Towards the Holy Grail? A Novel, Power Dense, Low Noise Permanent Magnet Motor

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Synopsis

High power, high efficiency propulsion equipment with a high shock resilience capability that occupies the minimum volume, with a low weight and a very low noise signature is a "holy grail" of naval propulsion. Significant steps towards this goal have been made in the area of naval electric propulsion in the last 30 years, but it is hard to combine all these features in a single design since some features tend to militate against others. Solutions, therefore, require a balance between the thermal challenges of high power in a low volume and the requirement for shock proof, low signature machines.

A permanent magnet propulsion motor with a patented novel cooling system designed for power density and low structureborne noise is being developed, manufactured and tested as a technology demonstrator. It is part of a programme part funded by InnovateUK under the Optimised Electric System Architecture project in partnership with the University of Nottingham and the University of Warwick. The primary market for the motor is envisaged to be naval and marine research vessels where power density and low noise is important. The motor is low speed and designed for direct mechanical coupling in the shaft line to the propeller and will be suitable for full electric or hybrid propulsion since the design is inherently scalable from relatively low powers up to those required for full electric warship propulsion.

This paper describes the principles of the design and the approaches used to achieve the combination of high power density, high efficiency, high torque and low noise. It describes the thermal management approach and how the thermal behaviour of the different elements of the motor have been modelled. It also shows how advanced modelling techniques, combined with laboratory based and simple, practical testing have been used to develop the design and the manufacturing techniques required by this innovative solution. The paper also describes the testing approach used to validate the machine and its integration into a wider Direct Current or Alternating Current distribution system that could include energy storage elements. Finally, the performance of the motor is discussed along with the probable next stages in its development

Keywords: Propulsion; Marine systems

1. Introduction

Naval electric propulsion motors require a number of features that are rarely combined in other applications. A naval motor is typically high power, to achieve high top speeds. It needs to be small to fit in a hull that must achieve those speeds but must also be efficient enough to enable the vessel to achieve demanding range requirements. It must be capable of withstanding high levels of shock impulse while continuing to operate and may also be required to deliver an extremely low noise and vibration (N&V) signature (Lewis and Salter, 2014). Inevitably some of these features work against others which means that naval propulsion motor design becomes an art of compromise, balancing features in order to achieve the best overall result. The outcome of this

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optimisation may vary depending on the specific application and operational tasking of the platform for which the motor is intended.

2. Background

2.1. The Problem

The fundamental requirements for a naval propulsion motor can be summarised in the following table:

Table 1 Requirements Summary

	HIGH	LOW
1	Power	Volume
2	Efficiency	Weight
3	Shock Capability	N&V Signature

A naval motor is typically required to have high power, efficiency and shock capability while also having a low volume, weight and N&V. As the table hints, there are contradictions inherent in this requirement set. It is hard for a high power motor to have a low volume. The heat generated within a motor is proportional to its rating but its ability to dissipate heat is related to its volume. Thus row 1 indicates that heat management is a key issue for naval machines.

The efficiency of a machine can be improved by reducing the current density in its electric circuit and the flux density in its magnetic circuit. The one requires more copper and the other more iron for a given performance – which would inevitably imply more weight. Thus row 2 of the table suggests that there is a balance between efficiency and weight.

A key factor in the overall N&V signature of a machine is the extent to which the vibrations generated at the back of the stator core are coupled into the structure of the ship[1]. The more flexible the structure between the core and the motor seat, the less vibration energy is transmitted. However, for a solidly mounted, shock-proof machine the structure must be strong enough to withstand the very high accelerations applied during the shock impulse. This implies a very stiff structure for the motor which will efficiently transmit N&V energy to the ship structure as illustrated by the contradiction implied on row 3. If anti-vibration mounts are fitted below the motor feet, these can give rise to very significant movement under shock, which implies the use of a very flexible, high torque flexible couplings which are substantial in size weight and cost. This militates against low volume and weight.

2.2. Advances to Date

One of the key issues in motor design is the management of heat. In low speed propulsion motors. heat is primarily generated in a machine from conduction losses in the stator and rotor windings and magnetic losses in the iron. Once generated this heat must be removed and in most electrical machines this is done by air that is circulated around the active materials. This air is then typically cooled, either via the machine case (for small motors) or by an air/water heat exchanger for larger motors. Cooling improvements that have contributed to current naval motors include reducing the intervals between radial cooling ducts and improving the efficiency of heat transfer within them, increasing the velocity of air within ducts and, in some applications introducing axial ducts in the stator teeth.

Volume reductions have also been achieved. In some designs this has been done by increasing the flux density in the magnetic circuit and thus reducing the amount of iron required. In other designs this has been achieved by introducing permanent magnets into the rotor. This gives high airgap flux and reduces the total heat generated in the machine. However, there are significant operational considerations with the use of permanent magnets in a warship, particularly in a hybrid configuration, that have limited their adoption.

2.3. *The Challenge*

Given the current state of the art, summarised above, what techniques for improving motor characteristics are open to the machine designer, especially for the critical issue of heat? A range of such techniques, and their drawbacks are summarised below in Table 2.

Table 2 Techniques and Drawbacks

	TECHNIQUE	**DRAWBACK**
1	Chilled Air	Condensation, increased dependency
2	High Speed Air	Broadband N&V
3	Superconducting Coils	Immaturity, shock, cryogenic plant
4	Water Jacket Cooling	Lack of scalability
5	Direct Conductor Liquid Cooling	Complex to build and shock-proof
6	Indirect In-Slot Liquid Cooling	Higher current density in coil, end winding cooling
7	In-Tooth Liquid Cooling	Higher flux density in tooth, end winding cooling

It is readily apparent that there is no panacea for this, or any other of the key requirements for a naval motor. Improvement is achieved by novel combinations of approach, carefully balanced to achieve the best compromise between competing imperatives. A new combination has recently been developed that includes novel elements. This approach is described below.

3. The Permanent Magnet (PM) Motor Design Process

Since the commercialisation of voltage source variable speed drives, the induction motor has been the most common choice for electric propulsion in surface ships. In surface warships the GE Advanced Induction Motor, or variants of it, has been a common choice for its high power density, shock-resistance capability and low noise at part load (Lewis 2002). A comparative study was carried out on a number of different propulsion motor topologies compared to a reference induction motor, initially funded by GE and in later stages by the UK Ministry of Defence's Defence Science & Technology Laboratory (DSTL). The reference induction motor used in the comparison had been built and was in service.

3.1. *Motor Topology Selection*

A GE study was carried out evaluating a number of permanent magnet motor topologies. A follow up study in more detail was subsequently carried out, funded by DSTL. The size and mass of a motor is dependent on torque rather than power. Studies were carried out at three torque levels against a reference induction motor design. These were:

Table 3 Torque Levels

Torque (kNm)	**RPM**	**kW**
100	240	2500
191	150	3000
795	90	7500

The power density and efficiency of the surface mount and embedded PM was similar, and superior to the induction motor on both. The embedded PM motor with the magnets, surrounded by resin, embedded in a laminated iron rotor core was considered more shock capable.

3.2. *Embedded Permanent Magnet Design Process*

3.2.1. Cooling Technology

A motor intended for a naval application normally requires a low structureborne noise signature. Air cooled, power-dense motors require high velocity cooling air. This is a significant source noise due to air turbulence. Air-water heat exchangers are also required, which can be bulky. Water-water heat exchangers are more compact.

A novel cooling method was chosen with water circulating through axial passages in the stator teeth. The cooling concept has been patented (Salter, 2016). The embedded permanent magnet design results in very low rotor losses. The rotor and stator end-winding are cooled by low velocity air circulated by a low pressure head fan (~120 Pa). The stator is cooled by passing tap water though axial ducts in the stator teeth, which enters and exits via manifolds at each end of the stator core. This was a development from previous GE air cooled machine designs that had used axial ventilation ducts in the stator teeth. The small amount of heat from the rotor is transferred by the air to the back of the stator core. The stator end-windings are cooled by conduction to the slot portion and by the low velocity cooling air also transferring to the back of the core. Unlike an induction machine, which has significant rotor losses, the losses on the permanent magnet rotor are low, so the main source of heat to be removed by the air is from the outer parts of the stator end-winding. Previous experience with liquid cooled machines had indicated that the cooling noise using this method is extremely low.

Extensive computational fluid dynamics (CFD) modelling was carried out during the feasibility stage. Low velocity (less than 1 m/s) and low pressure (less than 2 bar) water was all that was required. Electromagnetic modelling was also carried out to verify that losses on the water would be very low. Since the water runs axially through the stator teeth it is magnetically coupled to the motor flux and a voltage will be induced along the length of the slot causing current to flow in the water. Tap water typically has a conductivity of 5 S/m, which gave losses in the water of only 35 W. The thermal model is illustrated in Figure 1. This shows sections through stator teeth and a part of the slot (the source of the heat) along the length of the core. The results showed a small temperature gradient from the water inlet end to the outlet and higher temperature at each end where the heat from the endwinding conducted into the slot portion.

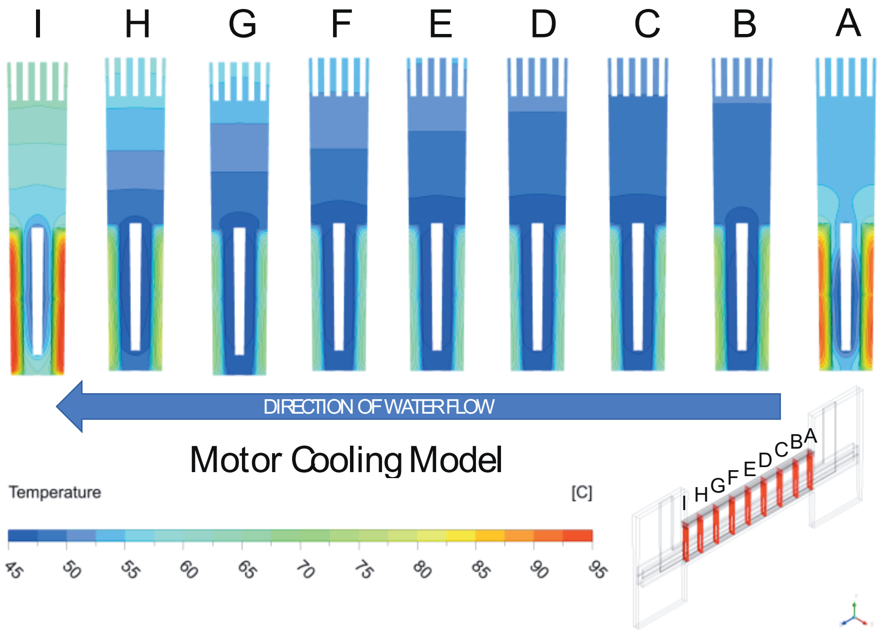

Figure 1 Cooling Model

3.2.2. *Experimental Test Samples*

A number of test samples were made to verify the sealing of the cooling water passages and the connection to the manifolds where the water enters. An example of one of the test sample design is shown in Figure 2. Tests for corrosion from the cooling water were also carried out in the research labs of GE Power and Water. This study evaluated corrosion rates within the cooling circuit, and optimization of the anti-corrosion additives within the freshwater coolant. These additives ensure the build up and maintenance of a thin protective layer between the coolant and the ducts that inhibits further corrosion. The laboratory also examined a “damage recovery” scenario, considering the implications of recovering from trauma to the coolant system. A process for stripping excess corrosion, restoring the protective layer and returning the cooling system to full capability was identified.

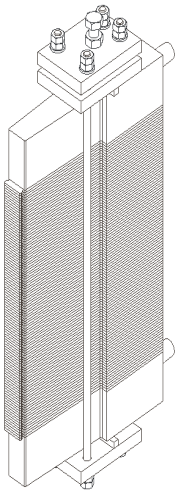

Figure 2 Test Piece

3.2.3. Motor Design

The motor rating was chosen to suit existing equipment at the site where it would be tested. A 1 MW converter and an existing embedded PM machine that could act as load were available.

The rating for the design was:

	Base Speed	**Top Speed**
RPM	100	160
kW	1000	1000
Volts	690	690
Amps	1010	887
Power factor	0.89	1.0
Open circuit Voltage	587	919

This rating gives a machine of a similar size as the 2.5 MW, 240 rpm motor used in the comparison study. At 240 rpm this motor would be rated at 2.4 MW. The rated torque of this machine is 95 kNm, close to the 100 kNm case for the topology study. The converter provides magnetising current at base speed which is reduced as the speed increases to top speed to maintain constant voltage. The magnetising current can also be reduced at part load to increase efficiency and the reduced flux and current would also result in lower noise.

The motor was designed to prove the technology rather than be a specifically navalised. It was not, therefore, specifically designed for low noise or for shock compliance; for example, it uses rolling element bearings. However, the underlying technology is capable of navalisation and it is anticipated that this will be proven in a future project. Preliminary analysis has, however taken place.

Shock studies on the machine, especially the PM rotor, were carried out to identify the accelerations and stresses that were likely to be experienced. Tests were also carried out on the component materials in order to understand their behaviour under shock conditions.

The predicted structureborne noise of the technology demonstrator was assessed to be 68 dB re 10^{-5} ms^{-2}, and airborne noise assessed as 41 dBA. The rotor technology was chosen so that adding skew would be straightforward, though skew was not applied in the technology demonstrator.

The initial electromagnetic design was carried out by proprietary GE analytical software, followed by more detailed electromagnetic finite element (FE) analysis. The FE analysis was also used to predict the top speed performance. High grade, rare earth permanent magnets were chosen for power density.

Mechanical FE analysis was to predict the contact between the water manifolds and the stator core compression.

4. Manufacturing and Preliminary Testing

Manufacture of the motor and pressure testing of the stator cooling system have been successfully completed.

The stator core was built up using standard manufacturing methods, with just the water manifolds at each end of the core replacing a standard component that maintains even pressure in the core after manufacture. (Figure 3). The manifolds perform the dual function of maintaining even pressure on the core and transferring water from the radial inlet pipes to the axial cooling passages in the core.

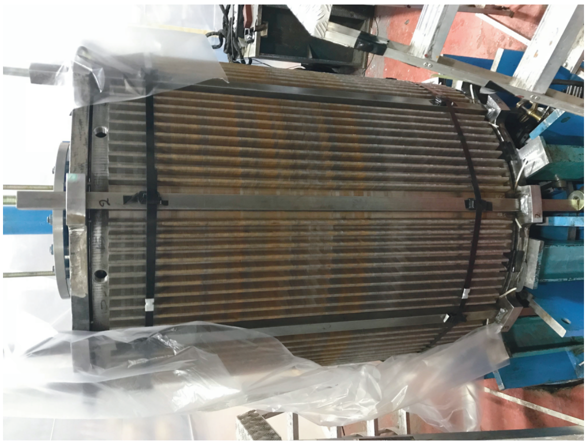

Figure 3 Motor in Core Build

Following the core build, the core pack went through the vacuum pressure impregnation (VPI) process prior to winding and then another VPI process after winding. The wound stator is shown in Figure 4.

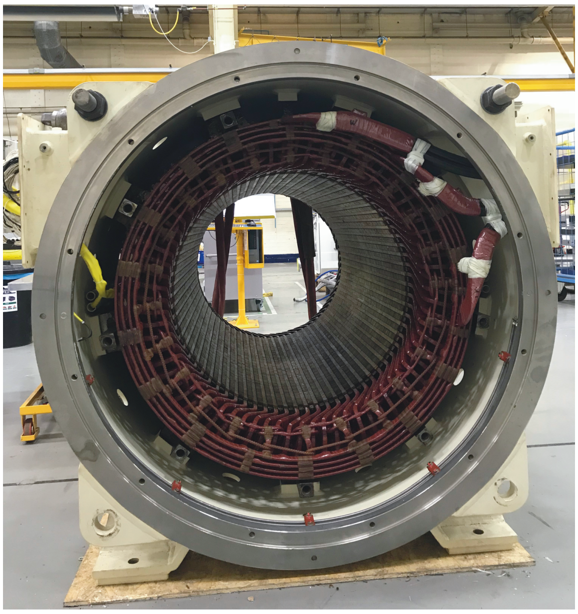

Figure 4 Stator Mounted in Frame

The motor is shown in Figure 5 in final assembly with the terminal box and cooling pump about to be fitted.

Figure 5 Motor in Final Assembly

The completed rotor passed a pressure test of the cooling water circuit at three times operating pressure. This was carried out at the manufacturing facility before shipping the motor to the test site.

5. Load Testing

At the time of writing, testing is beginning at GE's Marine Power Test Facility (MPTF), including open circuit characteristics, thermal testing at base speed and top speed, and structureborne noise testing. The motor is coupled to a gearbox, which in turn is connected to a permanent magnet motor generator set. Both the PM motor and the test motor are connected to the 690V bus via an active front end (AFE) converter. This enables a "back to back" power circuit where the mechanical power delivered by the motor under test is turned into electrical power by the load generator and fed onto the system bus by its converter. This power in turn feeds the test motor converter and is turned into mechanical power by the motor, thus completing the circuit (see Figure 6). The system losses are made up by a small electrical feed from the test site. In this configuration GE's PM machine can be tested as a motor i.e. conventional Power Take-In (PTI) or as a generator in Power Take-Off (PTO) mode.

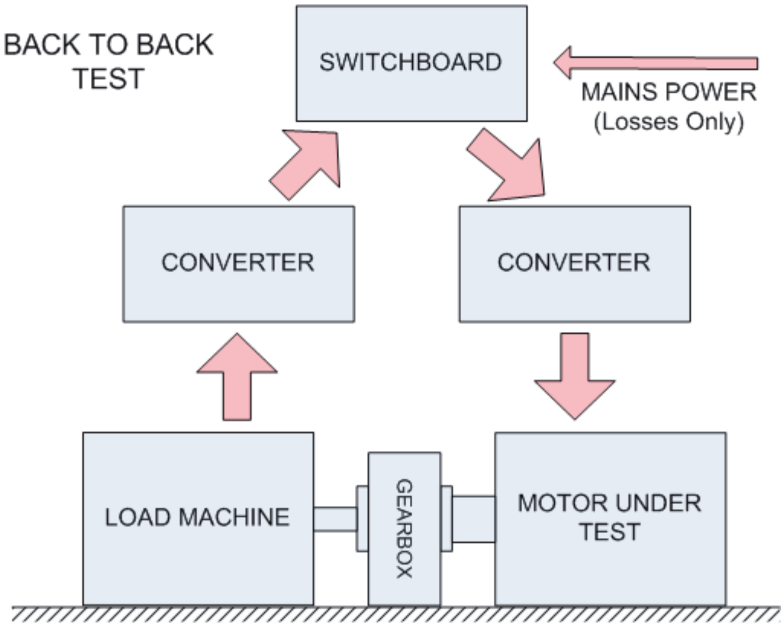

Figure 6 Back to Back Test Arrangement

The test arrangement enables any desired torque and speed to be applied to the motor under test in order to fully explore its performance envelope. The PM motor itself is carefully instrumented so that the modelled performance of various aspects of the machine can be compared with measurements, to enable calibration of the models themselves. This is important since the models effectively serve as design tools for future implementation of the design at different rated torques and speeds.

The tests will include the following:

Table 4 Test Function

Test	Purpose of Test
Open circuit characteristics	Measure open circuit voltage up to 160 rpm. To validate the design calculation. To provide a measured value of the V/rpm value typically used in simulation models
Full load heat run at rated speed	Run the motor 100 rpm, 1 MW, 690 V. Monitor temperature until stable as defined in IEC60034 To validate the design calculations on temperature and power factor
Overload heat run at rated speed	Run at rated speed on overload. To determine the thermal limit of the motor.
Field weakening test	Run motor up to 160 rpm at 1 MW, 690 V, reducing the magnetising current to maintain constant voltage Validate operation at top speed Validate design calculations
Part load test	Run at part load on a propeller curve Validate design calculations Determine optimum V/f curve
Structureborne noise	Measure structureborne noise at the motor feet at points on a propeller curve This motor was not specifically designed to be quiet, though the technology was, but this will give a baseline figure for the next stage of development.

6. Next Steps

GE's PM machine that is currently under test is proving the fundamental technology behind the motor concept. In order for this to become a truly naval machine there are various further steps to be completed. One step is to create a version of the machine that has been designed to minimise all sources of noise and vibration. This could build in key noise reduction technologies developed and employed on other machine types. Another step is to demonstrate shock performance of major sub-assemblies.

These tasks, while important, do not present such considerable technical challenges as those already addressed, and they have already been performed in the past on several different motor technologies. GE's PM motor concept is therefore rapidly approaching the point where it can be employed as a practical naval propulsion technology.

7. Conclusions

This paper has looked at options for approaching the "Holy Grail" of naval electric propulsion, a motor that is power dense, efficient, ultra-low noise, shockproof, mature and affordable. The technologies available for approaching this ideal have been considered and the vital importance of the heat balance in the machine has been highlighted. The combination of a non-heat generating permanent magnet rotor combined with a scalable water cooled stator was identified as the most likely contender. A permanent magnet motor technology which is straightforward to manufacture, power dense, quiet and efficient has been designed, manufactured and is under test. It offers high power density and low noise and is suitable the be designed for shock withstand.

The next step is to develop this technology demonstrator into a product suitable for both commercial and naval marine markets.

8. Acknowledgements

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