THE PERMANENT MAGNET PROPULSION MOTOR

FROM INFANCY TO ADOLESCENCE

BY

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This is an edited version of the paper that was first published by SEE – Société de L'Electicité, de Electrique et les Technologies de l'Information et de la Communication at the AES 2000 *Conference held at Paris from 26 – 27- October 2000.*

ABSTRACT

This article presents an update on the Permanent Magnet Propulsion Motor (PMPM) Technical Demonstrator Programme (TDP). It looks at the history behind the TDP before concentrating on the design and development of the motor. The article highlights the manufacturing processes involved in building such a novel design, and the motor testing programme, both complete and forthcoming at the time of writing the article.

Introduction

The All Electric Ship (AES) concept has been discussed in many papers over the years and the Rolls-Royce Permanent Magnet Propulsion Motor (PMPM) has been the cornerstone of several AES concepts. The motor's superior power density ensures that it is part of a very compact form of propulsion and its projected efficiencies allow large fuel savings and therefore lower Through Life Cost (TLC) for a vessel. These factors make the PMPM very suitable for small monohulls or multihull vessels, podded drives and submarine applications as well as offering cost savings to commercial operators. Due to these factors, the MoD's research into AES, and more specifically Integrated Full Electric Propulsion (IFEP) architecture, has incorporated the PMPM.[1] With the Future Carrier (CVF), Future Attack Submarine (FASM) and Future Surface Combatant (FSC) projects looking at IFEP architectures, such a motor could have far reaching advantages for the Fleet.

Aim

The aim of this article is to provide an update on the PMPM Technical Demonstrator Programme (TDP). The article summarizes the design, manufacture and testing that has been carried out on the PMPM to date.

Background

For some time the UK MoD has had an active programme for considering the suitability of full electric propulsion for future RN vessels, which has been well covered by several papers.[2, 3, 4] From this a requirement for an efficient, power dense motor was identified. A competitive tender was run that involved conventional motors, axial, radial and transverse flux permanent magnet motors. The ROLLS-ROYCE PMPM Transverse Flux Motor (TFM) was selected for further development. Many factors were taken into account in this decision but the novel way the magnetic flux path utilizes the machine's volume within the PMPM showed that it had great potential, as highlighted in previous papers.[5]

The contract was placed in March 1997 and over the past 3 years the MoD, and ROLLS-ROYCE Marine Systems have worked on the TDP to determine if the PMPM could fulfil its potential. The programme involves the co-ordination of ROLLS-ROYCE Marine Systems, ROLLS-ROYCE Strategic Research Centre, ALSTOM Drives and Control, PEBBLES ELECTRICAL MACHINES (PEM) and the Defence Evaluation Research Agency (DERA) in the design, manufacture and testing of a representative 2.45MW motor, with associated converter and auxiliaries. This PMPM system has been successfully built and the test programme will complete by the end of summer 2000.

20MW TFM Topology

In order to explain the design process, the full-scale version has to be understood. The 20 MW TFM comprises of 4 rotor discs, each with 2 pairs of rims. Each rim interacts with 2 rings of stator cores and 2 armature coils fixed within the stator cores, as shown in (FIG:1).

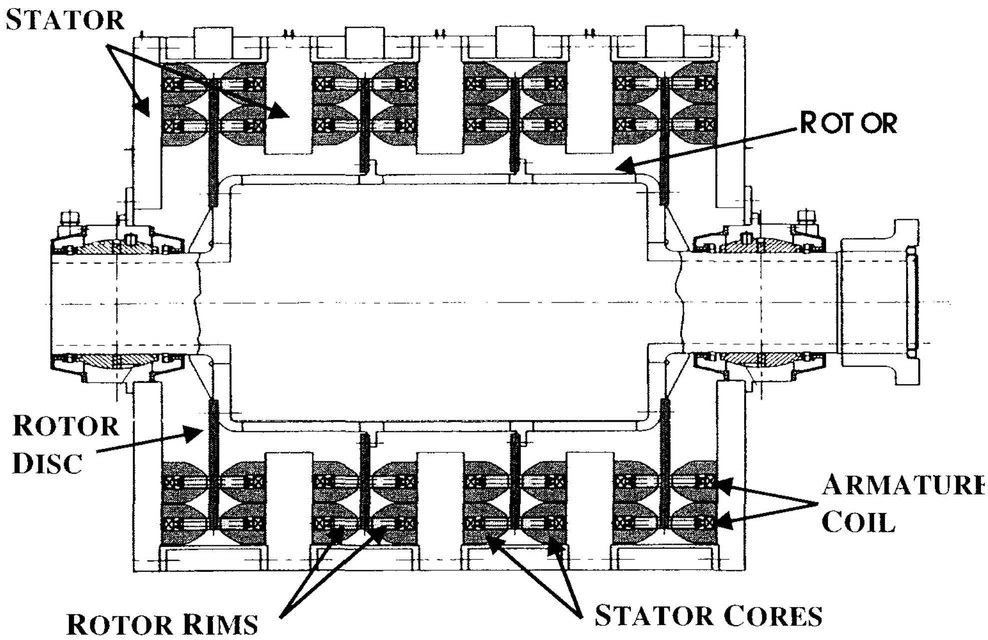

FIG.1 — 20 MW TFM TOPOLOGY

The geometry of a half a rim is shown in (Fig.2). The active part of the rotor comprises a series of laminated pole pieces (which are bolted to a rotor disc) and a number of interleaved magnets (which are bonded between the poles). The magnets are magnetized in the circumferential direction with their polarities alternating so that the pole pieces form successive N and S poles.

The active parts of the stator comprise a number of stator cores enclosing a single solenoidal armature coil. The stator cores carry the magnet flux around the stator coil by completing the flux path between one (north/south) rotor pole piece and the adjacent (south/north) rotor pole piece.

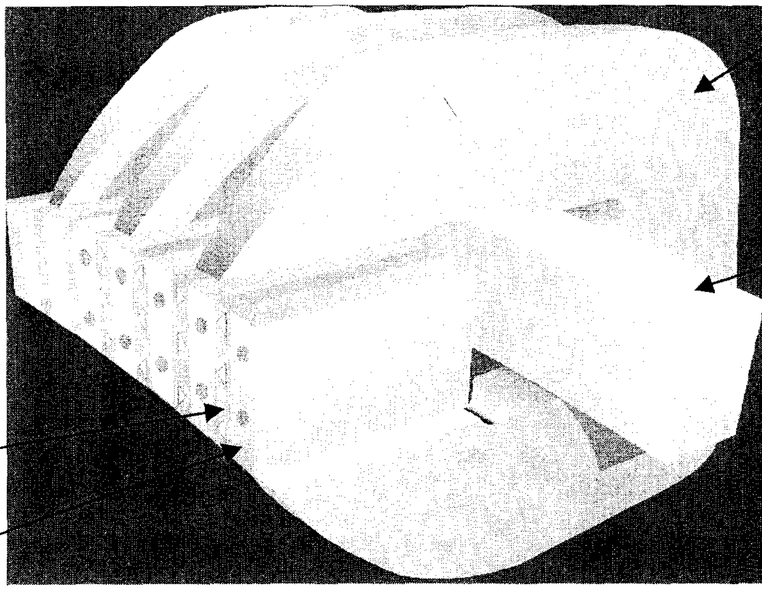

FIG.2 — TFM HALF RIM TOPOLOGY

A single rim of the TFM produces motor torque when the armature coil is excited with an alternating current. However a single rim TFM does not produce a continuous torque. For the TFM to produce a continuous torque, it is necessary to have at least two rims.

To develop such a motor, a number of key stages were involved:

(*a*) Linear Validation Rig (LVR).

(*b*) No Load Rotation Rig (NLRR).

(*c*) 2.45MW representative motor (TDP).

At each of these stages the 20MW TFM calculations for pole pitch, axial rim length and radial depth of magnet and air gap was used to ensure validity. For the TDP the rated force density for the 20MW was the design fulcrum.

LVR

The LVR (FIG.3) was designed to primarily establish the feasibility of manufacture, validate the static electromagnetic performance of the TFM and validate the design methodology and Finite Element (FE) analysis.

The static force was measured over a range of different rotor positions and armature currents and is shown in FIG.5. As it can be seen the measure force was consistent with FE predictions.

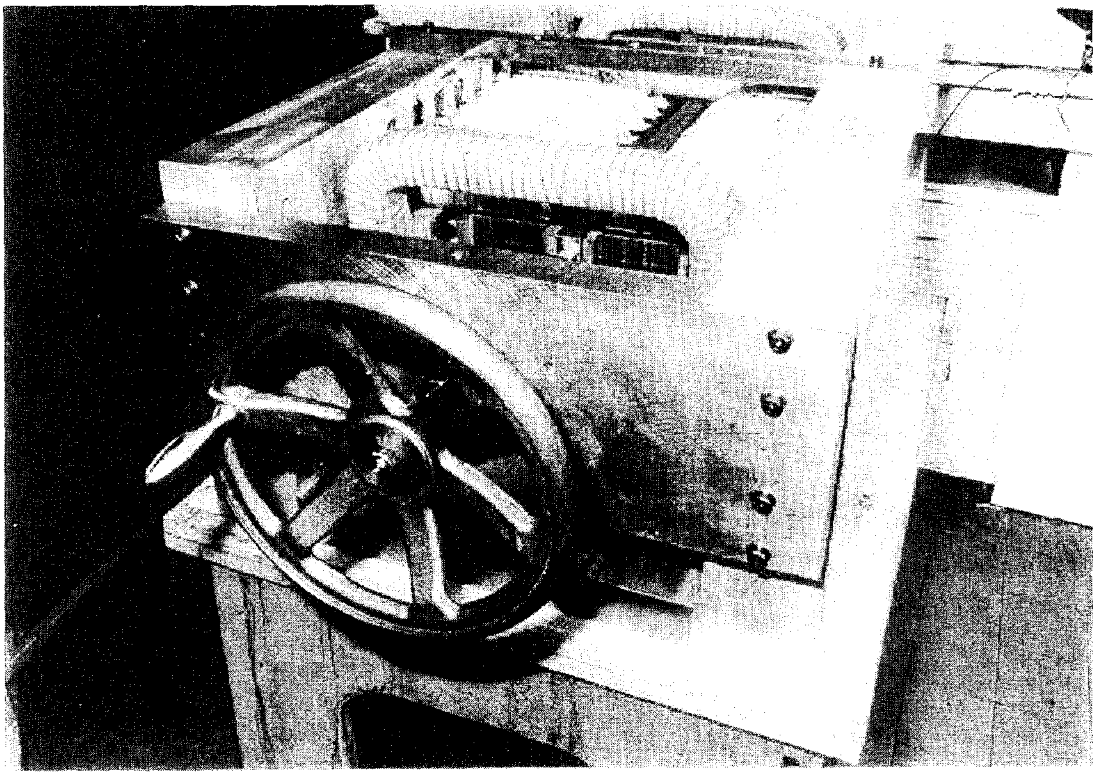

FIG.3 — LINEAR VALIDATION RIG

Measurements also confirmed predictions on the following key parameters:

(*a*) Flux linkage in the stator cores.

(*b*) Variation of flux density in the air gap.

(*c*) Aligned and unaligned armature reactance values.

(*d*) Deflections of the rotor rim assembly under a magnetic load.

NLRR

The NLRR (FIG.4) was designed to primarily evaluate and further the manufacturing techniques of the TFM. It also investigated the mechanical behaviour of representative TFM components and evaluated the performance of the magnetic circuit without excitation.

The NLRR was designed as a 2 phase machine, but with only 2 rims on a single rotor disc. The phase displacement is achieved in the relative angular position of the 2 sets of stator cores, which are separated by half a pole pitch (90 electrical degrees). Two types of stator core were tested, one set of stator cores comprised of strip-wound C-cores and the other comprised of hybrid stator cores. The machine has a vertical shaft supported on rolling element bearings, with a belt drive from a 22 kW variable speed driven induction motor.

The diameter of the NLRR is the minimum diameter that accommodates the required number of stator cores to maintain a representative pole pitch and a representative radial depth of magnet and air gap. This results in a 42 pole machine with a mean rotor rim diameter of 0.61m and a rated rotational speed of 558 rpm (i.e. electrical frequency of 195 Hz).

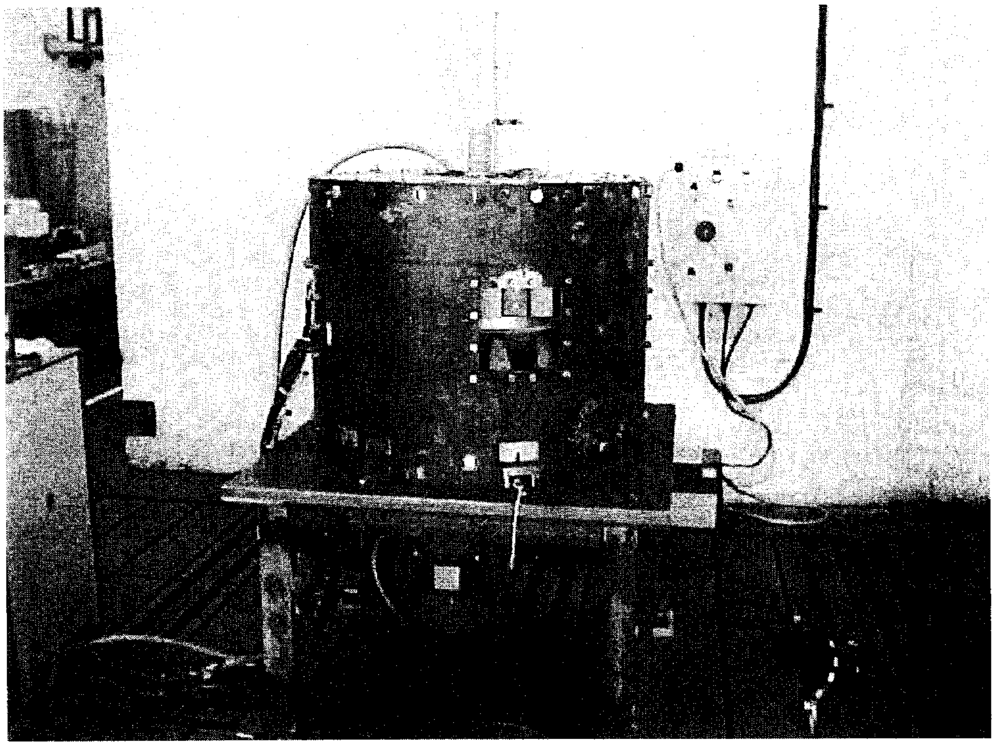

FIG.4 — NO LOAD ROTATION RIG

Again, the static force, or cogging torque, was measured over a range of different rotor angles. (FIG.5) shows the good correlation that was found. In addition, good correlation between flux linkage in the stator cores and FE predictions were achieved and the power losses measured were less than the designed worst-case expectations.

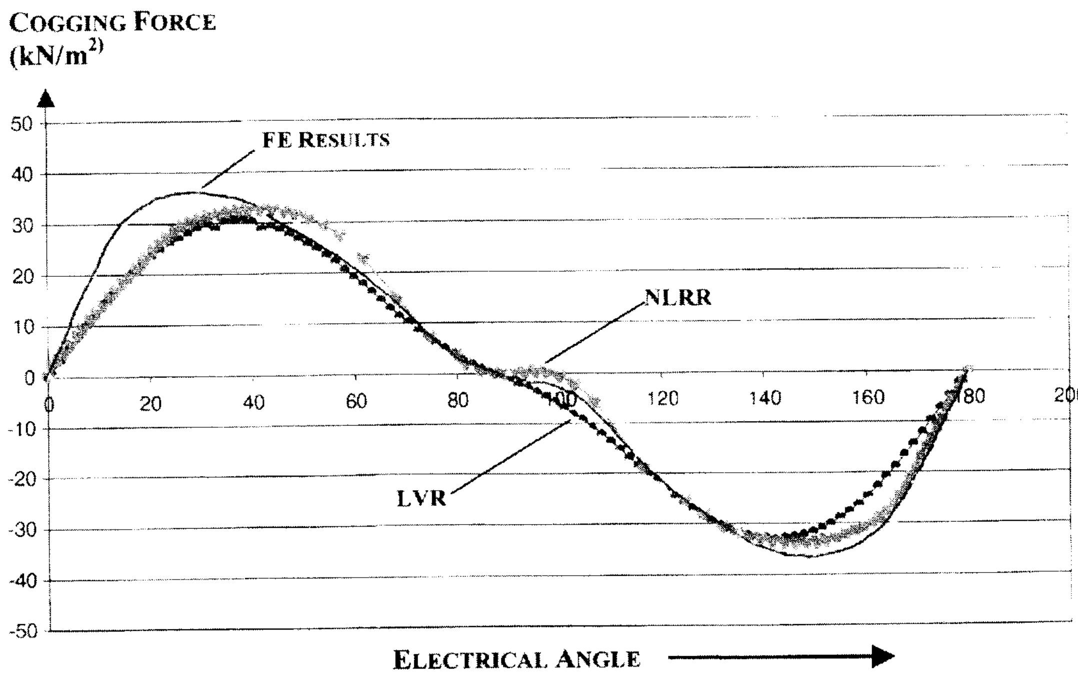

FIG.5 – LVR AND NLRR COGGING FORCE PER COR (PER UNIT AREA)

The NLRR was extremely useful to establish the preferred C-core design. It was found that a wound C-core design was insufficient to prevent creep and delamination in the radial direction. The hybrid stator core performed as expected and hence was selected for the demonstrator.

Representative Machine

The representative TFM is shown in Figure 9. It was designed to provide a thorough demonstration of proposed 20MW TFM technology ahead of any full scale development.

The representative TFM has 2 rotor disc with one pair of rims per disc, compared with 4 discs and 2 pairs of rims per disc on the 20MW TFM. The representative machine is therefore a 2 phase machine with each phase displaced by 90°. The stator comprises of hybrid stator cores set within 3 aluminium frames with 2 intermediate casings.

The designed power rating is consistent with the mean torque production from the proposed 20MW TFM outer and inner phases and a rated rotational speed which equated to a rated electrical frequency of 195 Hz. The mean rim diameter is therefore 1.1m and consists of 76 poles thus maintaining a representative pole pitch. The resulting representative TFM rating is 2.45 MW at 308 rpm. This is the motor currently under test at DERA Pyestock

Manufacturing

The representative TFM was built at Peebles Electrical Machines premises in Edinburgh. (FIG.6) shows one rotor disc being loaded with magnets. The titanium through studs clamp the shaped pole stacks and the magnets are glued into the interspaces. The addition of an outer glass reinforced plastic ring completes the assembly.

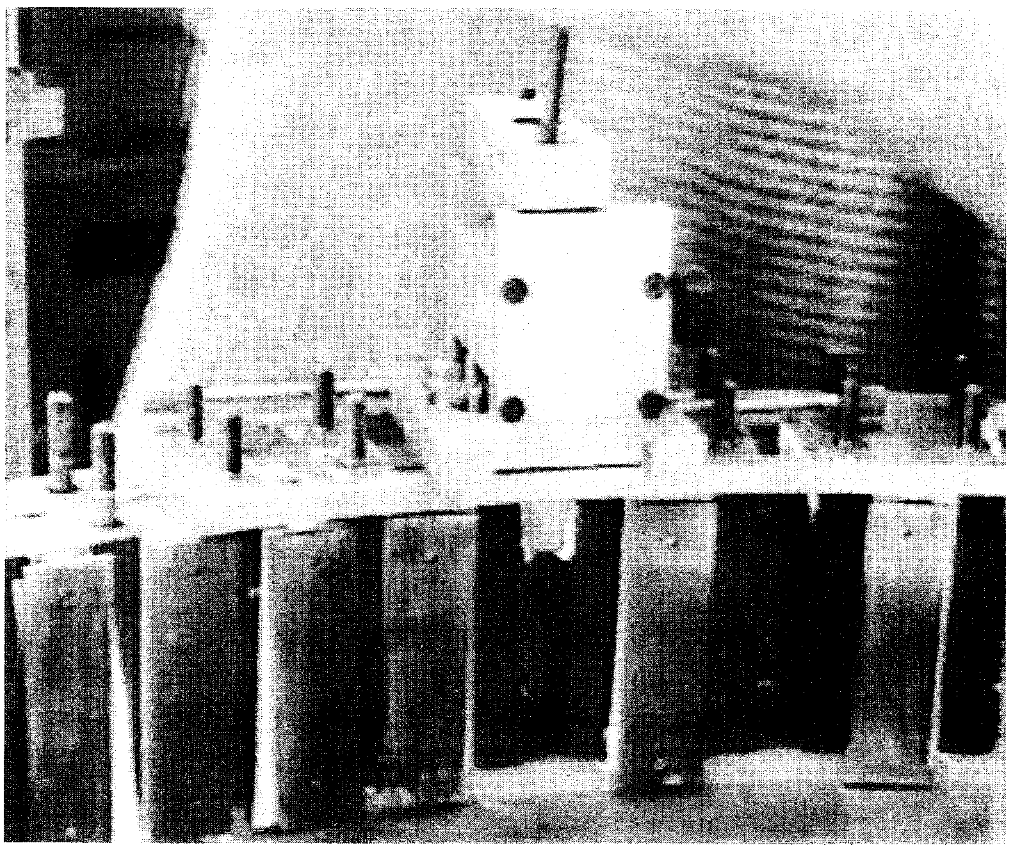

FIG.6 – LOADING MAGNETS ON ROTOR

(FIG.7) shows the completed two disc, four rim rotor ready for balancing.

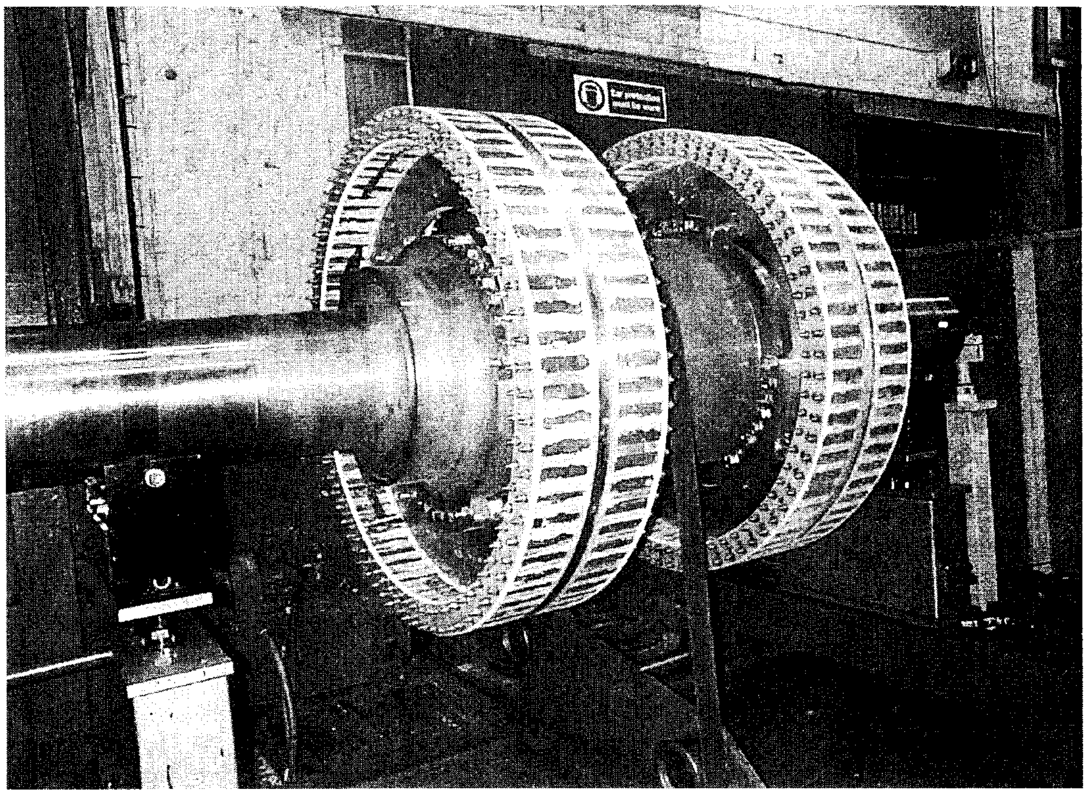

FIG.7 – COMPLETE ROTOR

(FIG.8) shows a completed stator. The solenoid winding is secured at the base of the stator core jaw and blocking is inserted between individual stator cores, both to provide rigidity and to duct the cooling air required for high power running over the rotor rims.

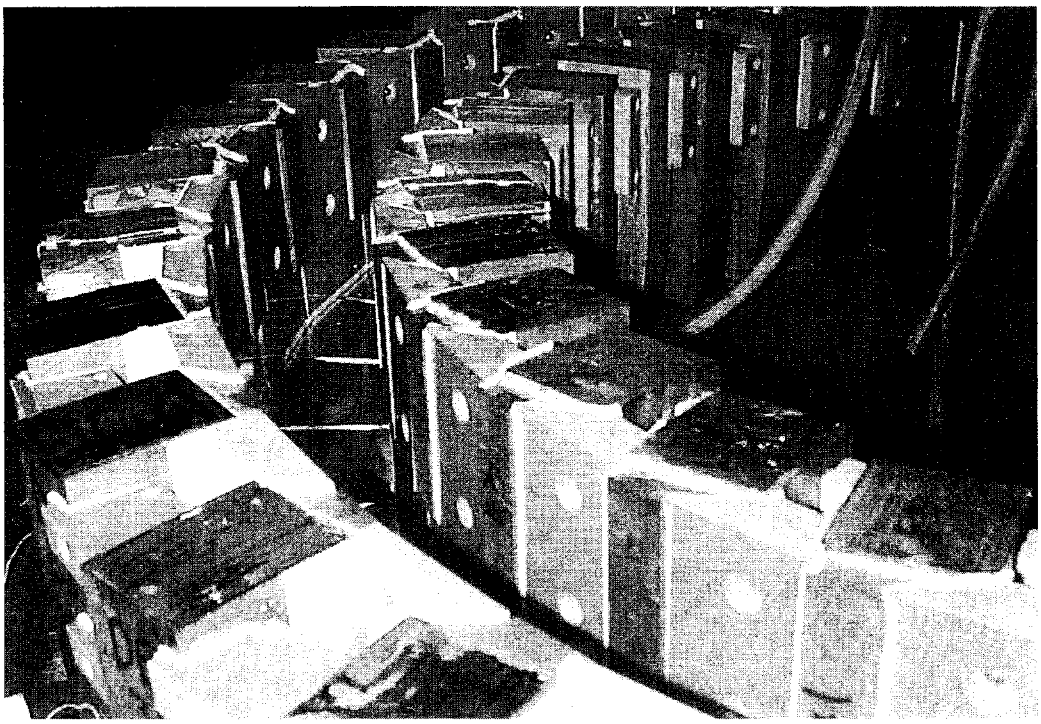

FIG.8 – COMPLETED STATOR

There are three stator frames, the end frames populated with stator cores on one side and the middle frame populated on both sides. These stator frames are water cooled to remove the bulk of the motor waste heat. Stator frame spacers are fitted to separate the stators and retain the longitudinal clearances.

(FIG.9) shows the complete machine. The rotor is accurately located within the machine by the zero clearance rolling element bearings. These are external to the machine and adjustable to enable the air gap to be tightly controlled for test purposes.

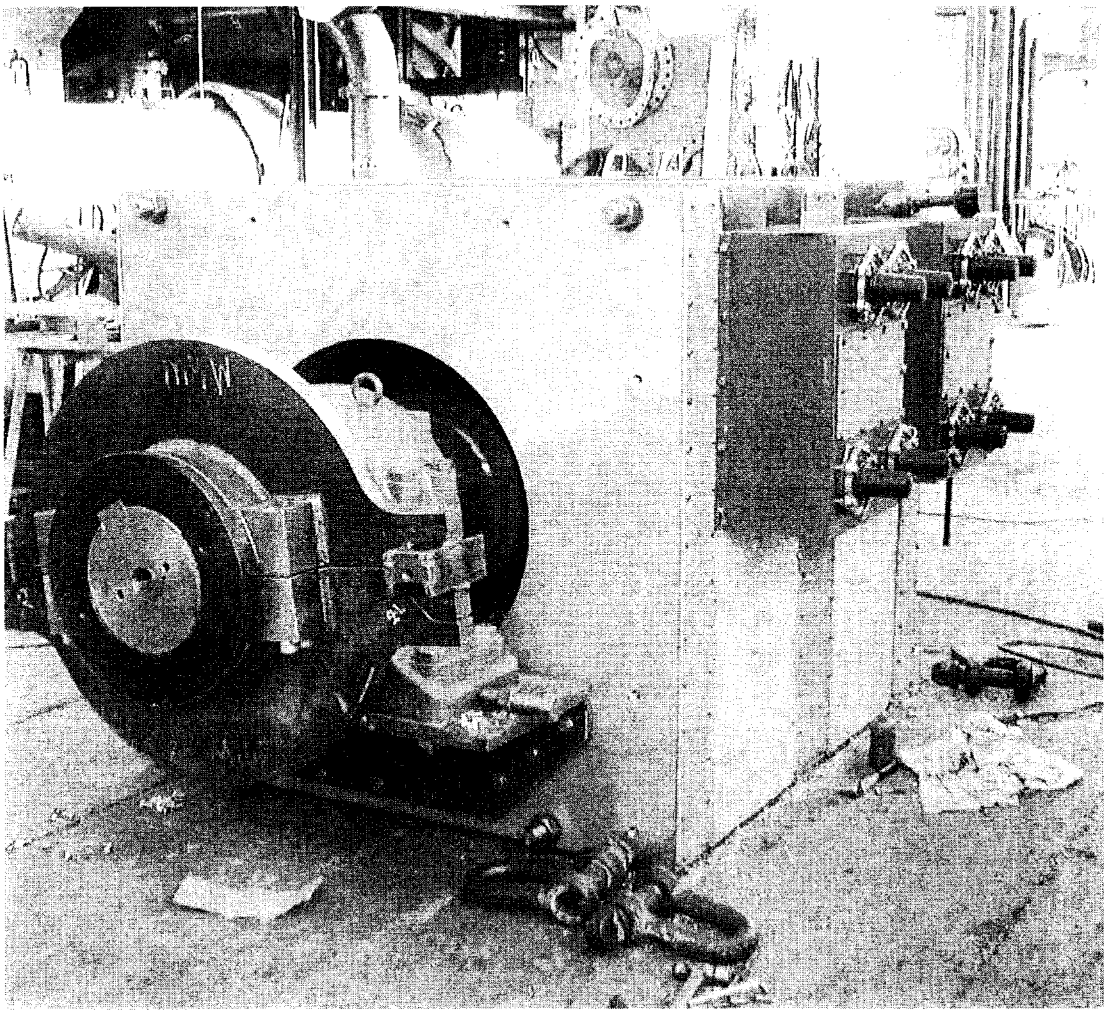

FIG.9 – COMPLETED MACHINE

At 13 tonnes and 1.475 x 1.5 x 1.55 metres, the motor is rather larger than is necessary for a 2.45MW point design as it represents the electro-magnetic conditions and C-core dimensions of a 20MW machine. The completed motor was delivered to the test site at the end of last year.

Testing

A schematic of the DERA test site is shown at (FIG,10). The site was commissioned at the start of this year at Pyestock. The test arrangement consists of a transformer to convert incoming grid supplies to power the converter that controls the motor. The motor is loaded by a pony motor and hydraulic water brake. The pony motor is a 1.25MW DC submarine motor that can be used as a load or to drive the motor. The water brake is used to provide the additional load.

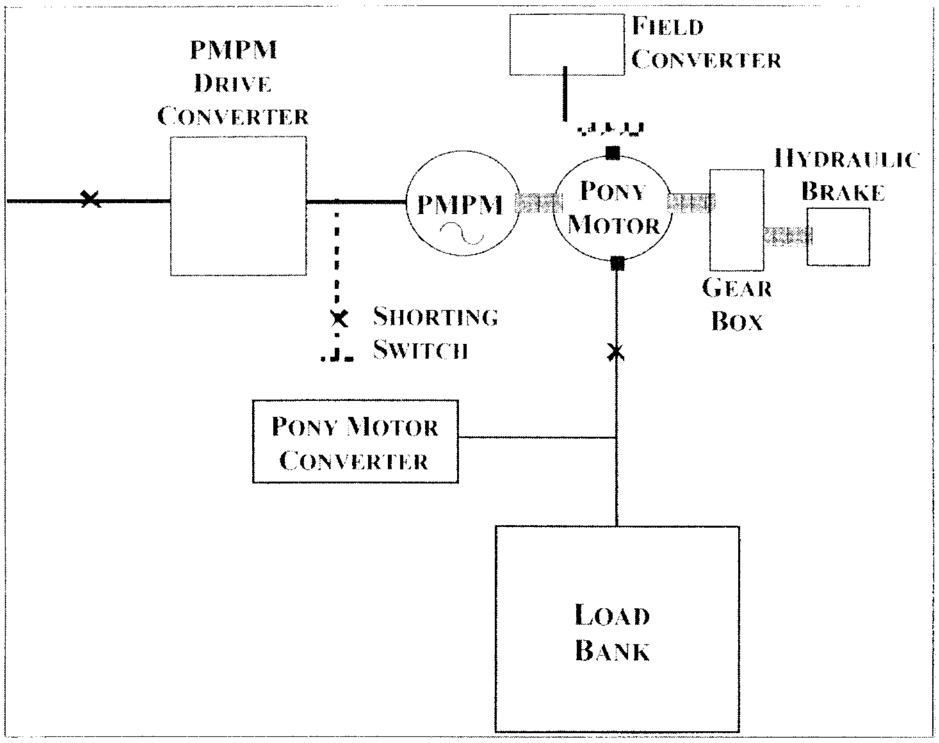

FIG.10 – DERA PYESTOCK TEST SITE

The following tests had been completed at the time of writing in May 00:

- Driven the TDP at 110% speed.
- Achieved 1.5MW from the TDP at 100% speed.
- Measured static cogging and motor torque.
- Optimization of operating strategies commenced.

(FIG.11) shows the results of the measured static cogging torque of the representative motor with the predicted results based on FE and NLRR results. It can be seen that the practical and predicted results are in close agreement.

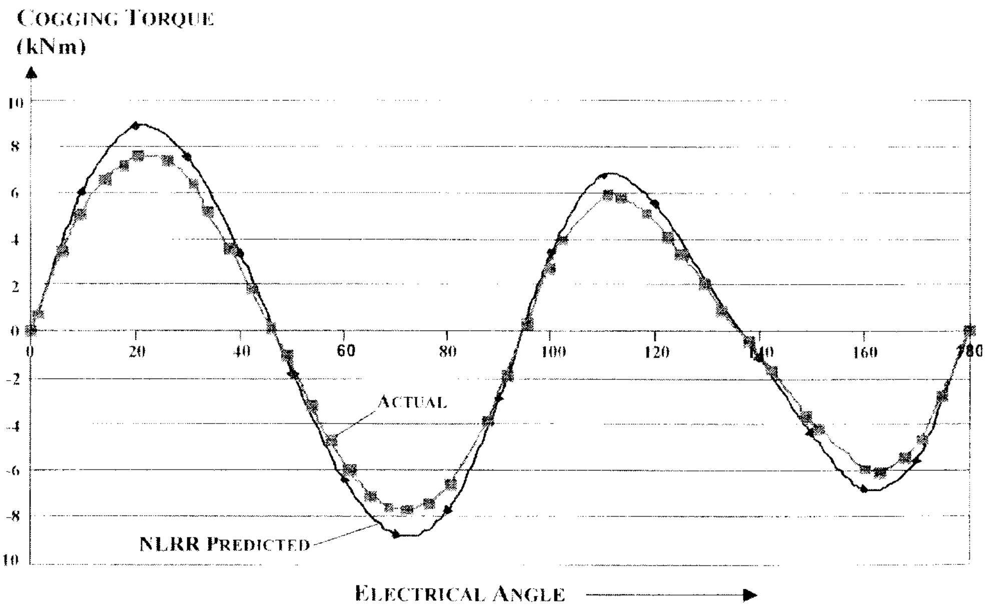

FIG.11 – REPRESENTATIVE TM COGGING TORQUE

The tests to be conducted are:

- Further optimization of operating strategies.
- Full power runs.
- Baseline characteristics.
- Torque ripple measurements.
- Vibration monitoring.
- EMC assessments.
- Magnetic signatures.
- Endurance tests.
- Transient test.
- Short circuit tests.

Testing conducted so far has not been without its problems. The converter was found to contain a software flaw within the Controller. This caused a short circuit across the machine bridges, which damaged the Converter and imposed some delay. The motor became misaligned during trials and some minor damage was caused which required a motor strip down and further delay. However both failures have been valuable learning opportunities from which the experience contributes further in the revised 20MW design.

Conclusions

In conclusion, this article has shown the work undertaken by the UK MoD and Rolls-Royce in the development of the PMPM Technical Demonstration Programme. The requirement for a compact and efficient propulsion motor was identified in the mid 1990's and lead to the PMPM being developed after a competitive tender. The design and development phase that followed ensured a methodical and layered approach to this novel motor topology. The use of a LVR and NLRR resulted in many design issues being resolved before the representative machine was built. The manufacturing phase proved to be a challenging and rewarding engineering activity. Some of the processes involved have been highlighted and the motor was delivered to the test site at the end of last year. The testing phase commenced shortly afterwards and the article has shown that results obtained from this are in close agreement with the predicted results. This implies that the design methodology for the proposed 20MW 180 rpm TFM has been considerably de-risked. After many years of discussion and development, the concept has been constructed, scrutinized and interrogated; now is the moment of truth.

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