THE TRANSVERSE FLUX MOTOR A NEW APPROACH TO NAVAL PROPULSION

BY

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ABSTRACT

The Transverse Flux Motor (TFM) is one of the most exciting and promising technologies to be investigated in support of the UK Ministry of Defence initiative, Integrated Full Electric Propulsion. The motor is being developed by Rolls-Royce International Research and Development Ltd, who have carried out the initial concept and design feasibility studies. The article describes the main features and operating principles of the TFM and its power electronic converter and discusses possible future applications of this novel motor topology in vessels of the Royal Navy. Any views expressed are those of the authors and do not necessarily represent those of Rolls-Royce or Her Majesty's Government.

Introduction

The Royal Navy has adopted a new approach to the development of marine power and propulsion systems which has been endorsed at the highest levels within the MoD. The strategy is to apply Integrated Full Electric Propulsion (IFEP) architectures to all new surface ship and submarine designs, wherever possible. An IFEP solution is one in which the same prime movers normally supply both the propulsion and ship's service loads. The overriding motivation for this step change in direction is, of course, financial, with benefits to be gained in Through Life Cost (TLC) from efficient operation, simplified support and reduced manning.[1,2]

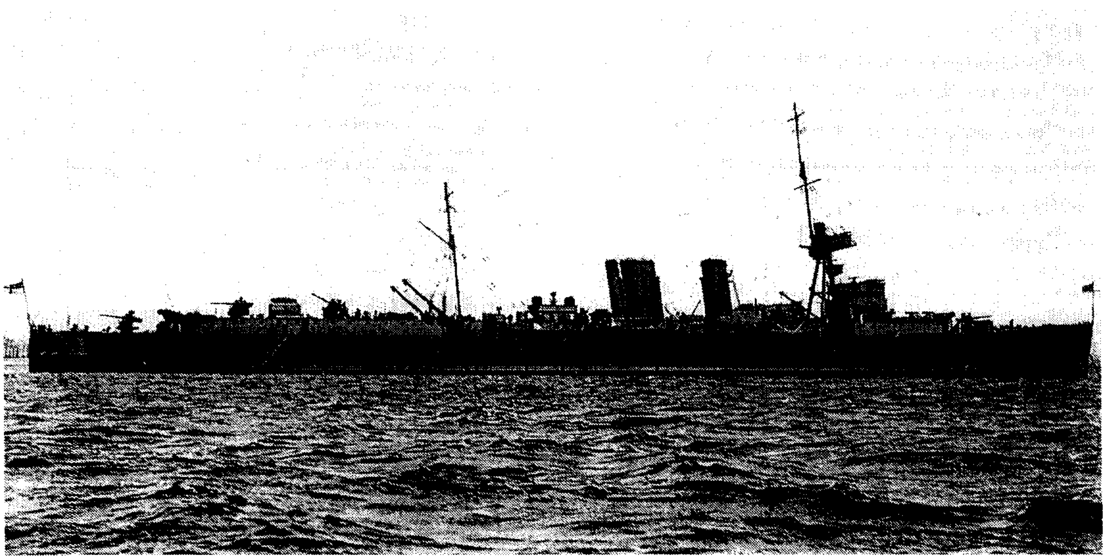

Fig. 1—HMS 'ADVENTURE'

The philosophy is by no means new; electrical propulsion schemes have been in existence in surface ships of the RN since the 1920s, when HMS *Adventure* (FIG. 1) was commissioned into service, and are commonplace in the merchant marine. The designers of modern warships are, however, faced with different constraints from those of the old and of the contemporary merchant fleet.[3,4] Until now, electrical propulsion systems have been too large and heavy for modern military applications, however, the power electronic revolution and the advent of permanent magnetic materials have gone some way to eliminate these disadvantages. If an IFEP solution is to be realized for a frigate, typically 4000 tonnes in displacement, propulsion machinery must not only offer high torque density but must be efficient across the power range, particularly as a warship will tend to operate away from its design point for the majority of the time.

Background

The requirement for efficient, power dense propulsion motors became evident in the late 1980's when it was established that novel motor topologies utilizing permanent magnet materials should be exploited. Early risk reduction and design analysis studies were undertaken by Rolls-Royce International Research and Development Ltd (IRD) and centred on the Transverse Flux Motor (TFM) topology, proposed by WEH[5,6] and discussed by MITCHAM[7]. These studies have been used to assess the potential of a Permanent Magnet Propulsion Motor (PMPM) and reduce the risk associated with subsequent programmes.

The next phase of development, a Technology Demonstrator Programme (TDP) for the design, manufacture, assembly and test of a representative propulsion motor and power electronic converter, is based on the performance assessments and predictions of earlier studies. The aim of the PMPM initiative is to produce a validated design database for a 16–24 MW permanent magnet propulsion solution. IRD is a member of a consortium who, in March 1997, were successful in winning this 3 year development contract based on the TFM topology, which is considered to be the optimum machine configuration to achieve the higher power densities and efficiencies afforded by permanent magnets. The TFM efficiency is compared with that of conventional wound field synchronous and induction machines at (FIG. 2).

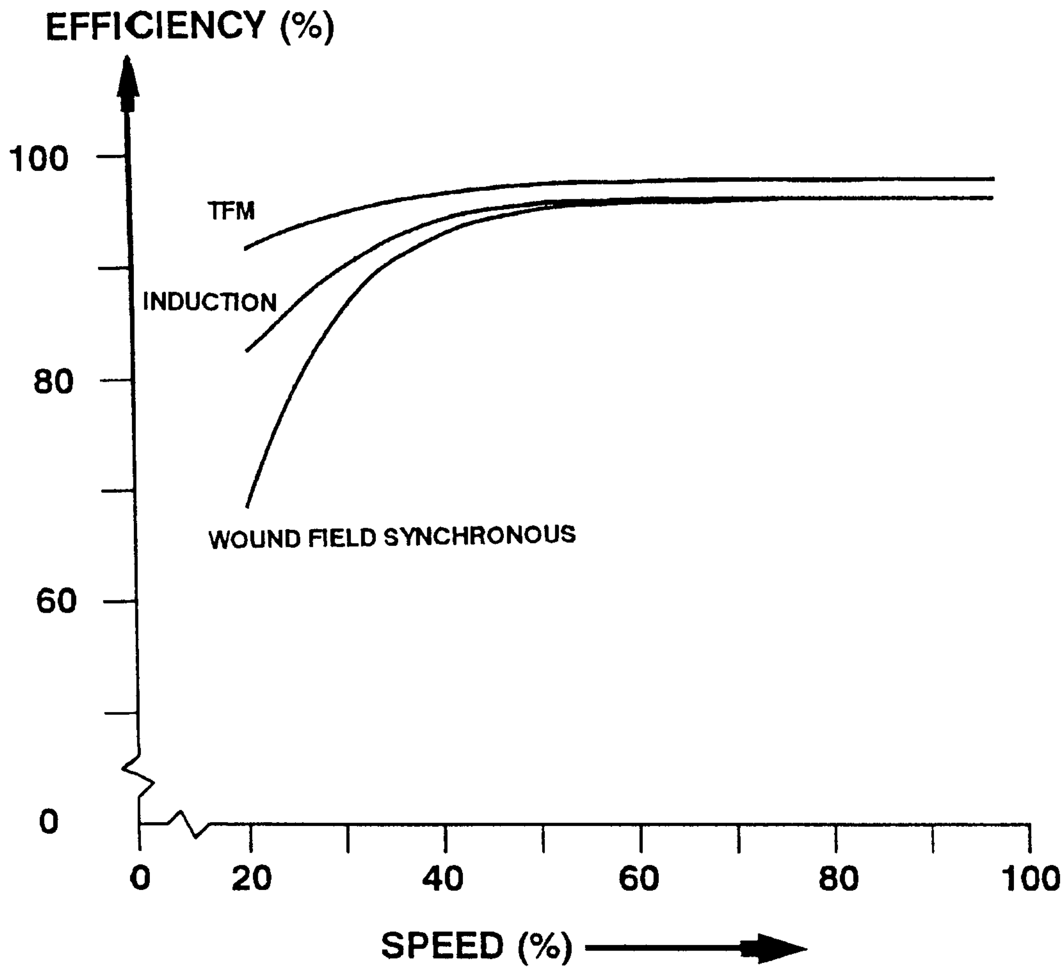

FIG. 2—COMPARISON OF MOTOR EFFICIENCIES

TFM Topology

The naval propulsion application requires a rugged, shock resistant motor which will produce a rated torque in excess of 10^6 Nm within a small volume envelope. Early TFM studies based on established topologies gave promising results but it was soon appreciated that a radical rethink on the machine topology[8] could lead to a better design that would be easier to manufacture, quieter and less vulnerable to naval shock (FIG. 3).

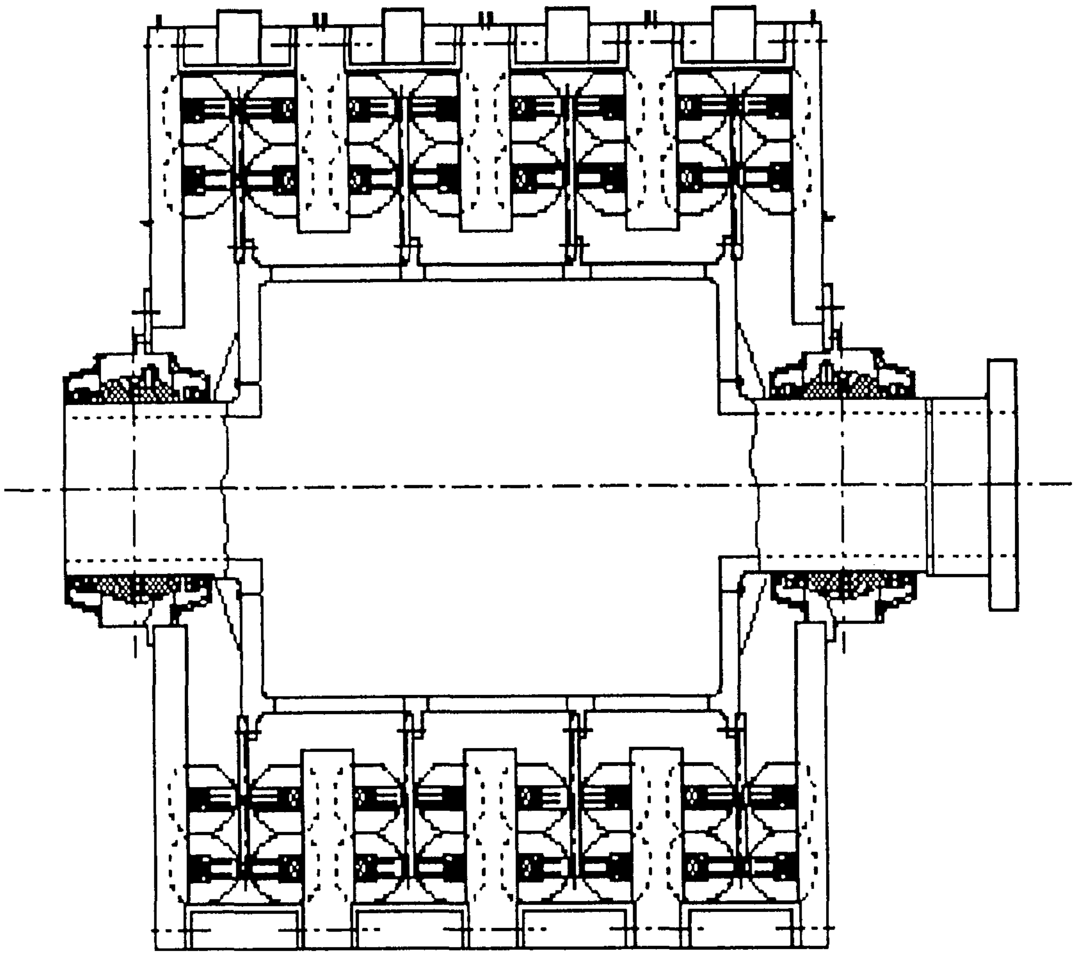

FIG. 3—MECHANICAL LAYOUT OF THE 20 MW TFM

As proposed, the 20 MW motor consists of four stainless steel rotor discs, each flanged to a carbon steel rotor drum (shaft). These discs carry the active rotor rims (FIG. 4); the rims are constructed with rare earth (NdFeB) magnets and soft iron pole pieces. The pole pieces are formed from laminated silicon steel to reduce eddy currents and are clamped to the rotor disc between glass-epoxy end cheeks. The magnets are bonded (and mechanically keyed) between the pole pieces and are circumferentially magnetized to achieve a high air gap flux density, using the principle of flux concentration. In practice, there is a need for magnet subdivision, to reduce the eddy current losses; this is achieved by bonding together smaller pieces of NdFeB material.

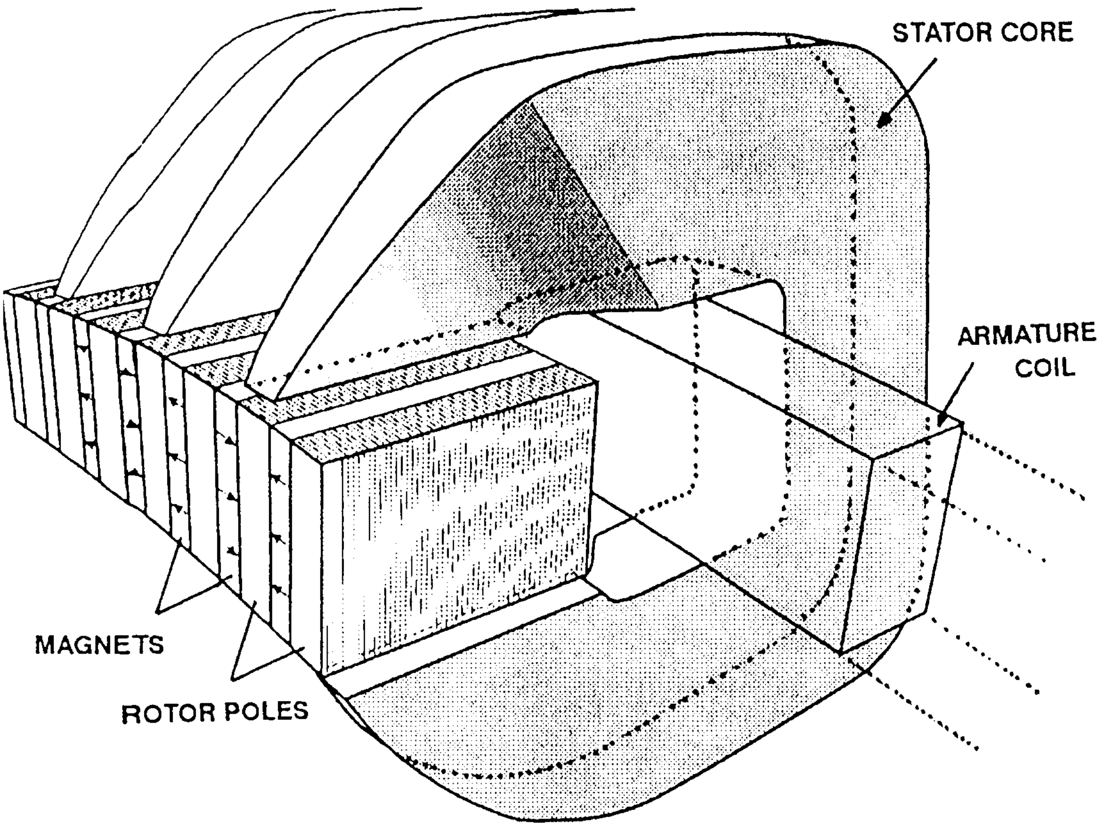

FIG. 4—GEOMETRY OF ONE PHASE OF THE TFM

The stator comprises a number of solenoidal armature coils (one coil associated with each rotor rim). The alternating flux, produced by the active rotor rim, is carried by laminated stator cores (shaped C-cores) which in turn form a flux linkage with the respective armature coil. Each pair of rotor rims with its associated armature coils and stator cores forms a separate phase of the motor, with the two coils of one phase being connected so that the current flows in opposite directions around the machine.

As shown in FIG. 3, the stator cores are supported by deep section aluminium frames; these are slotted for accurate location of the cores which are held using a combination of adhesive bonding and mechanical clamping. Stator cooling is achieved by cooling water passages in each of the stator frames. The armature coils are wound in a number of double layers using a stranded rectangular conductor to reduce the ac losses (eddy currents) arising from the coil leakage flux. The coil losses are removed by conduction into the water-cooled aluminium frame.

Effective design of the TFM necessitates using relatively high pole numbers and small air gaps. Typical design values and overall machine dimensions are given in Table I.

TABLE I. *Main parameters of the 20 MW TFM*

Rated Power	20 MW	
Rated Speed	180 rpm	
Number of Poles	130	
Nominal Frequency	195 Hz	
Number of Phases	8	
Supply Voltage (DC Link)	5000 Vdc	
Number of Rotor Discs	4	
Number of Rotor Rims per Disc	4	
Magnet Material	NdFeB	
Nominal Working Force Density	120 kN/m2	
Motor Outer Diameter	2.6 m	
Overall Length	2.6 m	
Shaft Diameter	500 mm	
Estimated Overall Weight	39 tonnes	
	Outer Phase	Inner Phase
Mean Rim Diameter	2.1 m	1.64 m
Turns per Coil	10	12
Coils per Phase	2	2
RMS Coil Current	750 A	500 A
Peak Coil Current	1000 A	670 A

The rotor is supported on flange-mounted bearings fitted to each end frame. As proposed, the bearings are self-lubricated and self-cooled. The end frame mounting has the advantage of allowing close control of air gap and build tolerances and also reduce the relative deflections of the rotor and stator under naval shock conditions.

Operating principles and performance

As already indicated, each pair of rotor rims forms just one phase of the TFM; this does not in itself produce a smooth continuous torque. A steady torque output requires at least two phases, with the phases appropriately displaced to minimise torque ripple. In the absence of saturation and with the motor fed from a sinusoidal supply, the torque produced by each phase closely approaches a sine-squared function; hence two phases separated by 90 electrical degrees are sufficient to produce a smooth torque. In reality, the presence of saturation and the likelihood of non-sinusoidal excitation mean that a higher phase number is desirable.

The total shaft torque is the resultant of all phases acting together and is relatively free of ripple; however, within the rotor, the phases are separated so each of the rotor rims experiences 100% torque ripple. This has important implications for the design. First, the components of the system (particularly the magnets and pole pieces in the rotor rim) have to be designed to withstand the cyclic stresses so produced. Secondly, the entire rotor system (and the stator system) have to be designed with a recognition of the torsional dynamics of the system.

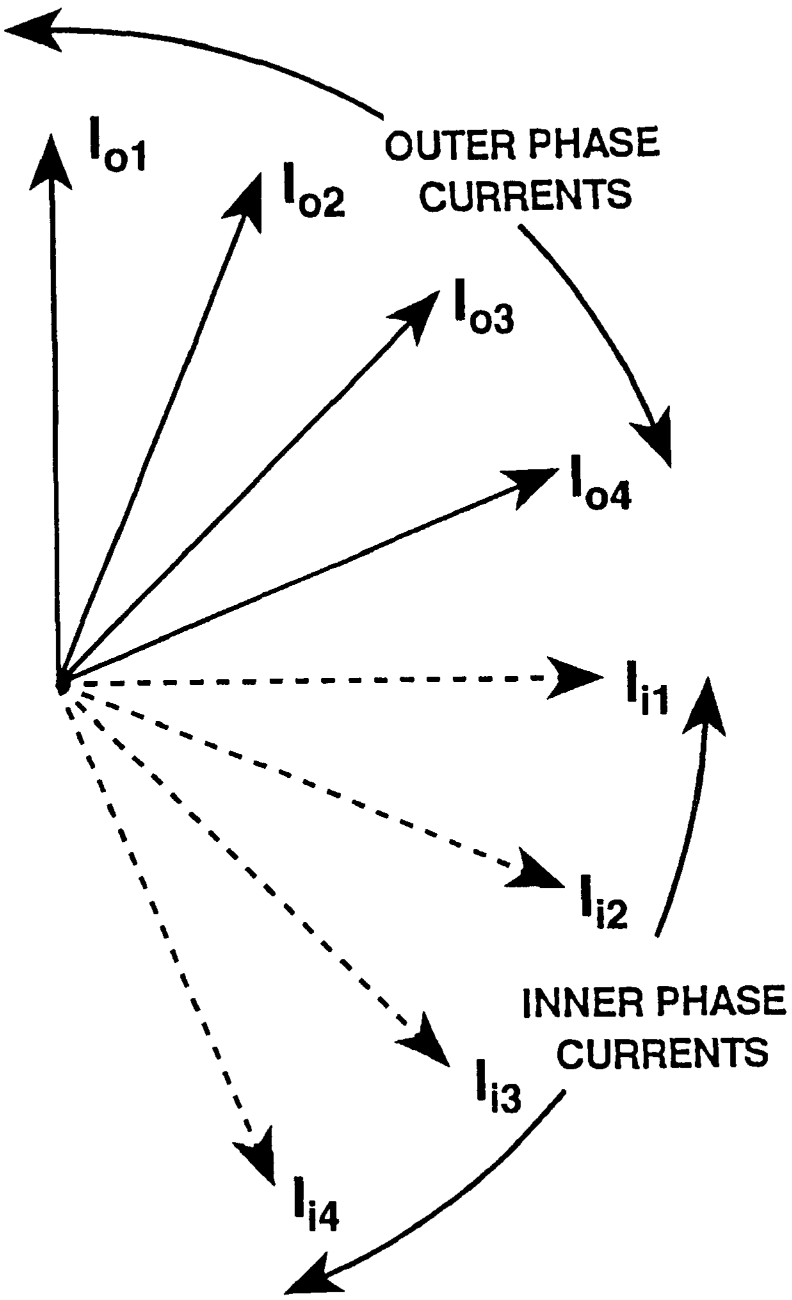

FIG. 5—PHASE ANGLE RELATIONSHIPS FOR 8 PHASE TFM

Clearly, the larger diameter outer rims (see FIG. 3) are able to produce a higher torque than the inner rims. The phase relationships required to minimize the overall torque ripple are as depicted in (FIG. 5). At low power the inner phases are driven harder than the outer phases so that torque ripple is largely cancelled within each rotor disc. At higher powers, the main components of torque ripple are cancelled between discs.

An essential feature of the TFM, as proposed by IRD, is the bolted construction of the rotor pole pieces. The pole pieces are held in compression by means of pre-tensioned through-bolts. The bolts themselves do not take the stresses associated with the torque force; the forces are accommodated by bending moments in the pre-compressed pole stack.

The following equations govern the instantaneous torque, flux linkage and terminal conditions for each phase:

$$v = iR + \delta\psi/\delta t \qquad (1)$$

$$\psi = \text{fn}\{i, \theta\} \qquad (2)$$

$$\theta = \omega t \qquad (3)$$

$$T = i\,.\delta\psi/\delta\theta.p \qquad (4)$$

where:

v = The terminal voltage
R = Phase resistance
θ = Rotor angle (electrical radians)
T = Torque
i = Phase current
ψ = Coil flux linkage
ω = Electrical angular frequency
p = Number of pole pairs.

The relationship between flux linkage, current and rotor angle can only be determined from detailed 3-dimensional finite element analysis. This is an exacting and time consuming process. Having obtained an accurate map of the flux linkages, it is then possible to determine the torque and voltage waveforms for one phase at a given motor speed.

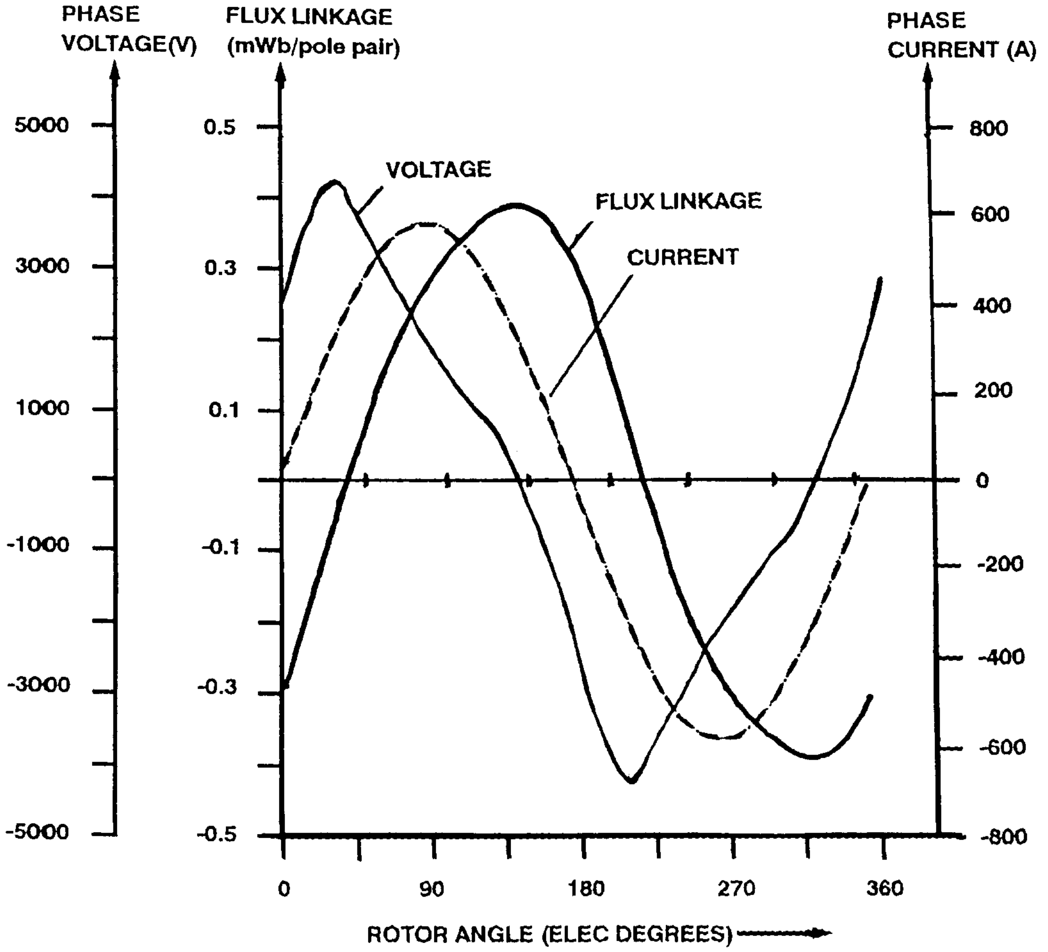

FIG. 6.—SIMULATED CURRENT, VOLTAGE AND FLUX LINKAGE FOR ONE PHASE AT 80% SPEED

A typical set of results is given in (Fig. 6). This shows the current, flux linkage and voltage for the 20 MW motor at 80% speed and 64% torque (assuming a typical propeller law operation). For the purposes of the analysis, the current is assumed to be driven as a sinusoid. It is clear from the curves that the TFM operates at a relatively low power factor and is subject to a degree of magnetic saturation. For these reasons (and to minimize the requirements for the converter) it is proposed to operate the machine with a trapezoidal drive for conditions above 80% speed.

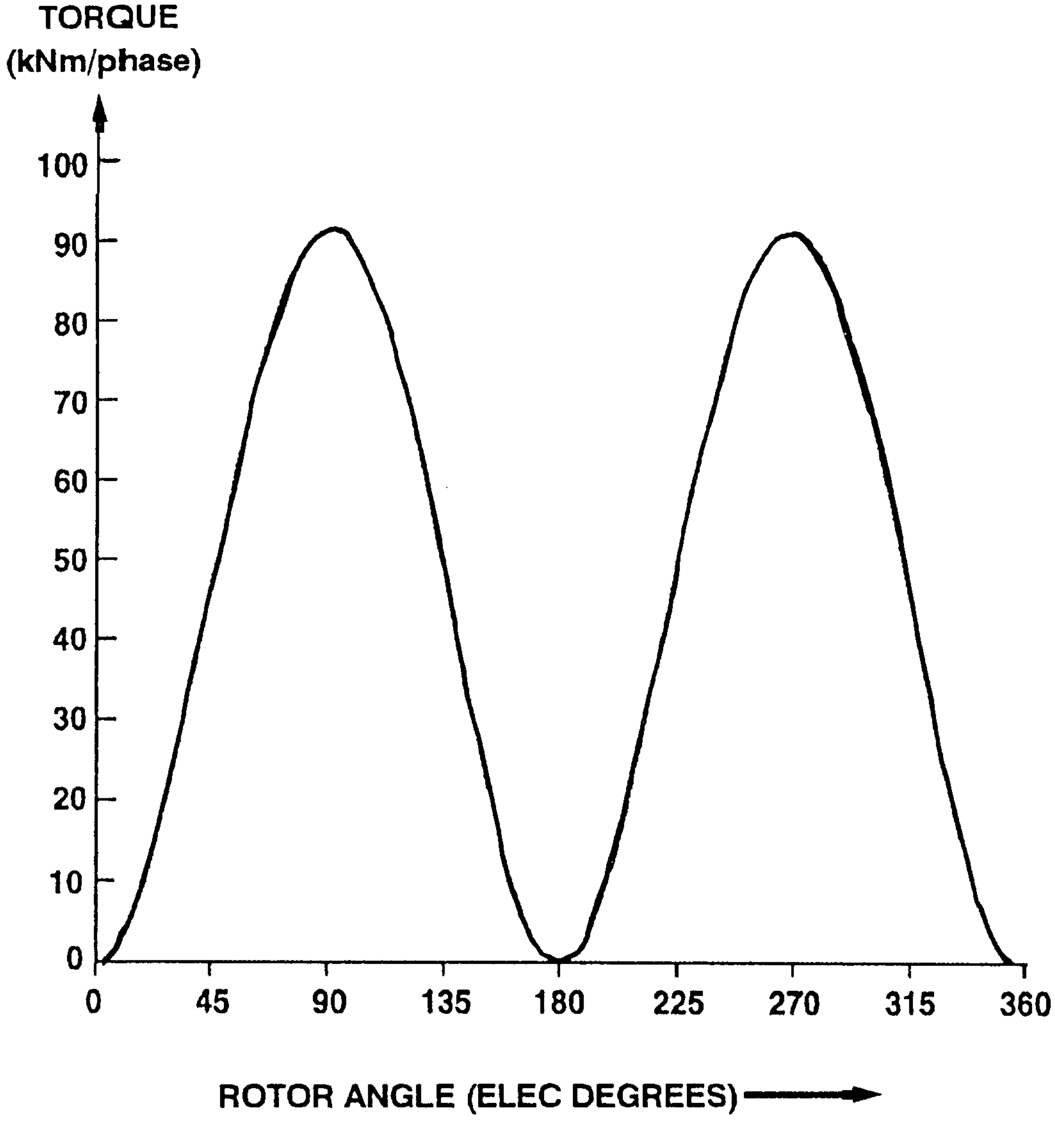

Fig. 7.—Predicted torque output from one phase

(Fig. 7) shows the time variation of single phase torque corresponding with the simulation given in Fig. 5. The torque for one phase is close to the ideal sine-squared function. Summing the results from all eight phases for this condition, the total torque ripple at the shaft is estimated to be just 0.6% of the steady torque.

The above analysis does not take into account the effects of cogging; this is independent of armature current and occurs even on no load. Analysis of cogging torque using finite elements is extremely difficult. However, measurements are available from a single phase linear rig from which it is possible to estimate the cogging torque for a full scale motor as given in

Table I. For the eight phase machine, the effect of cogging is to increase the torque ripple from 0.6% to 0.8%. The most significant component of torque ripple (arising both from the current-induced effect and also from cogging) is the 8th harmonic of supply frequency (for example, 1248 Hz at 80% speed). A lower phase number TFM would produce a higher torque ripple at a lower harmonic frequency.

The torque ripple predictions do not take into account current harmonics arising from the converter. Since the converter pulse-width-modulation frequency will be limited (to between 2 and 4 kHz) its modulation strategy will be crucially important in determining the harmonics in the current and torque. Several modulation strategies have been proposed but a full discussion is beyond the scope of this paper. The implementation of active torque control (using a form of torque feedback) remains a possibility, within the limits of the maximum driving voltage and modulation frequency.

The predicted efficiency of the motor at full load (20 MW 180 rpm) is comfortably in excess of 98% and detailed calculations have shown that it remains close to 98% at least down to 30% speed.

Power electronic converter

The outline specification for the eight phase converter is given in Table II. Rolls-Royce IRD are working alongside CEGELEC Ltd who are responsible for the converter development in the PMPM team. A key feature of the motor and converter is the separation of the windings and inverter power circuit for each phase. Consequently the converter comprises eight single-phase fully-controlled inverter bridges. This greatly improves the fault tolerance and possibilities for reversionary modes.

TABLE II—*Outline specification for converter*

Converter type	**PWM voltage source**
Semiconductor device	IGBT
Connection scheme	Isolated Phases
Number of phases	8
Power per phase	1800 kW (inner) 3200 kW (outer)
Nominal output frequency	195 Hz
DC link voltage	5000 V
Waveform at full power	Trapezoidal
Duty	Continuous
Cooling method	Direct water cooled

The preferred converter type for this application is a the Pulse Width Modulated (PWM) voltage source inverter. The high fundamental frequency (195 Hz at full speed) together with a need for close control of the current waveform and a compact overall arrangement mean that the preferred semiconductor power devices are insulated-gate bipolar transistors (IGBTs). The dc link voltage and peak phase current given in Table II suggest that there is a need for devices in series and parallel. As designed, the converter is directly water-cooled, with the power devices for each phase mounted onto a common water-cooled aluminium heat sink (using appropriate insulating wafers). The reduction of EMC and earth leakage currents is achieved principally by earthing the semi-conductor heat sinks at the mid-point of the dc link and ensuring that the devices are arranged for optimum dv/dt cancellation.

The effective rating for each single phase bridge is given by the product of dc link voltage and peak phase current. The figures given in Table II assume trapezoidal operation at full rated conditions.

Reversionary mode operation

In principle, the proposed design may be operated with any number of phases. However, in practice, operation with seven out of eight phases is to be avoided because of unfavourable torque ripple. Therefore operation is restricted to various pairs of phases (or just the outer four phases or inner four phases). Operation with six out of eight phases would provide up to 95% speed (90% torque) assuming that two inner phases are inactive, or 92% speed (84½% torque) assuming two outer phases are inactive.

Operation of the TFM is even possible (albeit undesirable) with a prolonged short circuit at the terminals of one phase. This would result in a twice fundamental frequency torque ripple but, because of the relatively high armature reactance, the fault torque and fault current would be substantially lower than the rated single phase values.

Development status

There is some way to go before the TFM can be regarded as a mature technology. To date, TFMs have only been built in relatively small sizes (up to about 200 kW) using motor topologies which are more relevant to these smaller machines (for such applications as electric vehicle propulsion and wind turbine generators).

Studies carried out by Rolls-Royce IRD have concentrated on the improved TFM topology described above and have tackled all the relevant aspects of the machine design including:

- Electromagnetic performance
- Mechanical design
- Manufacturability
- Naval shock tolerance
- Torsional vibration behaviour
- Heat transfer
- Materials and fatigue aspects.

In addition, a number of experimental trials have been undertaken:

(*a*) Investigation of adhesive joint configurations and measurement of bond strength (as applied to the joints between the magnets and laminated rotor poles).

(*b*) Trial manufacture of a linear section of the motor (concentrating mainly on the rotor).

(*c*) Measurement of the static performance of the machine using a linear rig.

(*d*) Trial manufacture and thermal testing of a representative armature coil using the proposed stranded rectangular conductor.

(*e*) Trial manufacture and testing of the stator cores.

(*f*) Cyclic endurance (fatigue) testing of representative rotor test pieces.

The trial manufacture and evaluation of stator cores and the cyclic endurance testing of the rotor test pieces are ongoing.

All of the tests have given useful data which, thus far, have confirmed the proposed manufacturing approach and validated the design. It is particularly noteworthy that the linear validation rig (FIG. 8) served to confirm the finite element performance predictions and confirmed the machine armature reactance.

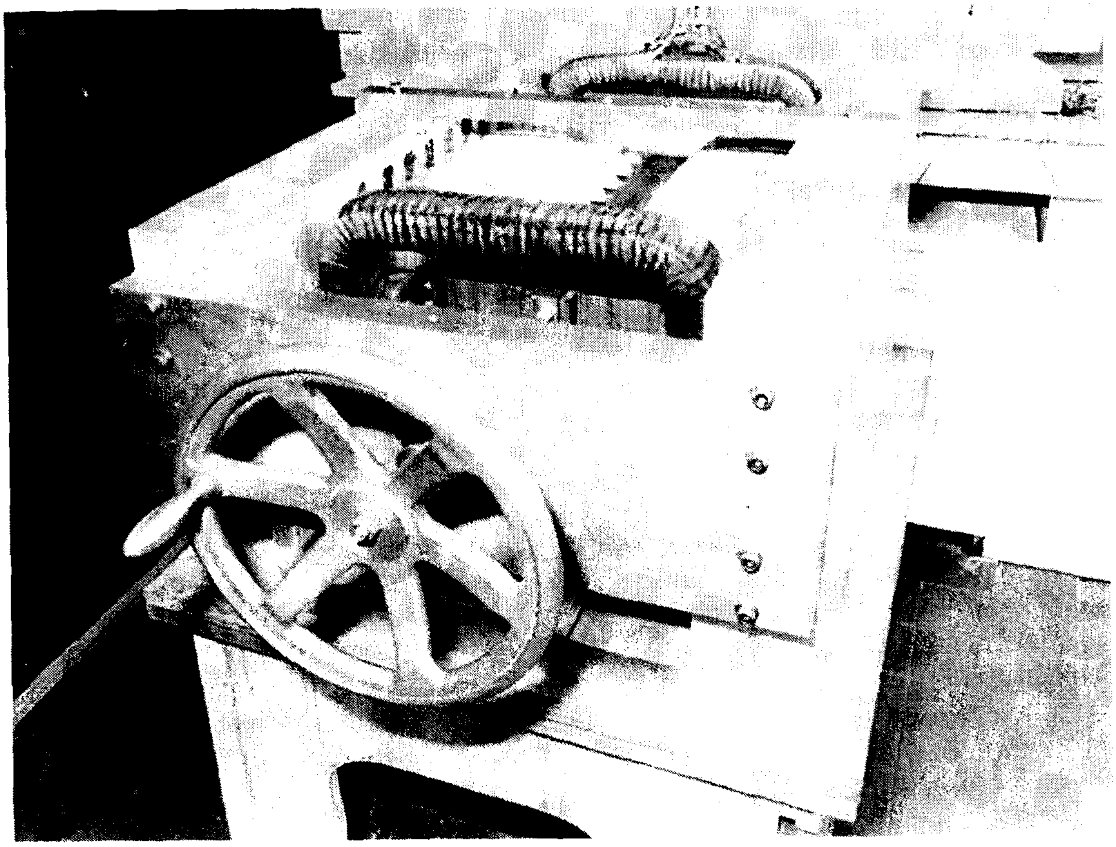

FIG. 8.—THE LINEAR VALIDATION RIG

The most immediate ongoing development stage is the build and test of a No Load Rotation Rig. This is a small scale (600 mm diameter) single-disc construction of the rotor and stator, which will be rotated (externally driven) to confirm the dynamic behaviour of the structure under the true conditions arising from the cyclic magnetic forces. A fully operational 3 MW motor and converter will be built and installed in a UK test facility towards the end of 1998.

Future applications

Development of the TFM is aimed at 3 future classes of RN vessels:

- Future Escort (FE) to replace the current Type 23 DUKE class frigates
- Future Carrier (CV(F)) to replace the INVINCIBLE class CVSG
- Future Attack Submarine (FASM) to replace the TRAFALGAR class SSN.

All of these vessels are expected to enter service during the early part of the next century.

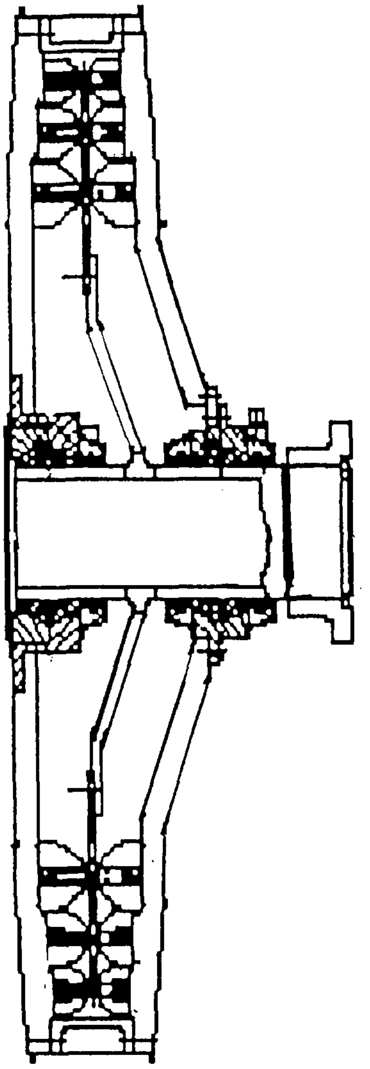

FIG. 9.—SUBMARINE TFM TOPOLOGY

The TDP is directed at FE and will result in a reduced risk, validated design database for a 20 MW, 180 rpm machine and converter. The CV(F) does not, of course, demand a high torque density propulsion motor as conventional machinery could be fitted in the larger hullform, however, the advantages of increased efficiency across the power range make TFM an attractive solution, assuming its initial purchase cost is acceptable. The motors may be installed in CV(F) in a tandem arrangement to provide 40 MW per shaft. The requirements for FASM are somewhat different, in power, shaft speed and architecture, and alternative arrangements have been considered (FIG. 9). The representative motor, having been designed to the same electromagnetic, thermal and mechanical loadings should de-risk the manufacturing and assembly techniques to enable the successful development of a machine for a FASM application, albeit with a different aspect ratio.

The TFM, and indeed IFEP, lends itself particularly well to novel hullforms under consideration for future surface vessels. Significant interest is being shown in the Trimaran concept (FIG. 10) for future warships which should provide distinct advantages in sea-keeping and survivability[9]. A flexible electrical propulsion system together with an efficient, high power density motor may be considered essential for this application. This becomes apparent when the installation of propulsion machinery in the narrow outriggers is considered.

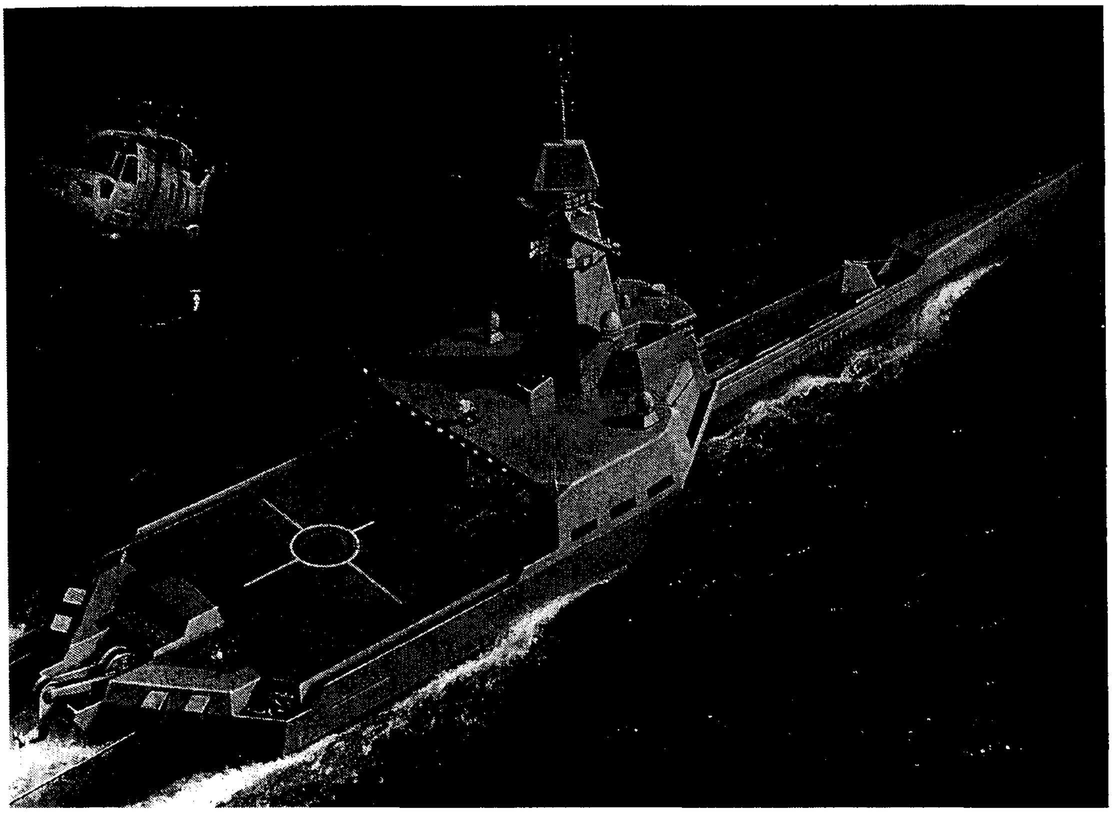

FIG. 10.—TRIMARAN FRIGATE

Alternatively, fixed and azimuthing podded drives are being considered for military propulsion systems and the TFM is again a highly attractive contender for these applications. The aspect ratio of such designs may be adjusted to offer minimal resistance to flow thereby improving propulsive efficiency. The advantages to the Naval Architect in design flexibility of an electrical propulsion solution are well documented and the TFM allows these benefits to be optimized for maximum efficiency. In all, the future of the TFM in a diversity of applications for marine electrical propulsion systems is encouraging and widespread use of this novel motor topology is expected.

Conclusions

The adoption of an IFEP installation for any future Electric Warship is dependent upon the successful development and integration of many technologies into a new power system architecture. The PMPM TDP is a crucial element of this overall requirement. It is centred around the TFM technology which offers a quiet, highly efficient, power dense propulsion solution through the optimisation of a novel permanent magnet machine.

Detailed analysis has shown that torque ripple from current-induced and cogging effects are both substantially cancelled by the proposed multi-phase topology. When compared with equivalent conventional wound field synchronous and induction machines the TFM is only one quarter of the size and exhibits a high efficiency, which remains so even at part load. The motor has an impressive tolerance to short circuit and open circuit faults and, together with its modular power electronic converter, possesses extensive reversionary mode capabilities. The TFM provides the opportunity for significant flexibility in ship design and optimisation of hydrodynamic characteristics, to enhance overall efficiency. This said, much work is still required to prove the design, manufacture, assembly techniques and performance before the TFM becomes a reality for naval propulsion.

Acknowledgements

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References

1. HODGE C.G; MATTICK. D.J. 'The Electric Warship'. *Evening Paper, The Institute of Marine Engineers*. 19 December 1995.
2. HODGE C.G; MATTICK. D.J. 'The Electric Warship II'. *Evening Paper, The Institute of Marine Engineers*. 10 December 1996.
3. BETTS C.V. 'Developments in Warship Design and Engineering', *Proceedings of the Institution of Mechanical Engineers*, 24 January 1996.
4. JOST V. 'Propulsion Plants for Naval and Civilian Ships—Possible Similarities and Necessary Differences'. *Proceedings of the International Naval Engineering Conference, Paper 10, Warship Design: What is so Different?* April 1996.
5. WEH H.; HOFFMAN H.; LANDRATH, J. 'New Permanent Magnet Excited Synchronous Machine With High Efficiency at Low Speeds'. *Proceedings of the International Conference on Electrical Machines*. 1988.
6. WEH H.; MAY. H.. 'Achievable Force Densities for Permanent Magnet Excited Machines in New Configurations'. *Proceedings of the International Conference on Electrical Machines*. 1986.
7. MITCHAM A.J.; DULLAGE B. 'A Novel Permanent Magnet Propulsion Motor for Future Warships'. *Cost Effective Maritime Defence, Paper 16, International Naval Engineering Conference*. 1994.
8. MITCHAM A.J.; CULLEN J.J.A. 'Motors and Drives for Surface Ship Propulsion: *Comparison of Technologies'. Electric Propulsion: The Effective Solution, Conference Proceedings*. 5–6 October 1995.
9. ANDREWS D.J.; JUN WU ZHANG. 'Trimaran Ships: The Configuration for the Frigate of the Future'. *Naval Engineers Journal*. May 1995.