PM machine, while an induction motor field will reduce (over time, when the motor is unpowered) to a small residual level. This has implications for any potential overhauling loads that the motor might be coupled to. If the motor was disconnected from the line, there could still be a substantial voltage at the motor leads if such an overhauling load caused rotation of the motor. Depending on the speed of rotation, it is possible to have a hazardous level of voltage present on an "electrically unconnected" motor. This could require special maintenance procedures in order to provide worker safety. This is no different than the case for dc brush type PM motors, or motion control PM brushless motors. However, the industry utilizing PM machines needs to be familiar with these characteristics.

When running a motor across a range of speeds, the transition from below base speed to above base speed requires a transition from constant flux to "field weakening." Motors operated strictly below base speed do not go through this transition. The dc shunt wound motor does this transition explicitly, with the field current being reduced in order to allow the speed to increase above base speed. In an induction motor run on adjustable frequency, the transition is a matter of the Volts per Hertz ratio (V/Hz) changing from a fixed value to a decreasing level.

For PM motors, the excitation from the magnets is constant, so "field weakening" is less of a natural phenomenon. Due to the constant magnet excitation, the PM motor has an open-circuit internally "generated voltage" that is a linear function of speed throughout the entire operating range.

$$E = \frac{p}{2} \times \Omega_r \times \Lambda_{pm} \qquad (1)$$

where,
E = peak phase voltage
p = number of poles
Ω_r = rotor rotational frequency in radians/sec
Λ_{pm} = magnet flux linkage in Webers

As a result of the constant magnet flux, operation of the PM motor above base speed requires that the stator current has a phase relationship to the rotor position that allows it to reduce the air gap flux. This can be thought of as having negative current in the d-axis. With PM motors that have no rotor saliency (Fig. 2) the stator current would be strictly in the q-axis for below base speed operation. As the motor speed moves beyond the base speed, in order to keep constant terminal voltage, there is a need to provide negative d-axis current – effectively "field weakening" the air gap flux. The higher above base speed the motor is run, to more negative d-axis current is required to counter the magnet flux. As a result, the total stator current (vector sum of the d-axis and the q-axis components) increases without a commensurate increase in output power. Eventually, the negative d-axis current is too high to sustain, which determines the maximum above base speed operation.

As opposed to the non-salient design, a salient pole type of PM motor (Figs. 3 – 6) does not derive all of its torque from the magnet flux. Instead, it achieves a portion of its torque via magnetic reluctance, similar to that for a synchronous reluctance motor. One advantage of developing torque via both magnet flux and rotor saliency is that there is less negative d-axis current needed to counter the magnet flux at high speeds. The additional design freedom to proportion the relative torque contributions of rotor saliency and magnets generally allows salient pole PM motors to be designed for greater operation above base speed.

Another "system level" issue for PM machines is related to this operation above base speed. While the inverter can control the stator currents to "weaken" the magnet flux via negative d-axis current, there is an issue which occurs if the inverter were to shut down while operating above base speed. In such a case, the motor terminal voltage would rise to the full value predicted by equation (1). While running above base speed, the motor terminal (line-line) voltage would have a peak value that exceeds the rated inverter dc bus voltage. The freewheeling diodes of the inverter output stage would then form an uncontrolled diode rectifier connecting the PM motor to the dc bus. The high motor terminal voltage would be rectified and deliver power onto the dc bus – resulting in a rapid rise in the dc bus voltage level. A scope trace showing this effect is seen in Fig. 8, where the bus voltage rose from 618 Vdc to 796 Vdc, with about half of that rise occurring in 10 milliseconds. For this system, the 796 V level was acceptable, but an inverter trip at higher speeds could have damaged the inverter components.

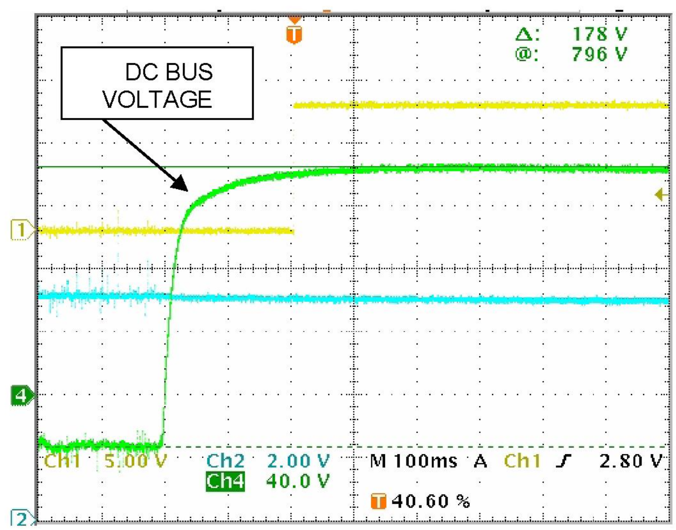

Fig. 8 – DC Bus Voltage Increase Due To Inverter Trip While at 7200 RPM on a 5000 RPM Base Speed PM Motor
Trace 4: DC Bus Volts, 40 V/Div

Another advantage that salient-pole PM motors offer compared to non-salient designs is the opportunity for "self-sensing" of rotor position. This can allow a high bandwidth speed and torque performance without the need for a speed or position sensing device such as an encoder or resolver. By taking advantage of the fact that the stator winding inductance can be quite different in the d and q-axes, the salient-pole PM motor can essentially provide its own rotor position feedback information.

III. COMPARATIVE PERFORMANCE INDUCTION / PM

It can be seen in Figs. 9 and 10 that PM motors provide an opportunity to extend efficiency to a level beyond that defined by EPACT as well as NEMA Premium®. In addition to the improved efficiency at rated load seen for the PM motors in Fig. 9, there are also advantages in regard to more lightly loaded efficiency (Fig. 10(a)). Due to the reduced no load current as a result of the magnets providing the required flux, the PM motor efficiency stays quite high even at fairly light loads. This same feature of having the flux provided by permanent magnets also provides very high power factor, especially noticeable at light loads (Fig. 10(b)).

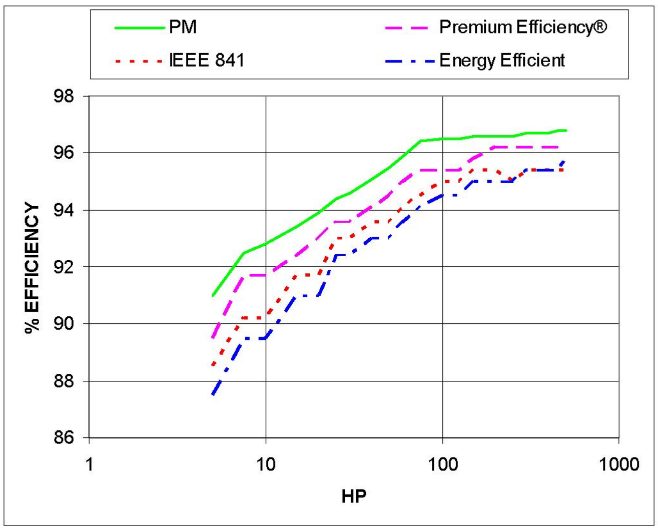

Fig. 9 – Efficiencies of Low Voltage, TEFC, 1800 RPM Induction and PM Motors

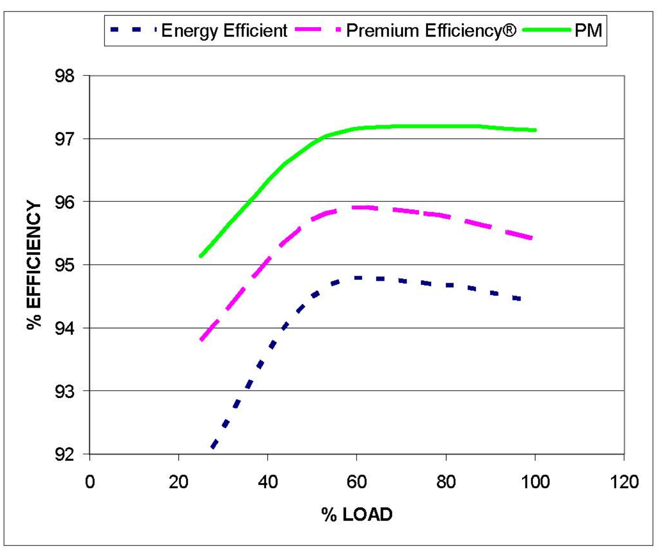

Fig. 10(a) – Typical Partial Load Efficiencies of 75 HP, TEFC, 1800 RPM Induction and PM Motors

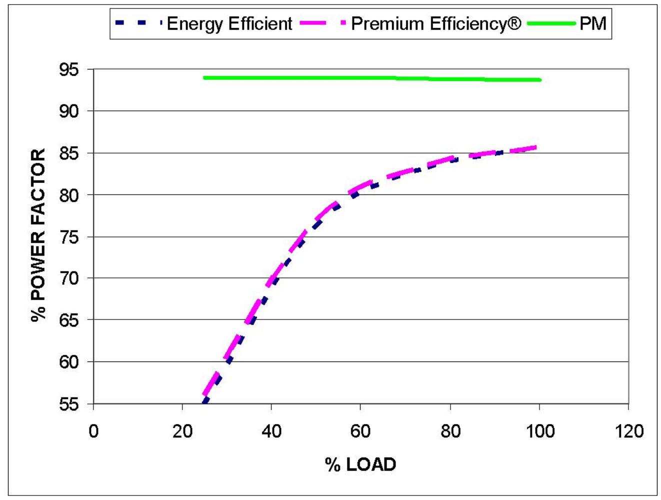

Fig. 10(b) – Typical Partial Load Power Factors of 75 HP, TEFC, 1800 RPM Induction and PM Motors

IV. COMPARATIVE TEST DATA

The motor used for the comparative testing of induction and PM rotors is a laminated frame NEMA 250 shaft height, Totally Enclosed Fan Cooled (TEFC) motor. It should be noted that the motor is not a standard NEMA cast iron frame motor, but is manufactured for a wide range of variable speed applications. A picture of the surface PM test motor can be found in Fig. 11. It is interesting to note that the DC load motor that it is coupled to is both larger in size and has to be internally ventilated to achieve the same rating as the TEFC PM motor.

The rating chosen for the test was 75 horsepower at 1800 RPM base speed. Three motors were manufactured using identical stator laminations and core lengths for this testing. Every effort was made to minimize the variations in cooling while optimizing the performance of each motor. Since these motors were design for variable speed operation all test data are with the motors powered by a PWM inverter. After the testing of the surface PM motor resulted in a large gain in efficiency, it was decided to test the salient pole PM design at a yet higher torque rating – corresponding to the torque of a 100 HP motor. The following sections will present the result of each motor and a summary to compare the overall results.

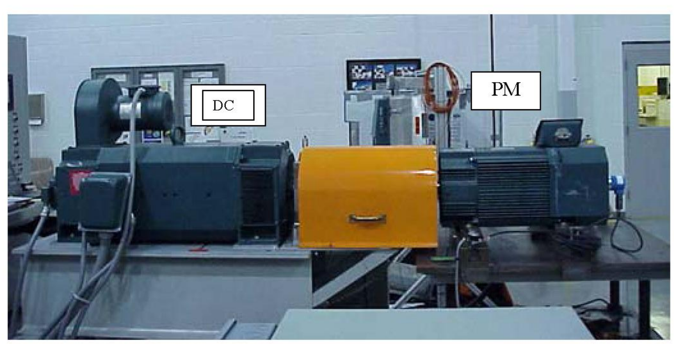

Fig. 11 – 75 HP, TEFC PM Motor (on right) – Coupled to DC Load Motor

A. Induction Motor Test Data

The first test is for an induction motor with a cast aluminum rotor. In order to minimize material variations the motor rating was increased to 75 horsepower. Typically, this motor would be rated at 60 horsepower. Since the insulation system of this motor is Class H (180ºC) the motor is capable of operation with a Class H temperature rise (125ºC).

The frame size of the motor is FL2586 which is a NEMA 250 frame shaft height and is not designed to conform to the NEMA rating per frame size table. A 250 frame NEMA, TEFC motor would have a maximum of 20 horsepower in this frame. The induction motor was wound as a 4 pole motor with a 60 hertz base frequency. The motor was dynamometer tested on a 100 HP, DC dynamometer per IEEE 112 method B. The test results for this motor on PWM inverter power can be found in Table I.

TABLE I

Induction Motor Performance Data	
Horsepower (heat run)	**75.5 Hp**
Volts	**459 v**
Base frequency	**60 Hz**
Full load amps	**92.3 a**
Full load speed	**1768 rpm**
Full load efficiency	**93.6%**
Full load power factor	**82.0%**
Full load torque	**224 lb-ft**
Total motor losses	**3.88 kW**
Temperature rise by resistance	**111.5ºC**

B. Surface PM Motor Test Data

The second motor to be tested was the surface PM motor. The motor rating was identical to the induction motor with the exception that the base frequency was 120 Hz. The decision was made in the development process to wind this motor as an 8 pole motor. The surface PM 8 pole design had both performance and cost advantages over a surface PM 4 pole design. The stator lamination is identical to the induction motor lamination and because of the 48 slot design it could also be wound for an 8 pole surface PM stator.

The stator core length, fan, fan cover, and end shields are identical to the induction motor. The motor was also operated on a PWM drive with different software for the PM motor. As with the induction motor the rating was 75 HP at 1800 RPM. A picture of the surface PM rotor can be found in Fig. 12.

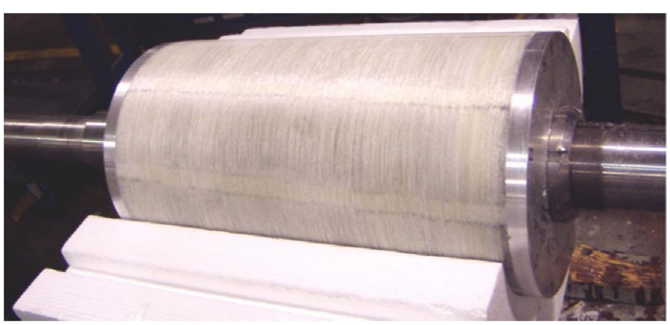

Fig. 12 – Surface PM Rotor

The surface PM motor was load tested per IEEE 112 method B (as modified for an inverter-fed PM motor) on the same 100 HP DC dynamometer. The test results on PWM inverter power can be found in Table II.

TABLE II

Surface PM Motor Performance Data	
Horsepower (heat run)	**75.4 Hp**
Volts	**405 v**
Base frequency	**120 Hz**
Full load amps	**85 a**
Full load speed	**1800 rpm**
Full load efficiency	**96.2%**
Full load power factor	**98.1%**
Full load torque	**220 lb-ft**
Total motor losses	**2.23 kW**
Temperature rise by resistance	**70.7ºC**

C. Salient Pole PM Motor Test Data

The final motor to be tested was a salient-pole PM design. Similar to the induction motor, this motor was designed as a 4 pole motor. The motor used the same stator and winding as the induction motor. The fan, fan cover and brackets were also identical to those used in the induction and surface PM motor. A picture of the salient-pole PM rotor can be found in Fig. 13. Because of reusing the induction motor stator, and also due to the increased torque rating of the test point (300 lb-ft, rather than 220 lb-ft), the operating speed was limited by voltage considerations. The fact that the reduced speed gave less cooling air for this TEFC motor was determined not to be significant for this comparison.

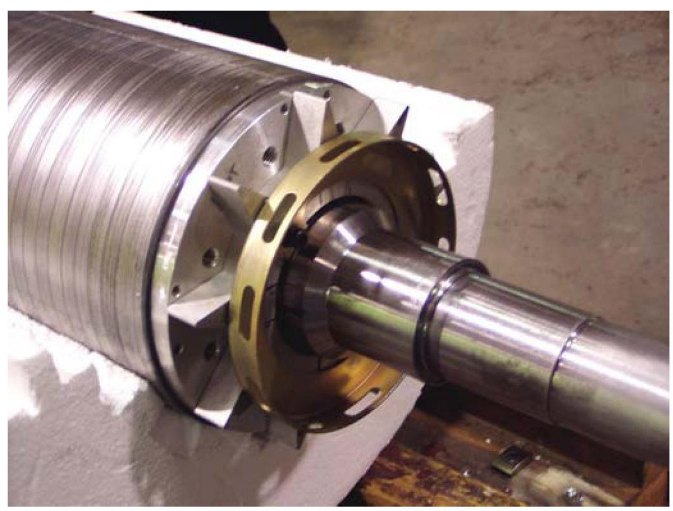

Fig. 13 – Salient Pole PM Rotor

The salient-pole PM motor was also load tested per IEEE 112 method B. Test results on PWM inverter power can be found in Table III. The efficiency data can not be directly compared to the other two designs because of the change in both speed and torque. This test point instead demonstrated the ability to achieve over a 30% torque increase over the induction motor by utilizing the salient pole PM configuration.

TABLE III

Salient Pole PM Motor Performance Data	
Horsepower (heat run)	**68.9**
Volts	**417**
Base frequency	**40.2**
Full load amps	**88**
Full load speed	**1206**
Full load efficiency	**96%**
Full load power factor	**84%**
Full load torque	**300 lb-ft**
Total motor losses	**2.14 kW**
Temperature rise by resistance	**90ºC**

D. Comparison of Test Results

It can immediately be seen that a PM motor can provide a more efficient, higher power factor, cooler running motor for this 75 HP, 1800 RPM rating. As an alternative to simply increasing efficiency and reducing temperature rise, it can also be seen (through the salient pole PM test results) that a substantial rating increase is also possible.

The salient pole PM motor has since been redesigned to achieve operation at the improved power factor range as shown in Fig. 10(b). This redesign also reduced cogging torque by a factor of six compared to the design shown in Table III. While not yet quantified, the PM designs also demonstrated a reduction in audible noise compared to the induction motor.

V. CONCLUSIONS

It is clear that a premium will continue to be placed on energy efficiency in motors. The circumstances around global warming and the availability of future oil supplies only increase the focus on electric motors as key elements in the efficient utilization of energy resources. Permanent magnets offer an important tool in the quest for cost effective ways to further increase motor efficiencies. The characteristics of PM motors are sufficiently distinct from that of induction motors that users need to understand their operation in order to insure successful applications.

While non-salient PM rotor construction provides high efficiency and high torque density, salient-pole construction offers some distinct advantages – especially in regard to “system issues.” These system issues include the ability to sense rotor position without an external encoder or resolver. The ability to operate in a constant power mode above base speed without a danger of uncontrolled generation is another advantage to the system when using a PM design with rotor saliency.

Full flexibility to utilize other than 50 or 60 Hz base frequencies to further optimize performance obviously requires application with an inverter. Once the decision is made to use an inverter, however, the variable frequency “degree of freedom” in regard to pole selection works in the favor of the PM motor design.

The improving performance to cost relationship of permanent magnet materials is getting to the point where the increased power density of the PM motor can be large enough to offset the cost of the magnets. While the authors would not suggest that PM motors are going to supplant the widespread usage of induction motors, the PM motors provide an interesting alternative, especially in the case where an inverter is to be utilized in the application. It is for those inverter-fed applications that the first substantial usage is expected in the petrochemical industry.

VI. RECOMMENDATIONS

At this time it would be prudent for NEMA and IEEE (including PCIC) Standards (and Application Guides) to be revised to reflect the application of PM motors. Areas for revision may include starting performance, plus integrated behavior with adjustable frequency controls. Standards and Application Guides which should be evaluated for revision to provide PM machine considerations include NEMA MG1, IEEE 841, and IEEE 1349. Application guidelines for the use of machines without any slip would also be another area to consider.

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VIII. VITA

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