DESIGN, MANUFACTURE, AND TESTING OF A HIGH SPEED 10MW PERMANENT MAGNET MOTOR AND DISCUSSION OF POTENTIAL APPLICATIONS

by

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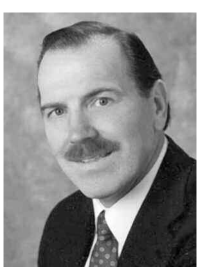

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ABSTRACT

The paper will present the design, manufacturing, and testing of a high speed 10 MW permanent magnet motor and discussion of potential applications. The paper will cover from concept through design and development to the conclusion of prototype testing. As part of the concept phase, potential applications will be briefly discussed that were used to justify the project. These applications include replacing variable speed gas turbines, steam turbines, and wound field, synchronous, and induction motors, as well as fixed speed electric motor/gear drivers. The mechanical and electrical challenges for high speed, high power permanent magnet motors will be presented along with the engineering developments that met these challenges. The paper will also touch on the various manufacturing and assembly hurdles needed to be overcome to bring the design to fruition. The paper will then present the prototype test data to show the design targets have been met or exceeded. Finally, a discussion on the extension of the prototype design to much higher power at lower speeds and to higher speeds at the same or lower powers will be presented.

INTRODUCTION

Gas and steam turbines are routinely selected to drive industrial compression and other process equipment, and have established well-known performance standards in terms of efficiency, availability, emissions, and power density. Interest in the application of electric motors to these services has increased in recent years, as documented in papers presented in past Texas A&M Turbomachinery Symposia. A key performance shortfall in the implementation of electric motors in such applications is the requirement to drive typical gas compression loads through a speed increasing gear, as traditional motor designs have been limitedin rotating speed to 3600 rpm in applications where the power is provided at 60 Hz and 3000 rpm in areas served by 50 Hz distribution systems. Typical industrial compression equipment operates at speeds significantly higher, necessitating the use of a speed increasing gear.

Permanent magnet (PM) motors cannot be powered directly "across the line" using a fixed frequency power source such as the local power grid. Specific controls are needed to match the power being supplied to the motor, the motor's response, and the load to ensure stable operation. These controls are readily implemented in variable frequency drives (VFDs). The required use of VFDs imposes a cost premium; however, it also eliminates the input power frequency limitation of 50 Hz or 60 Hz. The effect of enabling increased input power frequency is to enable a wider range of electromagnetic configurations. Some of these new choices can be exploited to enable improved rotordynamic performance and to increase the direct drive speed range of PM motors.

PM motors can also be designed to provide a wide operating speed and load range with extremely high motor efficiency, typically in excess of 90 percent from less than 50 percent speed driving a typical pump or compressor load to a peak range in excess of 97 percent for high speed applications. For the purpose of this paper, high speed is defined at rotor peripheral speeds in excess of 180 meters per second (m/s).

The focus of this paper is a flexible permanent magnet machine design, capable of achieving operating rotor peripheral speeds of up to 250 m/s that is axially scaleable from a low power rating of approximately 4 MW to a high of approximately 32 MW. The design was prototyped and tested at a design power rating of 10 MW, running at 6225 rpm. Basic features of the initial design objectives were to use a totally enclosed, water to air cooling (TEWAC) system typical of the petrochemical/industrial motor applications, a Class H rated insulation system with a Class F design temperature rise limit, and voltage range, depending on rating, from 4160 volts to 5500 volts maximum. The actual performance achieved was a power rating in excess of 11 MW.

STATOR DESIGN AND DEVELOPMENT

The basic electromagnetic design was highly dependent on the structural and rotordynamics analyses performed on the rotor to determine the lowest practical pole count that could be achieved at the 250 m/s peripheral speed. This value was determined to be eight poles, which, at 6225 rpm, corresponds to a fundamental operating frequency of 415 Hz. A basic departure from higher power rated machinery, which has historically been limited to 60 Hz or lower at power levels of greater than several MW, this fundamental frequency increase imposed specific material and manufacturing method challenges. Chief among them were the selection of litz wire for the stator core conductors, and relatively thin stator laminations that were specially processed to ensure no burrs remained from the punching process. The litz wire was needed to reduce the losses from skin effects due to the higher fundamental operating frequency, and the thinner lamination steel, and processing, were selected to reduce eddy current losses in the stator core.

The bulk of the electromagnetic design was conducted using traditional, empirically validated electric motor design methods. These methods were supplemented with detailed electromagnetic finite element analyses (EM FEA) where necessary, and, to develop a soon to be empirically validated EM FEA model of the basic geometry that could be used for other rotor diameter and axial length versions of this basic design.

Loss predictions were made using several numerical methods, which were calibrated using data from other machines and specific supplemental test data where needed. A thermal model of the stator geometry and materials was built using internally developed modeling tools. Computational fluid dynamics (CFD) analysis methods were used, employing the same geometry from the thermal model, to predict cooling air distribution in the machine, which was then coupled to the thermal model to predict the stator and rotor temperatures under steady-state and transients.

A fundamental difference from other electric motor types, a PM motor can be designed to have essentially negligible rotor losses, eliminating it as a heat source requiring a specific means for cooling. Consequently, in the subject design, no specific rotor cooling provisions, other than a fixed rate of flushing the air from the air gap, were found necessary.

To validate these computer modeling efforts, and reduce the risk of their application to extended versions of the prototype machine, it was originally intended to install flow measuring devices in strategic locations as well as 114 resistance temperature detectors (RTDs) to completely map the core and end turn temperature profile while also recording air flow. The high magnetic flux levels and frequency, combined with high velocity air flow made the air flow measurement goal impractical. As a result, only the detailed core temperature profile was available to validate the stator and rotor thermal performance predictions. Figure 1 shows the predicted rotor temperature profile, which ranges from a high of 150ºC (302ºF) at the center to nearly 70ºC (158ºF) at the ends. A similar temperature range was predicted for the stator, with the high approaching 170ºC (338ºF) the center. These values were within the rotor magnet temperature limit and the stator insulation system material design limits, so the design was approved for manufacture.

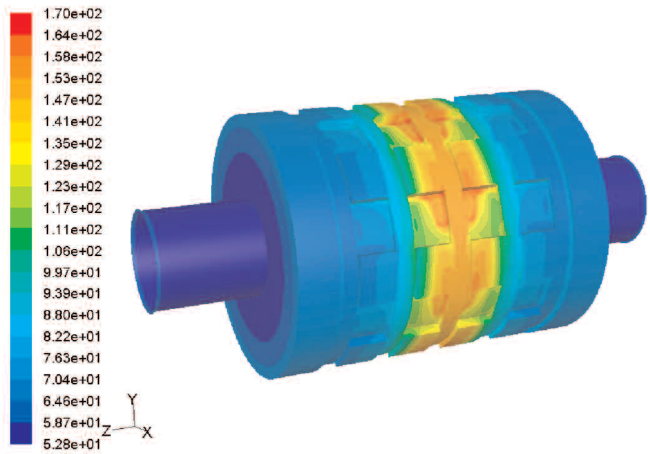

Figure 1. Predicted Rotor Temperature Profile from Thermal Model.

ROTOR DESIGN AND DEVELOPMENT

The biggest distinction between induction or synchronous electric motors and a permanent magnet motor is the rotor design. The stators for all these machines are basically the same in design, material selections, and manufacturing. The PM machine rotor carries permanent magnets while all other motor types use electricity running in loops on the rotor to develop the rotor magnetic field. This key distinction is one of the features of a PM machine that can be exploited to enable motor configurations that are not practical using other motor technologies.

Until now permanent magnet motor applications have been generally limited to low power (<500 kW, most under 100 kW), high speed service. Recently additional industrial application in low speed, high torque services have been proposed. Most of these existing PM motors use surface mounted permanent magnets, meaning the magnets are placed on the rotor, which is ferromagnetic material (steel) with their direction of magnetization aligned radially on the shaft. This is one of two design approaches used to attach magnets to rotors. The surface mounted magnets mostly use an adhesive to attach the magnets to the surface and a high strength fiber wrap around the outside of the magnets to keep them in place. This restraining membrane is typically either a high strength nickel based alloy (low conductivity and very thin to reduce eddy current heating) or a composite material (carbon fiber, for example). The second method to attach magnets to a rotor is called an embedded design. Here the magnets are held to the shaft by some mechanical arrangement. Prior methods of embedding magnets typically relied on the pole pieces, which limits speed and can restrict the magnet circuit so that the full benefit of the magnets is not realized.

The goal of the project described in this paper was to develop a design that addresses the limitations of prior art and significantly extends the speed-power capability of permanent magnet motors. The project would encompass a line of motors that extend from 5 MW to 120 MW and 3000 rpm to 15,000 rpm. The first frame size to be developed, with a mid-sized rotor diameter of 27 inches, is designated Cypress and covers up to 32 MW and 6200 rpm. The prototype selected to prove-out the Cypress frame size design, and the basic electromagnetic, structural, mechanical, and thermal approach to be used for the other larger and smaller frame sizes, were chosen to be a 10 MW, 6200 rpm, machine. The Cypress frame is currently being extended to 7000 rpm in Phase II of product development. The following presents the design, development, and manufacture of the prototype rotor goals.

Because of the inherent rotor heating and structural challenges of a surface mounted magnet design, it was decided to pursue an embedded magnet design. The design was also required to overcome the shortcomings of prior embedded designs. This dictated no bolted pieces holding the magnets, no nonmagnetic parts in the magnetic circuit, and no magnetic materials outside the magnetic circuit that could short circuit the flux path. Also parts outside the magnetic circuit needed to have low electrical conductivity to minimize eddy current heating.

The major steps in the development of this high speed, high power rotor design were:

- Select speed, maximum power, and dimensions for initial frame size design
- Select materials and test to optimize properties
- Preliminary design to perform mechanical and EM FEAs and conduct mechanical tests to validate predictions
- Finalize prototype design and release for build
- Manufacture and test prototype unit
- Optimize final design and release for production

Initial Size and Speed Selection

The initial rotor size was based on applications currently using midsize gas turbines. These type applications have speeds up to 6200 rpm and power requirements up to 32 MW. The initial electromagnetic design goal was to attain a given shear stress in the air gap. Criteria also required a minimum number of poles to minimize stator losses. The same electromagnetic analysis determined the preliminary magnet size. After several mechanical design iterations, the stage length and diameter of the rotor were chosen to meet these criteria. The mechanical analysis included building and exercising mechanical FEA and rotordynamics models. The preliminary FEA showed the initial frame size rotor diameter limits the minimum number of poles to eight.

Materials

Having sized the rotor, the next step was to specify the materials for each part that meet the electromagnetic and mechanical requirements for the design. Because of the nature of the application the materials used had to have specific mechanical and electromagnetic properties. The material requirements and selections for each part of the rotor are as follows:

- *Shaft*—Because the main shaft body carried the load of the rotating parts as well as being the means of transmitting torque, it had to have unusually high tensile and yield strengths, supplemented by unusually good fracture mechanics features, such as elongation and brittle fracture resistance. Because it was in close proximity to the magnets, it also had to be nonmagnetic to prevent short-circuiting the magnetic flux path. These restrictions limited materials to some combination of nickel, cobalt, titanium, chromium, and other nonferrous materials. To limit costs it was decided to use shrunk-on AISI 4340 steel for the stub shafts since those areas did not need to be nonmagnetic.

- *Laminations*—Laminations are materials of high magnetic permeability that are placed in a magnet circuit to ìurgeî the majority of the flux from the magnets to follow the design magnetic circuit. The laminations are made up of thin sheets of the selected material and joined together by bonding or other means to form the required size lamination. Laminating is required in electrical devices to minimize the heat generating effects of eddy currents. Typical electric motor laminations are made from silicon-iron, which give excellent magnetic properties. The mechanical strength, however, is too low to be used for the rotating laminations on this project. An iron-cobalt lamination material was chosen because it has high strength along with the required electromagnetic properties.

- *Magnet carriers*—Because of the inherent low strength of the magnet material, a special holder is needed to support the magnet and transfer the magnet's load to the shaft. The required material not only needs to be nonmagnetic but also have high electrical resistivity to minimize eddy current heating of the parts. The magnet holders also need to have high strength to weight ratio to support the magnets while minimizing adding additional load to the shaft. The selection was a titanium alloy that fit these criteria.

- *Magnets*—Rare earth magnets are the magnets of choice for permanent magnet motors. The two rare earth magnet materials available are samarium cobalt and neodymium iron boron. For this application neodymium iron boron (NdFeB, or NIB) was chosen due to its better magnetic and mechanical properties. NIB magnets offer the largest energy product of any magnetic material available below 200ºC (392ºF). Energy product is the field intensity (H) of the magnet times the flux density (B) of the magnet. H is measured in oersteds and is analogous to voltage in an electric circuit. B is measured in gauss and is analogous to current in an electric circuit. The product of the B*H is given in megagaussoersteds (MGOe). The magnets are made by compressing and sintering a powdered mixture Nd, Fe, and B. The downside of compacting and sintering rare earth powders is that the magnets are mechanically weak, especially in tension. This challenges the design of the magnet carriers to support the magnets in such a way as to ensure the magnet stresses are mainly in compression, with as little bending or tension as possible.

Design

The design goals for the first frame size to be developed were determined by looking at the most common driver power and speed for the market this PM motor is intended. Based on that study the following goals were established for the rotor design:

- Maximum continuous speed: 6200 rpm
- Minimum per stage power of 1.7 MW
- Maximum number of stages per motor to be at least 17
- Meet at least the following criteria:
  - 20 percent overspeed capability (NEMA MG 1, 1993)
  - Minimum of 5000 starts/stops (API 546, 1997)

Initial Design

The initial eight pole design is shown in Figure 2. The initial design consists of a vertically split titanium ring that captures the magnets beneath the bridge connecting the two rings and it straddles the laminations. The first choice to make in designing the motor was the number of poles. Since the number of poles is directly proportional to frequency for a given speed, the goal was to restrict the number of poles to limit the operating frequency of the motor to under 500 Hz. Preliminary FEA work showed for the rotor diameter, carrier/magnet, and lamination sizes, and speed chosen for the design a minimum of eight poles was required. Eight poles running at 6200 rpm require a frequency of 413 Hz. Figure 3 shows the increase in normalized stress as the number of poles is decreased. The initial magnet size was a first pass estimate by the electromagnetic designer. To expedite the project, project leaders decided at the beginning to do the electromagnetic and rotor mechanical design work concurrently as much as possible.

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The decision meant the rotor mechanical design would forge ahead based on the initial magnet size estimate. The plan for the mechanical design was to complete detail development work including FEA and build a single-stage rotor to perform straingauged spin tests including spinning to destruction. The design was completed, the single-stage rotor built, and the mechanical tests completed. A picture of the single-stage spin rotor is shown in Figure 4.

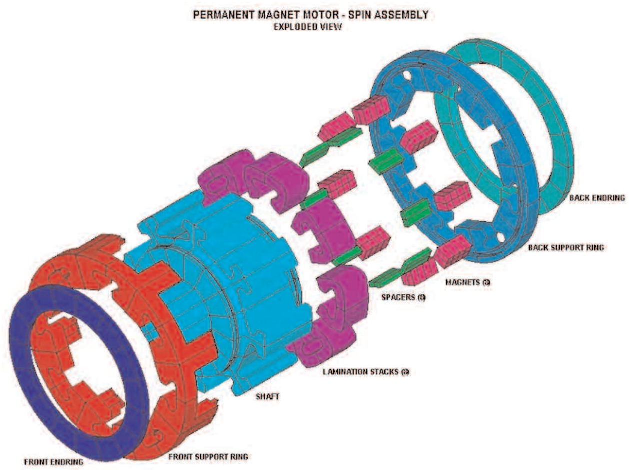

Figure 2. Exploded View of Initial Design.

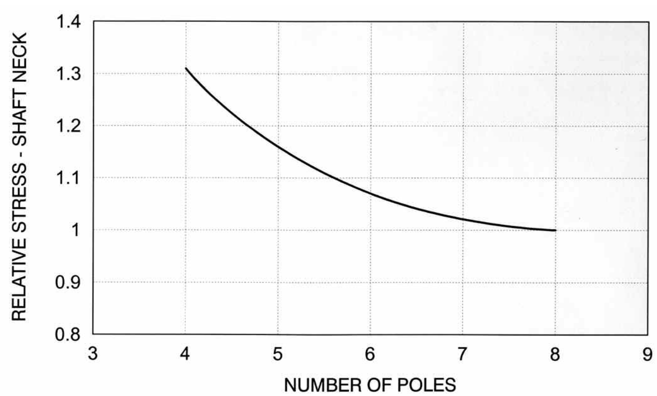

Figure 3. Normalized Shaft Stress Versus Number of Poles.

Figure 4. Single-Stage Spin Rotor.

Final Design

The FEA work supported by the spin test showed the initial design was marginal for overspeed capability. At the same time the rotor spin test was being performed, the electromagnetic FEA was completed and showed the magnets had to be considerably larger to attain the goal of 1.7 MW/stage. The rotor design was changed, moved the highest stresses from the ring to the shaft, and enabled the design to work with the larger magnets and have a comfortable margin of safety. The individual carrier design is shown in Figure 5.

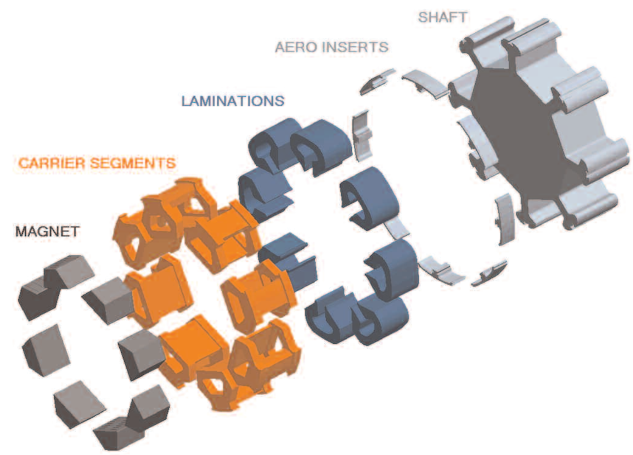

Figure 5. Final Desgn Exploded View.

Prototype Rotor Manufacture

Having finalized the electromagnetic and mechanical aspects of the rotor design, work began on building a 10 MW prototype motor to test. The most unique, and therefore significant, challenge imposed in building the prototype rotor was handling the magnets during the rotor assembly. The magnets were large and powerful requiring care and safety at every point in the process.

Special magnet handling techniques, fixtures, and procedures had to be devised. It was decided early that the magnetic flux would be contained at every step in the process of rotor assembly after the magnets were initially magnetized. This required the magnet carriers along with necessary clamps be sent to the magnet vendor.

The assembly fixture was designed to capture the magnets before the clamps were removed, and steel shunts were installed to reduce the magnitude of the flux field as the magnets approached and were installed into the slots in the shaft. The laminations were slowly lowered into place between the magnets using a hydraulic cylinder to prevent impact damage with the magnets. The complete ring assembly was then pushed axially onto the shaft using a specially designed sizing fixture. A picture of the prototype assembly is shown in Figure 6.

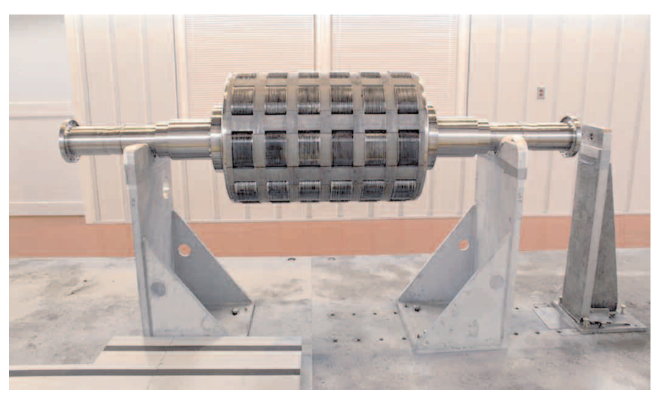

Figure 6. Prototype Rotor Assembly.

TESTING

Mechanical

The first mechanical test of the project was a straingauged spin test of the initial design. As discussed above, it was found before the test that the design would need to change. As with any FEA, the quality of the results is directly proportional to the accuracy of the model. Since the PM rotor model was an assembly of different materials, it was decided to go ahead with the spin test to correlate the FEA work with the straingauge data. The results of the tests showed an excellent correlation between FEA and straingauge data as shown by two typical gauges plotted against the FEA prediction in Figure 7.

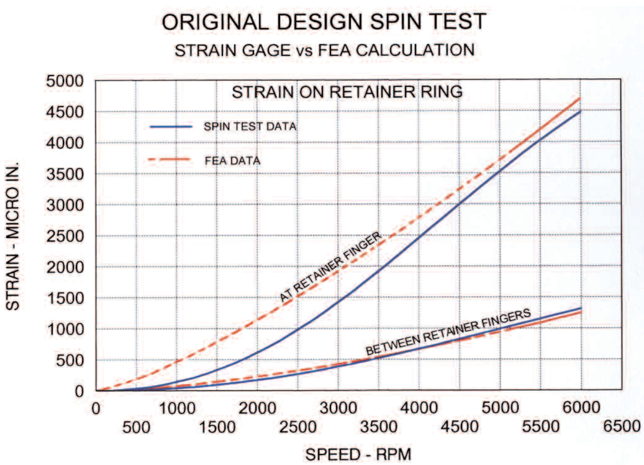

Figure 7. Results of Single-Stage Spin Test.

The rotordynamic analysis correlated very well with the actual results of the six-stage prototype motor test. Figure 8 shows the predicted first unbalance response and Figure 9 the actual rotor vibration results. The actual vibration level was much lower than the API requirement of a maximum of 1.4 mils at 6200 rpm. This was a result of the rigorous balance criteria applied to the rotor. Because the prototype design did not allow for center plane balancing, the shaft was balanced at speed prior to assembly. This allowed for both static and dynamic corrections at the end and midplanes. The carrier/magnet assemblies and laminations were moment weighed. A special computer program was developed to pair up carrier and lamination assemblies and locate them on the shaft to give the minimum residual static and dynamic unbalances. The complete assembly was then balanced at speed with minor corrections on the end planes. A center plane balance will be incorporated into the production version of the motor.

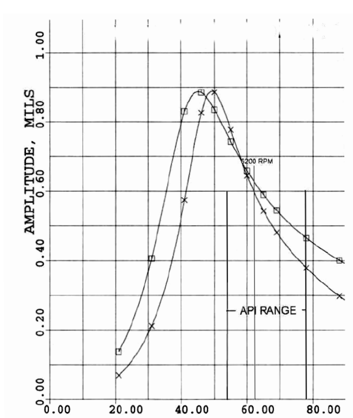

Figure 8. Rotordynamic Analysis of Prototype Rotor.

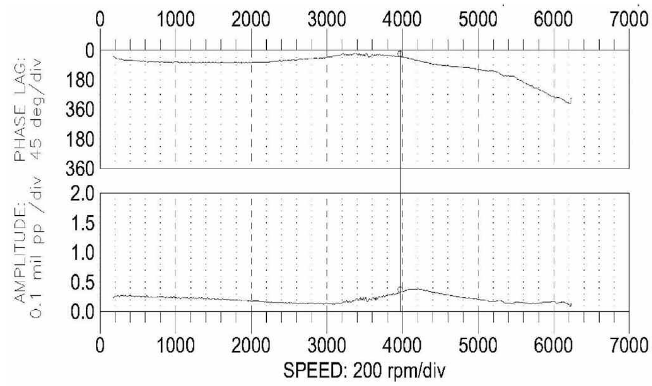

Figure 9. Prototype Rotor Vibration Probe Data.

Initial phases of the motor test program involved essentially routine electrical tests to establish the machine's initial conditions and compare them to the design predictions. A test spinning the motor to operating speed and recording the terminal voltage readings was the first, most significant test. The design voltage of 4160 VAC was slightly low, as the readings at typical room temperature were approximately 4100 volts. This, along with resistance and inductance readings confirmed the basic electromagnetic design had been reproduced in real materials.

The program budgets prevented a long term loaded test program at 10 MW using a conventional load, such as a water brake or compressor load. Consequently the prototype machine was wound as two independent three-phase machines, with the second three-phase winding offset to allow the machine to be run as a six-phase motor or generator, or allow the machine to be run as a 5 MW motor driving a 5 MW generator in the same electromagnetic envelope. A relatively small, under 500 hp, machine was built to test this concept and verify we could fully load the machine. Figure 10 shows a schematic of the loaded testing set up. Loaded testing was initiated and proved the machine met the design rating of 10 MW with significant margins, with the highest internal stator temperature reading at 152ºC (305.6ºF) at a load of 11.1 MW. This stator temperature corresponds to a predicted maximum rotor temperature of approximately 130ºC (266ºF). Both of these temperatures are well within the thermal limits of the design.

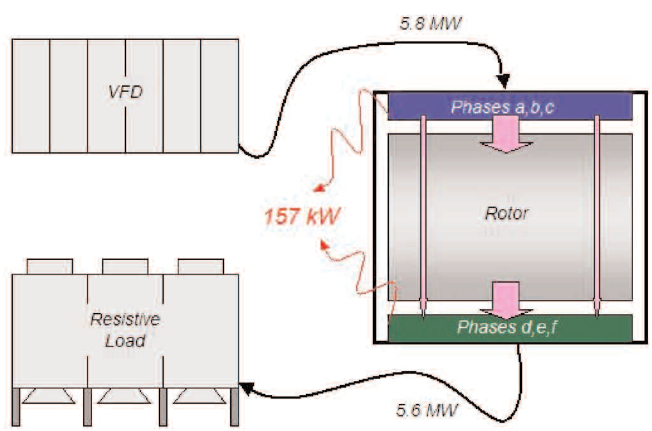

Figure 10. Prototype Test Schemaatic for Loaded Testing.

Once the proof of concept testing was complete, a number of special tests to validate some of the claimed benefits of PM machines were conducted. One such claim, that PM machines are not limited by thermal considerations in restarting when hot, was addressed by simulating a casualty where the cooling fans are disabled, the machine is allowed to operate until the hot spot temperature increases to 105 percent of its starting point, and then the machine is tripped, allowed to coast to a stop under load, left for a few minutes without the fans running, then the fans are turned back on, and moments later the machine is restarted under load. This entire set of transients was recorded using the 114 RTDs embedded in the stator, and the results are provided in Figures 11 through 13.

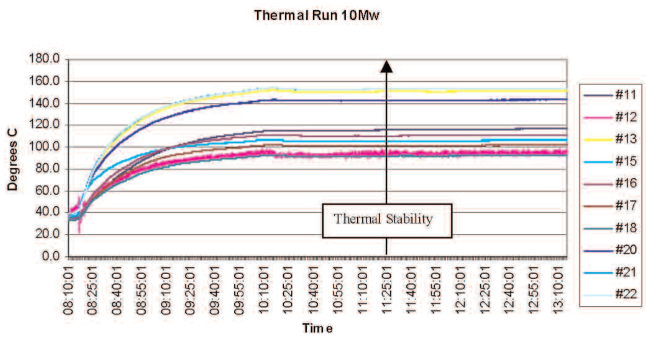

Figure 11. RTD Recording Showing the Highest Stator Temperatures at Thermal Equilibrium.

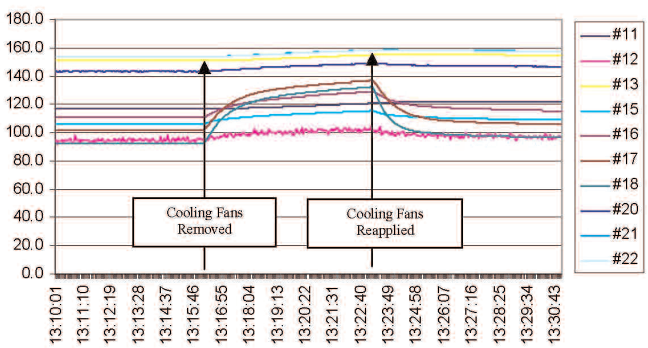

Figure 12. RTD Temperature Measurement Recordings During Extreme Operational Transient with Cooling Fans Shut Off and Motor Operating at Rated Load and Speed (Maximum Temperature Reached was 158.6°C [317.48°F]).

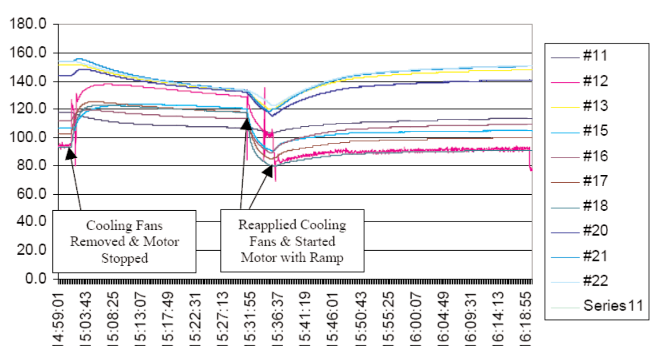

Figure 13. RTD Temperature Measurement Recordings During Simulated Emergency Shut Down with Cooling Fans Shut Off While Operating at Rated Load and Speed Followed by a Restart of the Cooling Fans and the Motor.

The data from the RTDs embedded in the hottest part of the stator, along with some distributed in cooler areas, are presented as Figure 11, as the machine reached and then stayed at thermal equilibrium for a reasonable period of time. Data from the same RTDs are shown in Figure 12, which displays the thermal response of the machine once the transient was initiated by shutting the fans off and leaving the load applied. In Figure 13 the fans are once again turned off with the motor operating at rated load and speed, and then the drive is tripped. The motor comes to a stop without re-energizing the fan motors. After several minutes with motor stopped the fans are turned back on, and then, several minutes later, the motor is restarted under load and ramped up to rated speed and load in 120 seconds. It is operated at rated speed and load until thermal equilibrium is approached.

The highest temperature reached in the machine, 158.6ºC (317.48ºF), occurs, as expected, when the machine is run at rated load and speed without the fans for several minutes (this occurs twice, and the second time the period of operating without the fans was much shorter so the highest temperature reached was somewhat less). In no other period of the transient performance testing did the temperatures even rise above the steady-state thermal equilibrium values. These data show the PM machine is essentially unaffected by a momentary loss of cooling, and can be restarted immediately after a shutdown without any extra thermal stress or imposing a waiting period for the machine to cool off.

CONCLUSION

The overall test results, summarized in Table 1, showed the design met or exceeded all of its design mechanical and electrical performance requirements with substantial margins. While no specific acoustic goals were imposed on the design, the airborne acoustic performance has been shown to be unacceptable “as-is.” This aspect of the design is being evaluated and corrective actions are being implemented for the prototype, which will be tested in June of 2006, and all future designs will be based on the Phase II improved rotor configuration that reduces the source of the noise as well as increases the speed rating from 6225 rpm to 7000 rpm.

Table 1. Summary of Test Results.

Test Parameter	Predicted result	Tested Performance	Performance Relative to Design Goal
Power	10Mw	11.1Mw	**+10%**
Efficiency at Full Speed and Full Load (11.1 MW)	98.5%	98.7%	**Met design goal**
Vibration	.43-.47 mils	.45 mils	**Met design goal**
Mechanical Losses	180kW	135kW	**25% improvement**
Highest Stator Temperature	180 C	152 C	**16% improvement**
Highest Rotor Temperature	150 C	135 C	**10% improvement**
Acoustic Noise	N/A	110dba	**Unsatisfactory**
System Stability at Steady State and in Transients	No hunting	No hunting	**Within design limits**

Based on the testing to date the benefits of PM machines, which range from improved efficiency, reduced size and weight, greater reliability, and available to improved safety and greater adaptability to driven equipment, appear to be significantly closer to becoming commercially available in the power and speed ranges needed for industrial and petrochemical processing.

REFERENCES

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NEMA Standard Publication MG-1, 1993, “Motors and Generators,” National Electrical Manufacturers Association, Washington, D.C.