Advances in Naval Propulsion Motor Technology

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Synopsis

Naval electric motors form the basis of the propulsion systems for many modern surface warships and submarines. The industry continually seeks to combine power density, robustness, noise quietness and efficiency to deliver the ideal combination of features. These features inevitably interact with each other and ultimately any design is a compromise that is optimised for a specific application. The compromises can involve different combinations of motor elements and different combinations of technology. Experience on how to apply the elements has developed over the large number of electrically propelled naval vessels that have seen service over the last 20-30 years. Furthermore, the technology underlying these elements has also developed in this timeframe, leading to significant advances. Some advances, such as experimental superconducting machines, while holding great promise appear unlikely to be mature enough for the next generation of platforms, others appear to be likely to applicable in the near term.

This paper looks at how electric motor technology has been applied to a range of naval vessels past, present and options for the future. It will consider where single motor, tandem and twin arrangements have been applied and also cover application of bearingless and spline shaft arrangements in naval vessels. It will also look at key technologies within motors for naval application, such as rotor and stator skewing, advanced anti-vibration mounting, shock-proofing and multi-phase windings. Recent developments in rotor and cooling design will also be discussed, building on the solution described in the Salter and Lewis paper at INEC2018, with the power density, noise quietness and efficiency benefits of the latest techniques being considered. Consideration will be based on advanced modelling combined with full scale testing results. In many ways this paper represents a retrospective of the career of the late Clive Lewis, a highly respected, regular contributor to this conference over many years and this paper will pay tribute to the enormous contribution he has made in this field.

Key Words: Manufacture, repair and upgrade innovations, driving energy efficiency, advanced modelling and simulation

Figure 1 Clive Lewis

Authors' Biographies
Ben Salter is the Naval Sales Director of GE Power Conversion, a Chartered Engineer and Fellow of the IET he has over 30 years' experience in the application of electrical technology. In that time he has worked on many naval programmes for several navies in both the surface and sub-surface arena. He also had the privilege of being a friend of Clive Lewis
Joseph Eugene is the Electromechanical Systems Integration Manager of GE Power Conversion, a Charted Engineer he has over 20 years' experience in the application of propulsion systems design. He has worked closely with Clive Lewis on many Naval projects and superconducting machines development.

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1. Introduction

On the 29th of January this year our dear colleague Clive Lewis passed away. Clive was one of the world's leading experts in modern naval electric propulsion technology and was a key participant in many of the programmes that have led to the hybrid and full electric warships of today. It therefore seems an appropriate moment to take stock of the journey we have travelled from the start of Clive's career until today. Table 1 is a reasonably full (though not exhaustive) summary of the application of naval electric propulsion technology to major warships in the last 30 years.

The key component in electric propulsion is, of course, the electric motor itself. The main components of an electric motor are as follows (see Figure 2):

Rotor: This typically comprises a shaft, to transmit the torque, which is supported on bearings. It includes iron laminations to carry the magnetic field and some form of electrical circuit (or permanent magnets) to generate that field. Rotors may be cylindrical or may have salient poles that protrude from the shaft in a non-circular cross section. A system may be built into the rotor in some motor types to provide power to the rotor circuit.

Stator: This is normally cylindrical in shape and surrounds the rotor with an airgap separating them. This also comprises iron laminations to carry the magnetic field and coils called "windings" that generate a magnetic field. It is the magnetic field that generates the torque between the stator and the rotor which in turn drives the shaft.

Frame: This is mechanically coupled to the stator and provides the reaction torque to hold it in place. It is also normally coupled to the bearings that support the rotor and ensure an airgap between it and the stator. The frame itself is mechanically coupled to the motor seat which is part of the structure of the hull.

Cooling: Motors have losses that reduce their efficiency [Ref 1]. The losses are manifested as heat within the machine which must be removed by the cooling system. This ultimately couples the heat into cooling water, normally via an air/water heat exchanger and fan system.

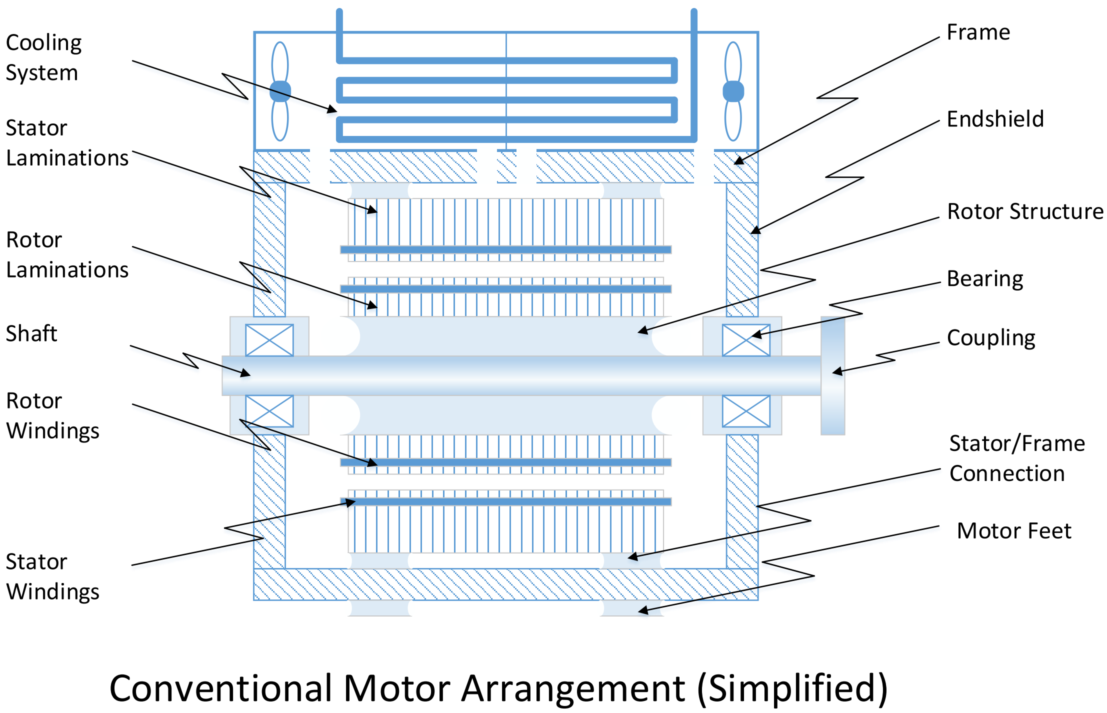

Figure 2

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2. Development of Modern Electric Propulsion

Fundamental Drive Technologies		**Application on Major Naval Vessel (public domain information)**				**Clive Lewis Contr^n**
Motor	**Control**	**Class**	**Type**	**Nation**	**Configuration**	
DC	Switched Armature	Submarine Applications		Several	Tandem	Yes
	DC Converter	Duke (Type 23)	FF	UK	Bearingless Two Shaft Hybrid	Yes
Wound Synchronous	LCI Converter	Albion	LPD	UK	Conventional Two Shaft	Yes
		Mistral	LHD	France	Pod	Yes
		Henry J. Kaiser	AO	USA	PTI/PTO	
		Wave / Lewis & Clark	SS	USA	Tandem	Yes
		Rotterdam / DeWitt / Bay / Choulles	LPD	Netherlands / UK / Australia	Conventional / Pod	
		Juan Carlos / Canberra	LHD	Spain / Australia	Pod	
Conventional Induction (High Speed)	PWM Converter	Makin Island	LHD / LHA	USA	Gearbox PTI	Yes
		Tide Class	AO	UK	Gearbox PTI/PTO	Yes
		Vulcano	AO / SS	Italy	Gearbox PTI/PTO	Yes
		Paulo Thaon Di Revel (PPA)	FF	Italy	Gearbox PTI/PTO	Yes
		Trieste	LHD	Italy	Gearbox PTI/PTO	Yes
High Torque & Advanced Induction	PWM Converter	Daring	DD	UK	Conventional Two Shaft	Yes
		Zumwalt	DD	USA	Tandem Two Shaft	Yes
		Queen Elizabeth	CV	UK	Twin	Yes
		Karel Doorman	SS	Netherlands	Conventional Two Shaft	Yes
		Baden-Württemberg	FF	Germany	Two Shaft Hybrid	
		City	FF	UK	Two Shaft Hybrid	Yes
Permanent Magnet (PM)	PWM Converter	Aquitaine / Bergamini (FREMM)	FF	France/Italy	Spline Two shaft Hybrid PTI/PTO	
		Daegu	FF	Republic of Korea	Bearingless Two Shaft Hybrid	
		Submarine Applications		Several	Tandem/Conventional	Yes
	Integrated Converter	Submarine Applications		Several	Conventional	
Exotics: Superconducting	PWM Converter	Hydrogenie Research		UK	Conventional	Yes
		NAVSEA Research		USA	Conventional	Yes
Exotics: Advanced Cooling	Integrated Current Source Inverter	APM Project		UK	Tandem	Yes
Exotics: Adv Cool plus PM	PWM Converter	APMM Project		UK	Conventional	Yes

Table 1 A Summary of the Application of Electric Propulsion in Modern Navies and Research Programmes

2.1 DC Motors

The foundational electric motor technology in this field is the Direct Current (DC) motor which combines high power density and robustness. However, the key benefit of the DC machine is controllability. The torque is fundamentally controlled by current and the speed is controlled by the applied voltage with further adjustment

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possible through field current. This means that for "classical" submarines, a very elegant application approach is possible. Two rotor/stator pairs that are electrically and magnetically independent are mounted within one motor frame and between one pair of bearings. This is called a "tandem" machine (see Figure 3). The submarine also contains two or more independently switchable energy stores. Shaft speed control can be achieved by various combinations of series and parallel electrical connection of rotors and batteries to create higher or lower voltages across the rotors and therefore different shaft speeds. Switching is achieved through electromechanical devices. This solution is therefore practical on schemes where distribution voltage can be variable and is dominated by the energy stores, but it is not viable on surface warships where fixed voltage Alternating Current (AC) distribution at higher powers is required and was therefore limited to 'SSK' submarine applications.

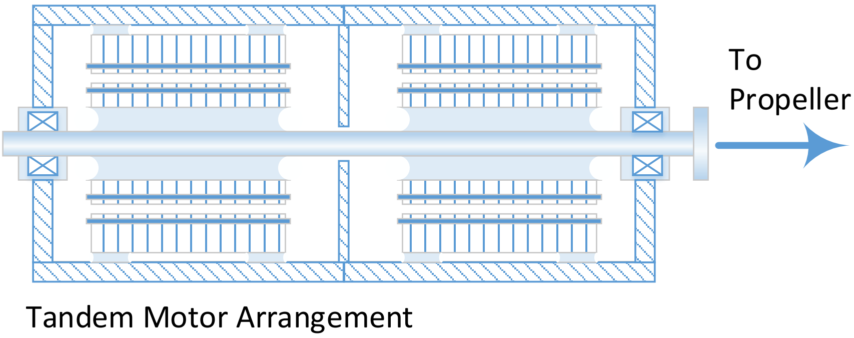

Figure 3

The breakthrough for surface ship electric propulsion came with the advent of reliable and robust power electronic switching. This enabled power to be distributed using conventional AC, which is far easier to manage safely, even at high power.

The pioneering warship for this technology is the Royal Navy (RN) Duke class Type 23 frigate. This anti-submarine warfare (ASW) specialist is a hybrid design which uses high torque DC motors aft of the mechanical propulsion gear, which is de-clutched, stationary and silent during quiet electric propulsion in ASW operations. In order to optimise the integration of the shaftline elements, the motors do not have internal bearings but instead the rotor is suspended between the gearbox and thrust block bearings. This arrangement shortens the shaftline and saves cost and weight. It is an approach that has been followed on one of Type 23's many hybrid descendants, the Daegu class.

Type 23 used a DC motor with a converter controlling the current and voltage fed to the machine. However, the electromechanical switching inherent to a classic DC motor, the most critical element of which, the commutator, limits the maximum voltage to less than 1000V, means ultimately that the power of such machines is limited. For the higher powers and voltages associated with full electric propulsion, an AC motor technology was needed.

2.2 AC Synchronous Motors

The AC motor type that is most straightforward to control is the wound synchronous machine. This typically has a stator, wound for three phase AC and, on the rotor, a DC field using wound, salient pole electromagnets which are fed by an excitation system. Such a machine can be powered and controlled by a relatively simple Load Commutated Inverter (LCI) which can take fixed frequency AC, rectify it to variable voltage DC link and then invert this to the required frequency output through the machine bridge. This approach does not suffer from significant inherent voltage or power limitations. Critically, it also means that the motor can be coupled to the main, fixed frequency, AC bus of the ship, thus enabling power from the prime movers to feed any load, whether ship service load or propulsion load, so called integrated electric propulsion (IEP).

The first naval vessels to use this technology were the Wave and Albion classes, and synchronous machines have proved very adaptable in their application to naval vessels. In the single shaft Wave class, a tandem arrangement was used to provide enhanced integrity and this approach was later followed on the Lewis & Clark class of T-AKEs.

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On Albion, there are two conventional individual motors, each with their own bearings on two separate shafts an approach later followed on the Rotterdam. Synchronous motors have also been mounted in pods on classes such as Mistral, De Witt, Bay, Choulles, Juan Carlos and Canberra. What all these classes have in common, however, is a limited shock capability. A low shock requirement is an enabler for the use of synchronous machines since the elaborate rotor construction and excitation arrangements make them difficult to shock harden to a high level. This is less of a problem when co-located with an engine on a skid (i.e. as a generator) but mounted low in the vessel on the shaftline it presents a significant difficulty.

2.3 AC Induction Motors

For “front line” warships, where high shock capability is essential, an extremely mechanically robust motor technology is required. The most widely used and robust motor technology is undoubtedly the induction motor. In these machines the rotor is a copper and iron cylinder whose “windings” are in fact solid bars of copper encased in iron laminations. Such machines can be constructed to take full shock loads without the need for resilient mounts. They are, however, very difficult to control precisely and it was only with the emergence of high power, voltage source, Pulse Width Modulated (PWM) inverters, combined with advanced software control algorithms, that this became possible. When this technology was coupled to induction motors that incorporated advanced cooling and multiphase techniques to increase the power density (called advanced induction motors” or AIMs) the first practical surface warship electric propulsion systems emerged. These have been used in the full electric Daring, Zumwalt and Queen Elizabeth classes. Similar approaches have also been used for the hybrid propulsion motors on classes such as the Baden-Württemberg and City class frigates.

In the case of the Daring class the motors were conventionally arranged, one per shaft. On Zumwalt a pair of tandem motors (one per shaft) were used and on Queen Elizabeth there are two motors per shaft in a twin arrangement, each motor on a shaft in a separate watertight subdivision (see Figure 4). The arrangement of motors in the frigate classes is also varied. On City class the motors are aft of the gearbox and can decouple from it using clutches to minimise structureborne noise when in electric drive. In Baden-Württemberg the motors are forward of the gearbox but with a gearbox arrangement that allows each motor to drive its shaft without engaging the gear cogs, for the same reason.

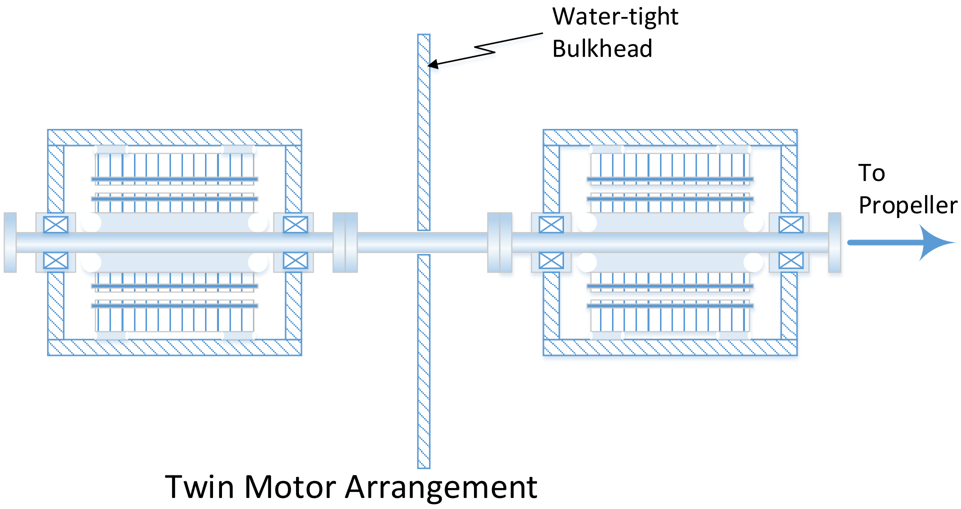

Figure 4

In addition to advanced induction motors, conventional machines have also been used on naval vessels. They are typically solidly mounted on support ships and resiliently mounted on warships. These motors are used for hybrid propulsion and operate via a gearbox. The more advanced among such systems are shock-proof and allow for Power Take Off (PTO) from the shaft back into the electrical system, as well as the more conventional Power Take In (PTI) when driving the shaft.

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2.4 AC Permanent Magnet Motors

In parallel with the advances in induction motors for surface ships, another motor technology became increasingly important in the submarine world - the Permanent Magnet Motor (PMM). These motors have rotors that incorporate high strength permanent magnets that are made from rare earth elements. These have the advantage of generating a rotor field without generating any additional heat in the machine. Such rotors can be constructed robustly and do not require excitation equipment. Control, however, is relatively complex and requires the same sort of inverter as an induction machine. Such machines are typically used where space and weight are at an absolute premium, hence their early adoption on submarines, where in some cases the inverter has been integrated with the motor itself. However, they have also been used on frigate classes such as Aquitaine and Daegu. In both cases the motor is mounted aft of the gearbox via a clutch. The Aquitaine motors have a hollow shaft through which the main drive shaft passes in a spline arrangement. Both the rotor shaft and the main drive spline shaft connect to the same flexible coupling aft of the motor, an arrangement that avoids the use of two flexible couplings. The Daegu motors have a bearingless arrangement and are solidly mounted. Such PMM arrangements need to cope with the operational challenges of dealing with a motor technology that cannot be de-excited under fault or battle damage conditions and will continue to generate high currents into a fault, whenever the shaft is turning.

3. Advancing Motor Technology for Naval Application

Technology	Equipment	Function	Naval Purpose	Clive Lewis Contr^n
Rotor Skewing/ Offset Poles	DC motors/ APM	Reduce MMF Harmonics	Signature Reduction	Yes
Stator Skewing	Synchronous/PM	Reduce MMF Harmonics	Signature Reduction	Yes
Stator Mounts	Any Motor	Decouple stator vibrations from frame	Signature Reduction	Yes
Shock Hardening	DC/Induction/ PM/APM/APMM	Withstand military grade acceleration levels without soft mounts	Maintain propulsion after shock event and simplify shaftline especially for main drive	
	Converters	Withstand military grade acceleration levels	Maintain propulsion function after shock event	
Soft Mounting and Flexible Coupling	Induction/PM	Reduce shock levels above mounts and/or signature below mounts	Signature Reduction and/or use of lower specification motor especially for auxiliary drive	Yes
Multiphase Windings	Advanced Induction/PM	Provide galvanically isolated sets of windings within a single stator	Signature Reduction. Enhanced resilience against equipment failure and action damage	Yes
	Converters	Provide independently operable, galvanically isolated power sources to a motor	Enhanced resilience against equipment failure and action damage	Yes
Electrical Filtering/ Cancellation	Converters	Reduce time harmonics in the electrical waveforms into or out of a converter	Power Quality improvement. Signature reduction	Yes
Common Mode Management	Converters	Reduce EMC effects on high power switched waveforms	Power Quality improvement. Signature reduction	Yes
Advanced Air Cooling	Air Cooled Motors	Optimise airflow within machine	Improved power density. Signature reduction	Yes
Liquid Cooled Rotor	APM	Insulating liquid to enhance heat transfer from rotor windings	Improved power density	Yes
Supercooled Rotor	AMSC	Very low loss high current windings	Improved power density	Yes
Liquid cooled stator windings	APM	Insulating liquid to enhance heat transfer from stator windings	Improved power density. Signature reduction	Yes

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Liquid cooled stator teeth	APMM	Enhanced heat transfer from stator windings	Improved power density. Signature reduction	Yes

Table 2 Summary of Naval Related Electric Motor Technology Developments

3.1 Introduction to Advanced Motor Technologies

Over the period of his career, Clive was involved in many aspects of improving the fundamental motor technologies used in naval applications (see Table 2). Some of these were matured to adoption and others are still in development. The remainder of this paper looks at the key design features that can improve the cooling, noise and vibration and shock capabilities of motors.

The increasing global need for high efficiency and low operational cost is a driver in the development of new ship propulsion technology. This has led to motor manufacturers looking beyond conventional copper and relatively mature PMM technology and look at exotic materials such as superconducting machines. Superconducting machines; High Temperature Superconducting (HTS) and Low Temperature Superconducting (LTS); offer high efficiency and reduced mass and size. The super cooled windings operate at cryogenic temperatures and require a vacuumed sealed rotor. This increases the electrical airgap and inherently the amp turns required to produce the required flux. The increased air gap amp turns are a fraction of the current density improvement on a superconducting winding, allowing an overall power density. However, the cost of the superconducting wire is significantly higher than conventional copper winding. Furthermore, the TRL (technology readiness level) of the cryogenic system required to cool the superconducting motor is low and it has not been reliable enough to support marine requirements. Several machines have been built and tested to prove the technology in high performance rotors, but it has not reached the maturity required for an operating vessel. Continued development of the superconducting wires and cryogenic systems will increase the possibility of future vessels with superconducting motors.

The power density of any electrical machine depends upon the effectiveness of its ability to dissipate losses in the form of heat. There are a wide variety of means of cooling, however, for naval propulsion it is necessary to focus on methods that combine high performance with low noise and a good TRL. Double Ended Radial (DER) air cooling is standard cooling technology for large rotating machines. For totally enclosed machines the internal air is forced through gaps between the stator laminations and is then passed through an air-to-air or air-to-water heat exchanger to remove the losses to ambient conditions. This keeps the internal air uncontaminated by external conditions. Using an air-to-water heat exchanger offers greater power density and higher efficiency compared with using an air-to-air heat exchanger. For large machines this enables a more evenly cooled machine compared with air entering at one end (Single Ended Axial).

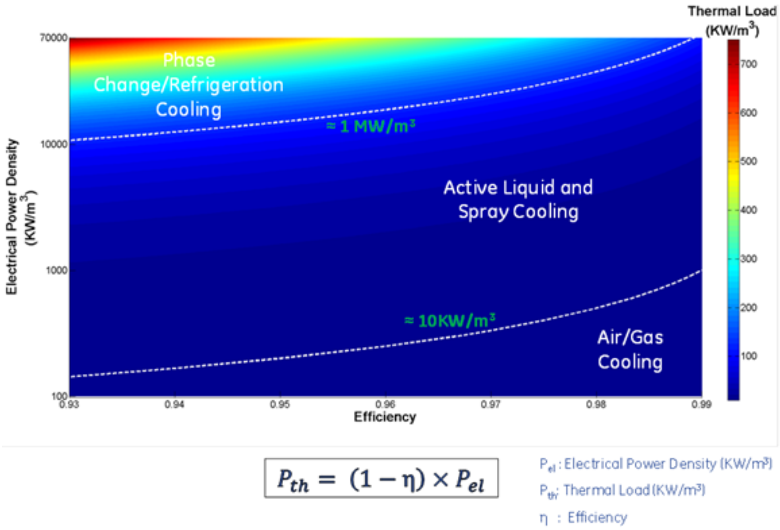

Figure 5 Cooling power density

3.2 Advanced Permanent Magnet Motors

Figure 5 shows different cooling mediums in relation to power density. It provides a good argument for the use of liquid based cooling. Conventional synchronous and induction motors require cooling of the stator and rotor, unlike PMM technology that only requires cooling of the stator. Using liquid to cool the rotor requires rotating couplings to transfer the cooling medium and reduces the reliability of the motor. Cooling of the stator winding can be direct or indirect. Direct cooling removes the heat dissipated in the winding by either submersing the winding in the liquid or passing liquid through the winding. The liquid must be a dielectric as it is in direct contact with the winding. The submerged cooling option requires a non-conducting cooling chamber in the airgap. This increases the rotor stator airgap and the amp-turns required to produce the required torque.

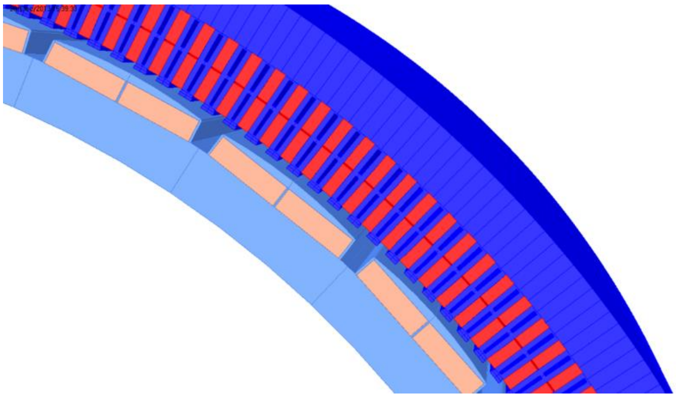

Figure 6 Advanced Permanent Magnet Motor Concept

The combination of PMM technology directly cooled by water offers a very power dense yet simply constructed motor [Ref 1]. This takes into account the motor and cooling system as a whole, an important consideration where space is limited. The use of a PM rotor adds to the simplicity of this concept by removing the need for any rotor cooling. A low speed, shaft mounted fan provides cooling air for the end windings while creating a much lower level of noise than a fully air-cooled machine. The liquid coolant used can be at a low pressure, which combined with a well compressed and sealed stator core ensures no leakage can occur through the laminations. The liquid coolant is not in direct contact with any electrically live components so a dielectric coolant is not a requirement – as would be the case if the liquid was in direct contact with the stator conductors.

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3.3 Noise and Vibration Considerations

Motor generated noise and vibration (N&V) is another key factor in the selection of the motors for naval application. N&V from the main motor is dominated by the geometric harmonics generated by the shape of the rotor poles interacting with themselves and the stator slotting. Fractional slot winding, skewing the stator slots or profiling the rotor pole and optimising the pole width are further refinements which can be carried out as part of a motor's design to reduce noise signature and cogging torques. The closer the pole becomes to a sine wave then the lower the magnitude of the geometric harmonics which are produced. However, this adversely affects the effectiveness of torque production from a given stator current. Thus, a compromise has to be made on the actual design parameters and this needs to be part of design optimisation in conjunction with Finite Element Analysis (FEA). A further electromagnetic signature mitigation technique is rotor pole offset, where the separation between adjacent rotor poles is varied to improve the noise and cogging torque. PMMs can be designed with a larger airgap to reduce noise at the expense of power density. Well-designed induction rotors naturally benefit from low cogging torque and do not require skew but PMM rotors need to make use of these techniques to achieve low signature.

The structural dynamics of the motor and its seating will determine the attenuation of the N&V between the source in the motor stator and the emitting surfaces. Soft mounting a motor is a trade-off between the N&V and the space and cost required for the coupling. The size of the coupling is determined by the torque transfer and the flexibility required for the shock. Additional N&V attenuation can be provided by specifically designed mounting systems such as stator mounts. These are carefully chosen mounts, targeted at higher vibration frequencies. They are utilised to isolate the active part of the stator core from the motor frame. The stator mounts allow high torque transfer in the tangential direction and low noise transmission in the radial directions with their orientation also allowing high shock capability. Stator mounts are particularly valuable on shock rated applications since they results in zero shaftline displacement and therefore do not require expensive flexible couplings. Resilient mounting can be extended to the motor fans and is effective for attenuating N&V from the fans' rotational and blade passing frequencies.

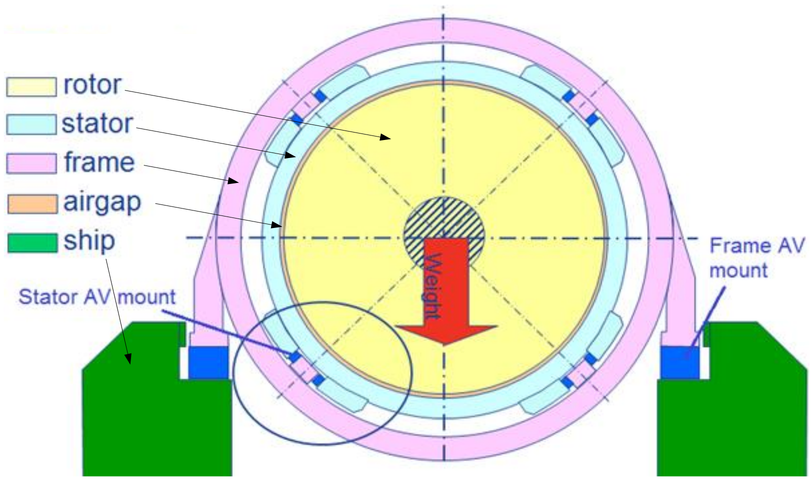

Figure 7 Stator Mount Concept

3.4 Shock Hardening Considerations

For warships, a propulsion motor is required to function during and after a shock event. The shock input is determined by the mass of the motor and how it is mounted on the ship. High torque rated motors can be solidly mounted to the hull structure and can be designed to meet the shock requirement. A single soft mounted option provides better N&V attenuation and can be designed to reduce the shock levels experienced by the motor (though this is not always the case). However, soft mounting a motor requires a flexible coupling between the motor and shaft line to accommodate the shock displacement which can be significant. This means that the flexible coupling

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can significantly increase the length on the shaftline of the overall motor system and its weight. It can also complicate shaft alignment and dynamics. Stator mounting can avoid this issue since it can accommodate shock loads without displacing the shaft. However, for extremely quiet operation the motor can be designed to have multiple mounts to further reduce the N&V to very low levels. Careful consideration is required in selecting the mounting system based on FEA modelling, shock table testing (limited weight) or shock barge testing. Typically, a combination of the first two are used, with expensive barge testing limited to fewer programmes.

4. Conclusion

Clive's career has spanned a period of extraordinary development in naval electric propulsion. It covered the span from the traditional DC machine right through to experimental superconducting technology. Part of Clive's quiet genius was to see how different, well understood technologies could be combined in new ways to achieve significant advances in applied technology in the naval propulsion arena. The widely used AIM is one example of this. Another example is the APMM, a true step change in naval power density that was the latest programme that he was working on. This power dense, low noise, shock proof development offers real promise of being the next generation naval technology and it may well provide a fitting coda to an illustrious career. Clive has been a real pioneer of naval electric propulsion technology and has made major contributions to many aspects of its technological development. This in turn has enabled its application to a very wide range of vessel types benefitting the navies of many nations. His contribution to its future will be sadly missed.

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