The electric warship

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Integrated full electric propulsion has become a normal first choice for several commercial operators, in particular for cruise ships where it proves to be a fuel efficient transmission system. Operating profiles for warships of frigate size and above are similar to cruise ships with long periods at well below full power. However, the size, weight and initial cost of electric propulsion equipment has generally precluded selection for warships. With the application of modern technologies, equipment power densities are being increased such that integrated full electric propulsion has now become a serious competitor to the mechanical transmission systems traditionally adopted for warships. This paper reviews the prime elements of an electric propulsion system and then assesses the potential impact of emergent technologies, combined with integrated full electric propulsion, on a frigate sized warship. Changes to other marine engineering systems are outlined, along with the requirement for platform management systems and the consequential manpower changes. Comparative costs are derived for mechanical and electric transmission.

INTRODUCTION

Current generations of warship utilise a Combined Diesel and Diesel (CODAD), Combined Diesel and Gas (CODAG), Combined Gas and Gas (COGAG) or, in the case of the Type 23 frigate, Combined Diesel Electric and Gas (CODLAG) propulsion configurations. The first of these descriptors is used to identify the cruise method of propulsion and the second identifies the boost or sprint method.

Warships are generally designed with a maximum speed of around 30 kn yet spend much of their time at slower speeds, typically 80% of the time is spent below 18 kn. The concept of ‘cruise’ and ‘boost’ propulsion capability allows machinery alignments that minimise fuel usage, for example CODAG has fuel efficient diesels for cruise and power dense gas turbines for boost. This laudable concern for fuel economy is not just to reduce fuel cost, typically warships have limited bunkerage and expect to refuel at sea, whatever the weather. Limited bunkerage and high power density gas turbines both serve a common aim: they reduce the volume of the ship required to support propulsion and leave more room for weapon systems in small displacement (and thus low cost) ships.

Over recent years the world order has changed and most nations which own warships are striving to reduce defence expenditure. As such, future generations of warships must be cheaper to buy (Unit Production Cost (UPC)) and cheaper to run (Running Cost (RC)). This pressure impacts on all that goes to make up the ship; however, it is very difficult to reduce the cost of successive generations of weapon systems, thus there is correspondingly more pressure to reduce the cost of the platform and its propulsion equipment.

This paper provides a high level view of the way in which electrical propulsion can contribute to reduced cost. To limit the scope, detailed discussion is confined to frigate sized, monohull vessels of some 4500t with a 30 year in-service life. It is also assumed that the vessel will come into service around the year 2010.

MECHANICAL AND ELECTRICAL TRANSMISSION

Virtually all current major warships use mechanical transmission where the prime movers drive a gearbox, which in turn powers the shaft and propeller (Fig 1). Such a mechanical transmission system achieves 95% efficiency at full power.

Authors’ biographies

After initial training as a mechanical engineer, and service as an Assistant Marine Engineer in HMS Warspite, Christopher Hodge joined HMS Orpheus as the Marine Engineer Officer in 1982. He subsequently took an MSc in Electrical Marine Engineering and served in the MOD as the project officer for electrical ship propulsion. After promotion to Commander in 1989 he served as the Marine Engineer Officer of HMS Conqueror before returning to the MOD as the Head of the Nuclear Steam Raising Plant electrical design authority. Since 1993 he has served as the head of the electrical power systems specialist group within the MOD.

David Mattick’s early career resulted from specialisation as a nuclear submarine weapon engineer. After service as the Assistant Weapon Engine Officer of HMS Warspite and in the MOD, he rejoined Warspite as the Weapons Electrical Officer. In 1982 he was appointed as the Marine Engineer Officer of HMS Swiftsure. After promotion to Commander in 1984 he headed the electrical power systems specialist group within the MOD, subsequently serving within the Vanguard class submarine project and then as a Project Manager in the Director General Ship Refitting organisation. Since 1994 he has been the Surface Ship Marine Engineering Desk Officer in Director Future Projects (Naval) whose current tasks are concept design of future naval vessels.
Neither diesels nor gas turbines operate easily in both directions of rotation, yet ships must be able to manoeuvre. Many clever, and some very complex, methods have been adopted to provide astern power, including: cp propellers, reversing gearboxes, fluid couplings and, to allow a diesel engine to be started in either direction, sophisticated valve gear mechanisms. All of these have disadvantages. The most common current choice for warships is the cp propeller which, due to the compromises on its shape, puts noise in the water that gladdens a submariner’s heart as well as reducing the transmission efficiency by some two points, equivalent to an additional £3/4M of fuel over the life of the ship.

One solution is to use an electric motor to turn the shaft (Fig 2). Reversing the direction of a motor is simple and is usually achieved these days by power electronics switching the polarity or phase of the applied electrical supply. This, on its own, is one reason for choosing electrical transmission.

With electrical transmission, generators convert prime mover rotational power into electricity, which is transmitted to motors and these convert electricity back into rotational power. As such, there are two conversions in the transmission train rather than the one of a geared mechanical system and greater losses result. Typical electrical transmission efficiency is 89% at full power. However, the efficiency of electrical transmission does not fall off as quickly with shaft speed as mechanical transmission and it can be more efficient at lower speeds.

There is another advantage to bring out at this stage. Propulsion is not the only requirement for power: the weapon systems and the ship’s company also consume electrical Ship Service load. A typical frigate with mechanical transmission has four prime movers to generate electricity and four to propel the ship. With electrical propulsion the same prime movers can be used for both duties and such a system is known as Integrated Full Electrical Propulsion (IFEP). With the Ship Services providing a baseload, the inefficient low load part of the fuel consumption curves can be avoided and better fuel economy results. Furthermore, with an optimised mix, the number of prime movers installed can be reduced, yielding both lower UPC and RC. In the case of RN frigates for example, the Type 22 with mechanical transmission has eight separate prime movers, the Type 23 with a hybrid CODLAG system has six and a future frigate with IFEP might have four.

The advantages of using the Ship Services as a baseload and the higher efficiency of electrical transmission at part loads are the main reasons for the cruise ship market widely adopting IFEP. The benefit of IFEP is maximised when much of the operating profile is well below maximum speed and when the Ship Service load is a significant proportion of the usual propulsion load. To put this in context, the prime mover running costs for a frigate with mechanical transmission are compared in Table I for the three operating profiles shown in Fig 3. The figures are pessimistic as they have retained the 6% lower efficiency of IFEP throughout the speed range.

What then are the main disadvantages of IFEP? There are two. Firstly, where a ship spends the majority of its time at close to full propulsion power the lower transmission efficiency of electrical transmission militates against IFEP; such is the case for many ships engaged in intercontinental trade such as tankers. In these ships, fuel savings are frequently realised by shaft driven generators which support the electrical load whilst underway. Secondly, the electric propulsion motors and the current generation of power electronic converters which control them are expensive, big and heavy. Studies of IFEP systems suitable for warships, undertaken by the MOD, indicate that the procurement cost of the equipment is some 25% more than that of an equivalent mechanical system, with the weight and volume being significantly greater. However, the majority of the excess weight and volume of the system is concentrated in the motor and converter. Accordingly, to make IFEP the natural selection in a cost constrained environment requires the motor and converter cost, weight and volume to be reduced.
This section of the paper reviews the recent advances, principally in permanent magnet technology, motor design and power semiconductor devices and variable speed drives, that are ready to reduce the physical size and mass of an IFEP system such that its bulk compares favourably to that of its mechanical equivalent; and, further, offers a much more flexible approach to the physical location of equipment, with consequent benefits to the overall design of the ship itself.

Permanent magnet technology

Rare earth permanent magnets can be broadly grouped into low and high cost categories. The low cost permanent magnet materials of Alnico, bonded ferrite and sintered ferrite do not have the necessary magnetic properties required in high power density marine propulsion applications. The two favoured high cost materials are Neodymium Iron Boron (NdFeB) and Samarium Cobalt (SmCo). NdFeB is less expensive than SmCo and possesses very good mechanical strength, but it suffers from a poor temperature performance and corrosion resistance. Alternatively, SmCo is more expensive and has a reduced mechanical performance compared with NdFeB, but it has a much improved temperature performance. These differing characteristics, together with their similar magnetic performance, make the choice of material between NdFeB and SmCo dependent on the exact application, and this primarily concerns the mechanical arrangement and thermal profile within the machine.

Motor design

Conventional machines appear to be approaching full development, and although they are available to suit the major-
Accordingly, this implementation does not improve the power density of the conventional machine to the degree that can be achieved by radical changes in machine topology, but it does reduce the rotor losses experienced in a more conventional machine. The radial flux topology is not suited to motors rated much higher than 7 MW at 180 rev/min.

The axial flux machine is invariably excited through permanent magnets and is also known as the disc motor. This novel arrangement is shown in Fig 5 and incorporates a rotor and two stators, each of which is disc shaped, with the axially magnetised permanent magnets located in pockets in the rotor disc. The permanent magnets drive the magnetic flux across the two annular air gaps into the stator core. The current in the stator winding coils interacts with the flux generated by the magnets producing a tangential force, and the machine torque results from the contribution of all these forces. Some loss of torque density arises from the varying radius at which individual conductors exert their force; some are located at significantly reduced radii compared to others and so are less significant contributors to the overall output torque.

The transverse flux motor is a novel topology which overcomes many of the constraints of the preceding topologies by implementing, as its name suggests, a transverse flux arrangement which optimises a flux concentrating principle to improve the electromagnetic performance of the machine. The basic arrangement of the machine is shown in Fig 6 and consists of a circular coil co-axial with the rotor. The stator winding links the flux generated by the permanent magnets by means of a series of stator hoop pole pieces. The flux path is shown in Fig 7. The configuration incorporates stator pole pieces inside and outside the rotor, which improves the electromagnetic performance of the machine, with useful torque being developed at both the inner and outer surfaces of the rotor. The most recent design proposed for a 180 rev/min 20 MW transverse flux motor is shown in Fig 8 and has been designed to improve both the electromagnetic and mechanical performance of the machine.

Power semiconductor devices

Power semiconductors have been employed in various motor drives for many years, but the pace of change has now accelerated to previously unimagined levels. Devices such as GTOs are driven by current flowing in the gate circuitry and these have thus been slow to commutate or switch off. The phase of commutation, when the device moves from a state of low voltage and high current to one of zero current and maximum voltage, is one of intrinsic high loss when compared to the two stable states it separates. Current drive devices being slow to switch have been generating significant heat in this phase. The resulting burden on cooling has made the overall drive bulky and expensive. However, recent developments have created devices driven by gate voltage, which has allowed a much quicker speed of commutation and thus reduced losses, and consequently allowed smaller drive packaging. In addition, the frequency of switching has been increased such that Pulse Width Modulated (PWM) frequency conversion is now possible, with very little harmonic distortion, either downstream or upstream.

The losses in a device dictate the requirements for cooling and very often this impacts significantly on the overall design of the equipment. Three broad categories for device losses can be drawn:

1. Switching losses are the losses which occur when the device is switched on and off. They are due to the power dissipated during these events when there is a substantial power loss, as the current decays and the voltage...
to the gate, albeit for an extremely short duration. Although this is a significant improvement over thyristors, which require a pulse of 100% of the current in the device, it is still significant and therefore the control circuitry remains complex and bulky.

In recent years the thrust of development has been towards improving the power density of static converters and new devices have emerged to compete against the GTO. The front runner of these new devices is the Insulated Gate Bipolar Transistor, or IGBT. The name derives from the fact that the gate is insulated from the device itself (in this case a transistor rather than a thyristor) and in terms of its external characteristics the device becomes driven by the voltage at its gate. This insulation of the gate of a traditional bipolar transistor is achieved by driving the gate through a MOSFET (Metal Oxide Silicon Field Effect Transistor), whose high gate-to-device impedance is achieved by incorporating a layer of silicon oxide between the gate and the device itself. The recent development of IGBTs has allowed these double device packages (MOSFET and bi-polar power transistor) to be implemented monolithically on one slice of silicon. IGBTs are commercially available up to a voltage and current rating of 1600V and 600A, although higher current ratings are available at lower voltage ratings. These are obviously well short of the GTO ratings, but have other advantages and are still rapidly evolving. Their major advantage is that they are voltage driven and hence the control circuits are much simpler, with a commensurate reduction in weight and volume. The IGBT can also be switched at frequencies greater than ten times that of the GTO, for example module packaged IGBTs have a switching frequency of 20 kHz. This has

increases, equal at any time to their instantaneous product. The higher the switching frequency the larger the switching losses.

2. Conducting losses are the losses which occur while the device is switched on. They are due to the constant forward bias voltage drop across the silicon junction which, therefore, causes a power loss proportional to the current carried (as compared to a normal resistance which generates a power loss proportional to the square of the current it conducts.)

3. Minor losses associated with semiconductor devices are due to leakage current, when in the blocking state, currents flowing in the snubber circuits and losses associated with the gate firing circuits.

The majority of high power static converters at present use Gate Turn Off Thyristors (GTO) as the semiconductor technology. As the name suggests these devices, unlike their thyristor counterparts, can be switched off without the need for forced commutation circuitry. Furthermore, the switching frequency of thyristors is limited by the requirement to hold reverse device voltage for tens of microseconds. GTOs have therefore allowed a reduction in volume and an increase in switching frequencies. Commercially available GTO devices have voltage and current ratings of the order of 4 kV and 3.5 kA, respectively. Although GTO devices are an improvement over thyristors they are current driven devices and require a current pulse to be applied to the gate to ensure the device changes state. In the particular case of switching off, the device requires a negative current pulse of approximately 20% of the current in the GTO to be applied to the gate, albeit for an extremely short duration. Although this is a significant improvement over thyristors, which require a pulse of 100% of the current in the device, it is still significant and therefore the control circuitry remains complex and bulky.

In recent years the thrust of development has been towards improving the power density of static converters and new devices have emerged to compete against the GTO. The front runner of these new devices is the Insulated Gate Bipolar Transistor, or IGBT. The name derives from the fact that the gate is insulated from the device itself (in this case a transistor rather than a thyristor) and in terms of its external characteristics the device becomes driven by the voltage at its gate. This insulation of the gate of a traditional bipolar transistor is achieved by driving the gate through a MOSFET (Metal Oxide Silicon Field Effect Transistor), whose high gate-to-device impedance is achieved by incorporating a layer of silicon oxide between the gate and the device itself. The recent development of IGBTs has allowed these double device packages (MOSFET and bi-polar power transistor) to be implemented monolithically on one slice of silicon. IGBTs are commercially available up to a voltage and current rating of 1600V and 600A, although higher current ratings are available at lower voltage ratings. These are obviously well short of the GTO ratings, but have other advantages and are still rapidly evolving. Their major advantage is that they are voltage driven and hence the control circuits are much simpler, with a commensurate reduction in weight and volume. The IGBT can also be switched at frequencies greater than ten times that of the GTO, for example module packaged IGBTs have a switching frequency of 20 kHz. This has

Fig 8  Transverse flux machine 3
the effect of reducing the amount of filtering required and
gives a further reduction in overall weight and volume.

For similarly rated GTO and IGBT devices switched at the
same frequency, the switching losses for the IGBT would be
lower but the conduction losses would be higher. However,
in a PWM converter using a high switching frequency the
switching losses would begin to predominate over the con-
duction losses. Therefore the overall losses would be smaller
for an IGBT converter than for a similarly rated GTO based
PWM converter. One advantage of the GTO is that double
sided cooling of the device can be achieved due to its
packaging in a ‘hockey puck’ configuration; the geometry of
the IGBT makes this very difficult to achieve and only single
side cooled devices are available, however this is amelio-
rated because the losses are smaller. The latest develop-
ments aim to produce a 3 kV rated IGBT with corresponding
1600A current rating.

The MOS-Controlled Thyristor (MCT) has many similar
facets to that of the IGBT: both are bipolar semiconductor
devices with their gates driven by MOSFET transistors, and
both are therefore voltage driven devices capable of very
high switching frequencies. MCTs are, however, a relatively
new device and are commercially available only at a voltage
rating of 600V, with a current rating of 65A. They are some
way off IGBT capability, but again this technology is new
and evolving at great pace.

Having assessed the design implications of both available
and developing semiconductor devices the drive technolo-
gies that are suitable for variable speed marine drive appli-
cations5 will be briefly reviewed.

Variable speed drives

The ac-dc converter, commonly known as a rectifier, is either
uncontrolled using a diode bridge or controlled using
thyristor technology. This latter method provides direct
control of the dc output voltage for dc motor control applica-
tions or a variable dc link voltage for the inversion stage of
an ac-ac converter. It also allows the bridge to become the
building block for cycloconverters. At present, thyristor
devices are used for the higher power rating requirements,
however it is of note that even now other devices, such as
IGBT and Field Effect Transistors (FET), are being used at
lower but rapidly increasing power ratings.

The synchroconverter is essentially a two stage conversion
drive for a synchronous motor, consisting of first stage rectifi-
cation with a current fed second stage from an intermediate
line reactor. Control of the rectifier thyristor firing angles
governs motor voltage and the magnitude of the link current,
which ultimately determines motor speed. The inverter
thyristors are fired to ensure correct phase sequencing of the
link current to the motor and are commutated by motor
generated emfs. In this way the motor is synchronised to the
shaft and the output inverter bridge is dependent on the
synchronous motor back emf for its commutation voltages,
thus it is a Load Commutated Inverter. The drive readily
achieves four quadrant operation for reversal and regenera-
tion by appropriate phasing of rectifier and inverter bridges.

As previously mentioned, the cycloconverter uses the
basic fully controlled bridge rectifier to generate a variable
voltage output which, by correct phasing of the firing angle
of the devices, can be made to approximate to a sinusoidal
variation. Since each bridge needs to accept bi-directional
current, two fully controlled bridges are required in each
output phase, connected in anti parallel. Therefore, for the
simplest three phase arrangement a minimum of six bridges
is required, each with at least six devices. Thus the
cycloconverter has many more devices than an equivalent
PWM inverter or synchroconverter. In addition, the control
techniques necessary to ensure safe transfer of current be-
tween the two bridges in each arm across the current zero
(which will not in general align with the voltage zero) tend
to complicate the converter and also introduce more har-
monic distortion than might at first be expected.

The PWM converter is, like the synchroconverter, a two
stage conversion drive but the fundamental method of speed
control is different. The inverter is self-commutating in that
forced commutation devices such as GTO thyristors are
used, which, therefore, removes the dependence on the
synchronous motor load of a synchroconverter; ie, it is a
Force Commutated Inverter. The semiconductor devices are
controlled using PWM techniques which can drive the mo-
tor with near sinusoidal voltages, however this requires
devices capable of much higher switching frequencies than
either a synchroconverter or cycloconverter.

The pace of development of both semiconductor devices
and the converter topologies that they enable is so rapid that
any prediction about the type of converter to be used in an
IFEP ship is uncertain. However, it is thought likely that an
IGBT based PWM converter will at least be a strong con-
tender, if not the self-evident first choice.

THE ELECTRIC WARSHIP

With the advent of high power density motors and drives, as
described above, IFEP is likely to be the next major propul-
sion change for frigate sized warships. However, there is
likely to be an impact on the remainder of the electric
warship. There are various scenarios, of which this paper
outlines one.

Current generations of marine prime movers operate on
one of two ‘power speed’ characteristics, either the constant
speed required by electrical machines that generate a fixed
frequency (frequency being proportional to the speed of rota-
tion) or the propeller law required for direct mechanical
drives. Figure 9 shows the normalised specific fuel consump-
An electric warship prime mover need not be constrained by the ship’s power speed curve, but neither does it need to be a fixed frequency. Technology provides the opportunity to optimise for efficiency. Figure 10 is a block diagram of a typical 450V, 60 Hz high speed generator. A multiphase ac machine generates a high frequency which is rectified to dc and then inverted back to the required 450V 60 Hz output, or indeed any other output required. High speed generators rotating at, say, 10 000 rev/min have a much higher power density than conventional machines, which typically rotate at 3600, 1800 or 1200 rev/min when generating 60 Hz. It should be noted that whilst rectification is efficient with about 1% losses, inversion suffers about 4.5% losses.

This leads on to the next question: why invert to a 450V, 60 Hz output? The classic reason is that this is a convenient speed for motor loads. Indeed, it was the growing proportion of motor loads that finally convinced the Royal Navy to adopt ac electrical systems after World War II. However, even here times are changing. With the advent of cheap, reliable variable speed drives the speed of motor driven auxiliaries can be closely controlled. This, combined with a soft start capability, can reduce equipment and system design margins and cost: the motor can be cheaper (it does not have to survive the five times full load current of direct on-line starting); the rotational speed of pumps, compressors or fans can provide just sufficient flow to support the system’s duty and thus consume less power; and, by reducing system flow, the noise that escapes into the sea is reduced, a significant advantage to warships from a submarine threatening environment. In general, efficiency savings exceeding 15% are often claimed from the careful application of variable speed drives. In principle, a variable speed drive is a set of power electronics that does the same as the high speed generator: it takes the supplied ac, rectifies it and then inverts to the frequency appropriate to the driven motor’s required speed. Figure 11 adds the variable speed drive to the high speed alternator and shows that to supply this motor requires rectification and inversion twice. It also shows how variable speed drives can be supplied, with half the losses, by generating and distributing dc.

Very few weapon systems utilise 60 Hz motor loads. Whilst the majority consume 450V, 60 Hz they generally convert this to the particular power supplies required by individual elements of their equipment, for example low voltages for computers, high voltages for displays and medium voltages for heating and lighting. Accordingly, it seems that very little equipment in future warships will require 60 Hz and that most equipment would consume less power if supplied with dc. The merits of dc distribution systems as a means of minimising warship running costs need to be reconsidered.

Earlier in this paper the possibility of four prime movers being sufficient for an IFEP warship was suggested. Studies using a spreadsheet fuel model indicate that the optimum generator sizes for the frigate are:

1. A 1 1/4 MW machine to support efficiently the ship service load when at anchor; an anchor load engine.
2. A 7 MW machine to cover the majority of the lower speed operation and the ship service load; the cruise engine.
3. Two machines at around 22 MW for the higher speed operation plus the ship service load; the boost engines.

These engines lead to minimum running costs as long as only one machine runs whenever possible. Running two generators is more expensive than running one machine; whilst the difference in fuel usage may not be great, the maintenance commitment is. However, losing supplies to ship service systems of warships is undesirable, the weapons will not work. Indeed, some weapon systems with low data rates such as sonar, may take a long time to restore the tactical picture to allow the fight to continue. If normal operation is to be with only one prime mover running, then some method of maintaining supplies on loss of the single prime mover must be considered, and with a dc system this can be from a battery. Most nations have considerable experience of battery supported dc systems from their submarine programmes. The electric warship concept of this paper extends this experience into surface warships.

Figure 12 shows a conceptual electric power system.
There are two galvanically separate systems. Using a high voltage ac propulsion system reduces the currents to be supplied to the propulsion motor converters. The dc ship service distribution system is battery backed. The novel heart of the system is the two reversible inverter rectifiers which will link the two systems. With these, any engine, or the battery, can supply power to propulsion and ship services. If a submarine battery is used to support the power system, it can provide the action load and propel the ship at up to 12 kn for half an hour. The 7 MW cruise engine will support the maximum activity load and provide sufficient propulsive power for about 80% of the operating profile. As such, this will be the most used engine. If the complex cycle boost engines are not speed constrained one should be able to support the anchor load indefinitely, without reducing reliability or increasing the maintenance load.

Turning now to the distribution system, Figure 13 shows the two sides of the dc ring main passing through one zone of the ship. Within that zone there will be a power source, either a prime mover or a battery section, and supplies required by various consumers will be generated by Zone Power Supply Units (ZPSU). Each ZPSU will be supplied from both sides of the ring main and will output the required power supply to consumers. Essential consumers will receive duplicate supplies and non-essential consumers will receive a single output.

The ZPSUs are visualised as an assembly of identical, compact, intelligent, programmable power electronic inverter modules. Each module will be capable of generating one of a variety of outputs and can be configured by software if moved between locations and duties. The design will enable the inverter module to generate a wide variety of the special requirements currently generated by weapon equipment power supply units.

**ENERGY STORAGE**

With the battery a highly dependable and high power storage device the need for the plethora of other energy stores common to warships will not be required, and systems can be simplified accordingly. For example, steering gear and stabilisers have traditionally been powered hydraulically, as this gives the requisite energy storage in the accumulators for a loss of the hydraulic pump and the instantaneous availability of energy to cope with control surface reaction loads. Both of these requirements can be met by the battery and thus an electrical operating system can be adopted. Similarly with air systems, for which the only requirement should be for breathing. Needless to say, the adoption of IFEP removes the need for gearboxes and forced lubrication systems, albeit minor pumped oil systems might be required for individual equipment. As such systems are removed from ships, the inability to keep the fluid in the pipe no longer creates the interminable burden of ‘scrubbing out’ and the stored energy is no longer a constant safety threat, particularly in action.

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<tr>
<th>Table II</th>
<th>Comparative costings (GP operating profile)</th>
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<td>COGAG</td>
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<tr>
<td>UPC</td>
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<td>RC</td>
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<td>Discounted</td>
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<td>total (6%)</td>
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**THE PLATFORM MANAGEMENT SYSTEM REQUIREMENTS**

With high speed machines and electrical systems, the ability for human interaction other than for system realignments is negligible, thus a comprehensive, reliable and low cost automation system is required. There is also a great simplification of the remaining systems and a growing inter-relationship (most of the power electronic devices will need water cooling if they are to be power dense and not overburden the air conditioning system), and the platform management system should be able to cope with system realignments for normal, emergency and abnormal operations.

**COST OF EQUIPMENT, ITS INSTALLATION, MAINTENANCE AND OPERATION**

All cost data is inevitably very much an estimation. Where possible, equipment procurement cost data is based on manufacturers’ quoted prices which, in some cases, has been parametrically extrapolated. In other cases the data is based on estimates.

Fuel and maintenance data are derived from a spreadsheet based model which assumes a fuel cost and a maintenance cost per hour run for each type of engine.

Installation costs are coarsely approximated: a value of £5000 per equipment tonne and £7000 per equipment cubic metre has been used. This is assumed to cover installation, setting to work, cabling and piping costs, initial outfit and commissioning spares.

Table II shows a summary of the costing for a mechanical COGAG and a CODLAG propulsion system compared with the electric warship. It shows that whilst the equipment and installation costs for the electric warship are greater than for
a COGAG system, the UPC is lower than for a CODLAG system (there is less of it and it is high power density). Whilst the electric warship system attracts a larger bill from the shipyard by about £1M (some 5%), once in service this is rapidly paid back.

Over a 30 year ship life the net financial advantage of the electric warship, compared with COGAG, exceeds £4M and even discounting the running cost at 6% gives a healthy £1.5M advantage.

Again, these figures are pessimistic since the calculations do not allow for the additional losses at low operating speeds from gearboxes, nor do they include the additional maintenance load of lubricating oil and other auxiliary systems.

There is another advantage of the electric warship over COGAG or CODLAG that is virtually impossible to quantify, without doing relatively detailed ship designs, and this is the flexibility of layout. COGAG and CODLAG installations suffer the ‘tyranny of the shaft line’, i.e. the gearboxes and prime movers must be located such that they are aligned with the shaft and this leads to the traditional arrangement, with exhausts well forward from the stern. In frigate hull forms the prime movers are close to half way down the length of the vessel. With the electric warship the small propulsion motors can be well aft, with short shafts inside the hull or, if the motor is small enough, mounted outboard in pods. With cable as the only interconnection the prime movers can be mounted anywhere in the ship, adjacent to maintenance routes, where they are least likely to suffer action damage or where they are least likely to stimulate vibration or put noise energy into the sea. Suffice it to say that MOD internal studies indicate ship displacement can often be reduced by 8% by the flexibility offered.

The final topic to discuss under cost is manpower reductions. Since there is little possibility of human intervention with the control of high speed gas turbines and electrical power systems, the maintenance and support manpower can be significantly reduced. Indeed, initial studies indicate that the size of the marine engineering department is dependent on their non-marine engineering duties in general and damage control in particular. By applying modern technology to damage control the marine engineering departments of warships may well be able to tend towards the size of those of merchant ships. With the average cost of a man year at around £40k, significant savings will be realised.

CONCLUSION

This paper has presented the personal vision shared by the authors of the concept of the electric warship. Although much remains to be done, nothing appears likely to challenge significantly their view that the electric warship will not only be cheaper to own, simpler to operate, easier to maintain, and safer to use; but, more importantly, that it will be much more effective at war, possessing hitherto unimagined resilience to action damage. It is, in short, an opportunity which the authors do not believe the Royal Navy can afford to miss and thus is an essential strategy that requires activity to commence in the near future.

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REFERENCES

### Discussion

**Sir Robert Hill KBE, FEng (President, IMarE)**  
I congratulate the authors on a very good paper. The famous guru Herman Kahn said that when considering any future prospect one should ask three questions: Is it feasible? Do I want it? If I do not want it, can I stop it?

1. The authors have presented a convincing case for the feasibility of the Electric Warship. Personally, I want it. The concept is right because it continues the trend, which is correct for moral as well as practical reasons, of sending technology to sea and keeping men ashore. However, my concern is whether the arguments they have presented in favour of the concept are sufficiently strong and persuasive. The concept allows the warship to go to sea without a marine engineering department as we know it. However, for this to happen – allowing the full potential benefit of the scheme to be realised – the Warfare Branch would have to take responsibility for Damage Control, which is currently a Marine Engineering Department responsibility. Do the authors believe that the Warfare Branch will be happy to take it over, or will this matter become a reason for influential people deciding that they do not want it (the concept) and therefore seeking to stop it?

The subject could be taken Navy wide. We have seen now, with the introduction into service of the low manned Type 23, the requirement for Junior Ratings in the Operations Branch reduced to the point where the branch was unsustainable and it was necessary, in a hurry, to restore structural sustainability. This was done by bringing the Weapons Engineering junior rates into a new Warfare Branch. The introduction of Integrated Full Electric Propulsion would similarly undermine the structural stability of the Marine Engineering Branch, notwithstanding its submarine component.

For electric propulsion to be seen in a favourable light and win widespread support, and for the economic advantages to be seen in the round, the manpower structural consequences should be investigated. My guess is that such a study would reveal financial benefits greatly exceeding those identified in the paper – though it is ironic, to say the least, that I should be making such comment as President of this Institute!

2. The world’s most common propulsion system for small warships is CODAG, yielding diesel economy for cruise and high power/weight ratio for high power, without the higher cost of CODLAG. Have the authors done a cost comparison against this arrangement and, if so, does IFEP still show to advantage?

**Prof J O Flower (University of Warwick)**  
I enjoyed reading the paper. However, while realising that the time horizon is 2010 I thought that there might have been some mention of superconducting machines, particularly as the MOD seems to have had as much experience as any organisation in this field.

I also thought that fuel cells might have got a mention. Those of us particularly keen on doing things electrically would very much like to see the elimination of mechanical prime movers, and fuel cells seem like the best bet.

My personal belief is that switched-reluctance motors will figure quite largely in the marine world. They do have a reputation for being noisy but much work is being done on this aspect and not without success. Comment would be welcomed on these motors.

**Cdr C G Hodge and Cdr D J Mattick (MOD Bath)**  
The authors would like to thank Sir Robert Hill for his contribution to the debate. The authors entirely agree with the view that the Electric Ship architecture will lead to significant manpower consequences and very large financial benefits. To this end they are preparing to initiate the debate in this area throughout both the MOD and the Royal Navy.

As to the other question, no direct comparison work has been undertaken between CODAG and IFEP since the paper is based on work undertaken to assess advantages to the UK MOD and the Royal Navy, who do not use CODAG installations for major warships. Superficially however, with complex cycle gas turbines achieving the fuel economy of similar sized diesels and the derived running cost advantage of IFEP over COGAG, the cost difference between COGAG and CODAG is the first or Unit Production Cost (UPC). Since diesels tend to be cheaper than gas turbines then the period in service before the higher UPC is repaid by the lower running cost of IFEP is longer. The authors would expect an increase from about 3–7 years. One disadvantage of CODAG is the volume and weight consumed by the installation when compared with COGAG.
siderable advantages for certain marine applications, but they believe that they cannot match the levels of power and torque density offered by novel topology permanent magnet motors, which are crucial to the feasibility of an Integrated Full Electric Propulsion System and thus central to the Electric Warship concept. However, they do recognise that switched-reluctance motors could find application within an electric warship as auxiliary drives and this will be considered during the system and equipment development.

H Rush (ASA Consulting Engineers Limited) I congratulate the authors for producing a comprehensive paper, including personal visions of an encouraging future for the Electric Warship. I suggest that it goes further than that, because it gives hope for concepts that may also advantage other areas of the maritime industry. To read this enthusiastic paper must gladden the heart of any marine electrical engineer who has dreamed of the way in which his profession may add even more value. I have several questions.

Do the authors believe that an Electric Warship design will be judged by the same criteria and values as any competition it will face? In this context, what is the most important competitive advantage that the Electric Warship must be able to demonstrate?

The paragraph about platform management systems is almost dismissive although it recognises very important features. How do the authors envisage this system will be developed to avoid it becoming too complex, or an Achilles heel to the high integrity necessary?

In the conclusion, the authors claim ‘hitherto unimaginable resilience to action damage’. To what extent have studies been made to support this assertion and can it be quantified in any way?

Cdr C G Hodge and Cdr D J Mattick (MOD Bath) The authors would like to thank Mr Rush for his congratulations and his contribution to the debate.

The authors do believe that the Electric Warship must and will be judged by the same criteria as any competition, and the most important criteria must be cost. The proposed electric ship architecture will need to demonstrate a low total cost of ownership to the purchasing navy. Once this has been achieved then flexibility of installation, allowing more weapons to be carried and greater survivability, will persuade the thinking customer to buy the ship.

The point is well made that the importance of the platform management system cannot be overemphasised. However, in developing the vision the authors have not overconcentrated on this aspect, since achievements show that a wide variety of systems with suitable functionality are available commercially. The basic principles we envisage are: the ability for autonomous operation of individual equipment with elements of local control; redundant distributed processing that intercommunicates on fire, shock and EMP resistant dual or triple redundant fibre optic cables; a modularised approach to both hardware and software such that the minimum number of different equipments or modules of code are required; and a ship wide system that allows effective control and monitoring to be undertaken from a wide variety of locations.

With regard to vulnerability, several studies are underway but unfortunately only indications of the results are currently available. It is intended that this is one of a series of papers which will cover the results of such studies as they emerge.

Cdr R T Love (Directorate of Navy Plans and Programmes, MOD, Whitehall) Firstly (following on from another question), although the proposals in the paper would reduce the number of prime movers they would not reduce the number of types of prime mover. This potentially reduces the redundancy in the plant, and certainly increases the courses, training and stores required to support the additional types of prime mover.

Secondly, has the question of risk been addressed in the research for the paper and, if so, could the authors give a brief summary of their findings.

Thirdly, I would like to give a financial and programming perspective on the vision of the Electric Warship. I stress the importance of transferring or at least sharing as much risk with industry as possible; the importance of collaborative ventures, noting that a similar American project had been said to be well advanced, as stated by another contributor during the presentation of the paper; finally, the engineering community must be highly focused on the most cost-effective option and channel their resources accordingly.

Cdr C G Hodge and Cdr D J Mattick (MOD Bath) With regard to the effect that the Electric Warship concept has on the variety and number of prime mover types: we would expect to use only gas turbines, and thus our vessel would have four prime movers (two identical large ICR gas turbines, together with one medium and one small complex cycle gas turbine). When compared to a standard mechanical fit of two large and two small gas turbines and four diesel generators, it is self-evident that the numbers have been halved and that the variety is certainly no worse than before and has, in some respects, been reduced (no diesel engines and possibly a common design philosophy between the differing sizes of gas turbines). We therefore expect the Electric Warship to make less of an imposition on the training infrastructure and stores support resources of the Royal Navy than the current ships’ designs. Further, the concept of system integration between the propulsion and ships’ service prime movers prevents redundancy being reduced through reduction in the number of prime movers.

Risk is one of our prime concerns; it was our perception that only the MOD could remove the risk of not being able to realise a high torque density permanent magnet propulsion motor, that led to our development initiative. Other areas where risk might lie have yet to be fully investigated, but power electronic developments are proceeding apace and daily we become more confident that this area will not present insurmountable difficulties. Similarly, the fully integrated power management system that will lie at the heart of the overall system functionality is achievable now with current day technology, and indeed similar systems are in use now in the merchant navy.

We are grateful to Cdr Love for his comments with regard to financial and programming aspects of the Electric Warship initiative, and although, as he would probably agree,
this forum is not ideal for their discussion, we would like to mention that the opportunities for international collaboration and industrial partnership are never far from our thoughts.

Lt Cdr J M Newell (MOD, Portsmouth) Although a marine engineering surface engineer, I would support the concept of battery back up for main propulsion and essential supplies in the event that a prime mover trips.

As Marine Engineer Officers at sea in a warship our prime purpose when the ship goes into action is to provide a service: maintaining propulsion and the ship’s fighting capability to the command.

In this ship concept, one great possibility is for a significant reduction in marine engineering manpower and hence through-life cost. This reduction in manpower could impinge on our ability to achieve our goal of maintaining essential propulsive power and power for essential supplies, should a prime mover trip. A 20 min cushion could make all the difference.

So is the concept of a battery new? I would argue not. If a COGOG ship currently suffers a total electrical failure, and at the same time the driving engines trip for some related or unrelated reason, the only way to power the GT igniter circuits for a restart is to connect four 12V emergency navigation light batteries in series and hot wire them into the local panel; battery back up in a rather agricultural way?

Other arguments for having the battery might include ASW or mine transit operations when ship’s noise must be reduced to an absolute minimum. Could you not operate on the battery and shut down all prime movers?

Cdr C G Hodge and Cdr D J Mattick (MOD Bath) The authors are delighted to find a surface ship marine engineer who recognises the feeling of security that a battery brings to submariners. They also sympathise with the black start problems for COGOG ships and will make every effort to ensure that such problems are designed out of future ships. As to the additional arguments presented for advantages of a battery, we completely agree and would add one other – when an incoming raid of infra-red sensing missiles is anticipated, shut down all prime movers, hose down the funnel and let non-battery fitted ships take the hits.

However, and more seriously, in the current post cold war environment, marine engineering is not being tasked to provide improved capability, so the inherent assumption behind the vision is signature no better than for a Type 23. If the electric ship gives improvements, it is a bonus rather than a driver.

In direct answer to the question, the vision certainly includes the option of shutting down all prime movers and letting the battery take the load. This is one of the options being considered for the anchor load machine. If it is only used to charge the battery its part load efficiency is immaterial as it will spend all of its time on full load.

Lt Cdr K A Howard (HMS Marlborough) As the MEO of a Type 23 frigate, my propulsion plant (CODLAG) can put about 27 MW of power into the water; at cruising speeds I make do with 3 MW. The layout described appears to have up to 58.25 MW (plus battery) available. Is the envisaged hull significantly larger than that of the Type 23, or should one of the WR21s (25 MW) be omitted?

Cdr C G Hodge and Cdr D J Mattick (MOD Bath) Indeed, the vision of an electric ship described in this paper is overpowered compared with the Type 23 hull on which it is based. In part this is driven by the 30 kn assumption and in part by the optimisation process undertaken. Suffice it to say that both WR21s need only be run to exceed about 27 kn. It is fortunate that the next job being planned for Lt Cdr Howard to take up in ‘Director Future Projects’ will lead him to address just such issues.

Dr M A Hind (ERA Technology Ltd, Leatherhead, Surrey)

1. In view of the fact that much of the electrical power generated in the proposed system is subsequently rectified and distributed as dc, have the authors considered special designs of alternators to optimise their performance when supplying non-sinusoidal currents?

2. With the electrical supply system proposed, where main drive motors are supplied through inverters, there will inevitably be high levels of harmonic current flowing within the system. Have the authors considered solutions to the potential problems that harmonic currents can cause, in particular the use of active waveform correction which is now becoming an accepted technique for dealing with harmonic problems?

Cdr C G Hodge and Cdr D J Mattick (MOD Bath) Different designs of alternators have not been considered in detail to optimise their performance when supplying dc. However, the vision is of a high speed, multiphase ac generator supplying the rectifier, much as the machine developed for the Upholder Class SSK.

By adoption of the faster switching capability of future generations of power electronics, the vision anticipates a somewhat lesser harmonic problem than is typical today. Until converter design has progressed a detailed assessment cannot be undertaken, however the authors are fully aware of the highly successful active waveform correction work done by the questioner’s team, amongst others.

M Murphy (CEGELEC Projects Ltd, Rugby) The paper reflects the exciting times in the field of marine electric propulsion. As an observation, a large percentage of commercial marine projects are being placed with Unmanned Machinery Space operation as a requirement, so it is not inconceivable to envision the situation where the Officer of the Watch is also the Engineer Officer of the Watch.

My question, though, relates to costs. We have seen in the paper a very good case made out for the all electric ship, where it is clear that significant advantage can be shown in analysis on a through-life cost basis. Such analysis is a key to future procurement. What commitment is there in Ministry circles to such an approach, rather than on the traditional unit production basis of the past?

Cdr C G Hodge and Cdr D J Mattick (MOD Bath) As the questioner implies, government funded projects in general, and MOD in particular, are not well known for adopting
high first cost projects to realise lower through-life costs. Firstly, the authors would claim that the MOD’s attitude is changing, as evidenced by the Auxiliary Oiler mandating electric propulsion. Secondly, the driving force for the electric ship architecture to depart from current commercial marine electric propulsion practice of a large number of generators is the reduction of first cost of the installation. It is expected that when all the running cost and first cost advantages of this architecture can be assembled, the Electric Ship will be shown to have a similar or slightly lower first cost to COGAG with a much lower running cost than CODLAG, and a similar if slightly higher running cost than a commercial electric propulsion system but in a much smaller volume.

Lt M T W Bolton (Royal Navy)

1. How susceptible would a propulsion system, utilising transverse flux motor technology with a PWM drive, be to action damage, particularly regarding the shock characteristics of the motor and in view of the inherently complex PWM electronic control system?

2. It is readily accepted that the implementation of fewer prime movers in a propulsion system has many advantages; however would the authors agree that the introduction of a battery to the system is, effectively, an additional prime mover, which appears to be a backward technological step with many disadvantages?

Cdr C G Hodge and Cdr D J Mattick (MOD Bath) The transverse flux motor sketch design work to date has looked closely at shock performance. By adopting a drum rotor, discs to support the rims and short axial length rims, a more than adequate shock performance can be achieved with a 3 mm air gap. As regards the PWM electronic control system, complex electronics are no strangers to the military shock environment and the methodologies adopted for weapon equipment design will realise a battleworthy installation.

In the studies undertaken to enumerate the vision, a battery and a further prime mover were assessed. Although a battery is heavy, well in excess of the battery weight is typically installed as ballast in a Type 23. Compared with a suitable prime mover and its fuel, a battery requires much less volume; it is after all made of lead! With regard to costs, the battery is expensive and needs changing routinely. However, assuming a battery life of six years, the cost of ownership (including maintenance) is marginally less than for a diesel.

A battery also has other advantages that may be of use: it will provide a source and sink of power should fuel cells be required to replace oil engines due to emissions or if their efficiency is realised in practical, seagoing systems. It also provides stability to a power system when the rotating energy of prime movers and consumers is isolated by power electronics.

To be fair, both authors are submariners and could not be expected to consider a battery a backward technological step! We know it to be a quiet, reliable, trouble free source of stored energy.

Cdr C J Hockley (MOD, Directorate of Operational Requirements, Whitehall) During the presentation, and as a response to a previous question, the authors had indicated that there were a number of key areas that had to be considered at the outset of any electric ship design process; one had been shock and the other was EMC characteristics. Are there other areas that need to be similarly considered?

Cdr C G Hodge and Cdr D J Mattick (MOD Bath) Other key areas to be addressed at the outset of any electric ship design process include:

1. Harmonic distortion, particularly the conducted elements rather than the radiated element which can be classified as EMC.

2. Vulnerability, in that the ability to distribute most elements of the propulsion chain throughout the ship can be used to reduce vulnerability or to give naval architecture advantage to weapon installations.

3. Vibration, in particular its impact on acoustic signature. The motor is the most sensitive area and, whilst the expectation is that it can be directly mounted to the hull, the detail of the motor and its converter design needs to be addressed to ensure this.

4. Total installed power: although the requirement for top speed will dominate this, generators to support a significant ship service load can also provide reasonable cruise speed. The detailed mix of machines must be addressed early to minimise total cost of ownership.

A J Whitehead (Vosper Thornycroft Controls, Portsmouth) Firstly, I would like to congratulate the authors on an excellent paper and presentation.

1. The paper addresses flexibility of machinery layout for IFEP vessels. What thoughts have the authors had about putting the propulsion motors outside the hull, for example in pods, as is currently happening in the commercial marine environment? What advantages and disadvantages would pods have for a frigate with ASW capability?

2. How is it proposed to stop the IFEP frigate? With an installed propulsion power of the order of 40 MW, it is unlikely that the ship services load will constitute a large enough sink for regenerative power. Is the use of braking resistors being considered, and, if so, will their inclusion affect the conclusions drawn about size, weight and cost of IFEP compared to traditional propulsion systems?

Cdr C G Hodge and Cdr D J Mattick (MOD Bath) The authors would like to thank Mr Whitehead for his congratulations and his contribution to the debate. Addressing his two points individually:

1. Some work investigating placing motors in pods outside the hull has been undertaken. There are three potential advantages. Firstly a 15% increase in propulsion efficiency is claimed, however the authors are uncertain whether this is achieved throughout the power range or just over a narrow speed band, and, secondly,
the freeing up of space within the ship. Whilst this is undoubtedly valuable the amount freed is less significant with high power density motors than with more traditional machines. The third advantage is essentially a further shortening of the shaft line to give a lower probability of damage from underwater attack. Again, this is a significant advantage albeit, given a small motor, very short shaft lines can be achieved by changes to the shape of the stern of a ship.

The authors’ opinion is that podded drives for a highly manoeuvrable high speed warship may be a step too far in the 2010 timescale. The areas of concern are the stresses on the pod support structure in the face of high speed turns, the sealing of the shaft entering the pod and accessibility to the pod, and the transfer of thrust from the pod to the ship.

2. The vision currently is that ship stopping will be achieved by regeneration to the ship system. The 40 MW propulsion power is only required to achieve high speed and at high speed the hull resistance is also high. The Type 23 frigate has shown that acceptable handling can be achieved by regeneration and a future frigate will certainly have a greater ship service load than a Type 23. Furthermore, the battery is potentially a power sink which will further improve the handling.

R F Crook (Chief Electrical Designer (retd), Vosper Thornycroft UK) The authors are to be congratulated on their paper. In looking ahead to the all electric warship, however, in my opinion, we should have had such a vessel a decade ago. I trust our American cousins will not be the first yet again.

1. Maximum speed. In the introduction they say warships are generally designed for a maximum speed of 30 kn. My question is: is this speed really necessary? As the authors are aware the power required to go from 25 to 30 kn, the power curve ‘knots versus power’ is exponential, is therefore costly in machinery and hence reflects highly on the overall ship cost.

The authors are correct in that warships typically spend 80% of their life below 18 kn (US NAVSEA Code 614B March 1975 suggests 75%). At a discussion at the Royal Military College of Science in November 1980 on ‘A weapons/sensors/C3 package for a NATO frigate of the 1990s’, the ideal was for 30 kn maximum with a continuous speed of 25 kn in average weather. However, it was accepted that 25 kn would be acceptable because of the high cost of the extra 5 kn. 30 kn gave no real advantage for anti-submarine capability, but the extra speed could give some advantage when crossing from one side of the convoy to the other.

Although the discussion was limited to a monohull vessel of some 4500t, many of the points raised by the authors are contained in my article The Carrier of the Future,1 where the all electric ship could be equally applied to that part describing the Vosper Thornycroft ‘Harrier Carrier’.

2. Mechanical and electrical transmission. Why do the authors consider that less numbers of generating plant are an advantage? I agree that the lower the numbers the less maintainability is needed, but a larger number of identical generating sets are less prone to action damage and provide greater overall reliability. Also, one can optimise the number in use, bearing in mind the low percentage of operational time above 16–18 kn. The overhaul time is extended and therefore operational costs reduced.

3. Motors. Although current designs of suitable motors available are fairly large and heavy, our study and specification for the ‘Harrier Carrier’ (see Fig 1) were available both from the UK and from Juemont Schneider of France; these, of course, were synchronous machines (circa 1977).

There was a study carried out at University College London, in 1979 entitled The Fleet Destroyer Electrical Design (based upon a fleet destroyer 166m LBP, 19.4m beam and a displacement of some 8400t) by J A Shepherd. This explored various methods of electrical propulsion, including superconducting generators/motors. During this period the problem of providing the refrigeration was paramount, but I understand that the Americans now have small power superconducting machines operating at room temperatures.

What do the authors see as the future for superconducting machines, or do they feel that the transverse flux machine is a better option?

4. Variable speed drives. What do the authors consider as the most suitable warship application: the synchroconverter or the cycloconverter, bearing in mind that the majority of cruise liners use a cycloconverter?
5. The electric warship. When considering an electric drive and using the power generation with a ‘common’ busbar, do the authors agree that the reduction of harmonic distortion reflected on to the ship’s distribution is important?

In the T23 system large and expensive converters were used for isolation, where, in my opinion, the general equipment, for example motors, lighting, heating, could be fed directly via transformers, provided that the harmonic distortion could be contained within prescribed limits (say the American IEEE Harmonic Standard 519 (1981)).

On this same point I agree with the authors that all weapons equipment (with the possible exception of missile hoist weapons and gun mountings) require dc or 400 Hz ac, and require a dedicated supply, either a motor generator or, more recently, static inverter.

With reference to high speed generators when used with a dc ring main network; are there suitable bearings for 10 000–12 000 rev/min generators of, say, 22 MW? The authors may recall that in the 1950s the US Navy experimented with a World War II ship to determine if a 400 Hz system would be lighter and less expensive than a 60 Hz system. They found that bearing life was a limiting factor, with generators of some 500 kW running at 12 000 and/or 24 000 rev/min.

With reference to the proposed 480V dc would the authors please expand on the following:

a. Would the motors be 480V dc and would they be speed controlled by standard methods, or by the use of static electronic controllers?

b. Would the lighting system be fed from the 480V dc system via a static inverter or motor generator, bearing in mind the majority will be fluorescent? Presumably the Zone PSUs will cater for this.

c. What would be the estimated weight and capacity of the battery shown in Fig 12 of the paper as a back up, and able to supply an action load (typical) and propel the ship at 12 kn? Are there such batteries available? I know DRA were working on a high temperature cell with high volume capacity.

6. General

a. I agree with the authors regarding the operation of steering and stabilisers which could be electrically operated, battery supported, and thereby remove the requirement for hydraulics. However, there are some systems that have a self-contained motor/hydraulics, for example AEG steering gear.

But having said that, hydraulics ‘always leak’ and are vulnerable to action damage, for example hydraulic systems for helicopter handling on frigates. There have been electrical systems available for many years.

b. I assume that the reliability and maintainability of static inverters has improved over the last decade, such that they can be operated and maintained with the same ease, by ship’s company, as were the electro-mechanical predecessors, and, of course, well understood.

7. Conclusion

a. Never mind the future, there are weapons now that require large peak powers. These are the ‘Rail Gun’, peak power 40 MW, continuous power 2 MW, and the laser CIWS, being developed by Signaal and Anges, requires 200 kW peak.

b. If one accepts the 480V ring main system then a shore test facility would be required and this could well spell the death knell, because such a departure from the norm would be viewed with suspicion and would take years to become accepted.

There are first class computer simulations available, coupled with the small scale power systems active simulation at DRA, which could nullify the requirement for a full scale shore test.

c. Vospers Thornycroft, and myself in particular, proposed the CODLAG for the Type 23 (before it became the Type 23), albeit with a single 22 MW gas turbine driving through a combined box. The principle was difficult to get across to everybody concerned, but fortunately one had the full support of the Electrical Forward Design Group of MOD(PE), Bath.

The principle of an electric motor concentric around the propeller shaft line is not new; submarines have used it from the turn of the century, yet an expensive shore test facility was constructed at the builders. The modern cruise ships do not have shore testing for their electrical propulsion package, and they appear to work well without a shore test, even if it was practical.

d. With modern stand off weapons, in particular those carried by aircraft, including helicopters, one must question the need for a maximum continuous speed above 25 kn.

e. We must severely limit the number of studies if the electric ship is to become hardware, otherwise it will be a case of studies for studies sake, and the idea of the electric ship will disappear into the latter part of the 21st century.

Finally, I trust that the authors will persuade the Royal Navy to go ‘all electric’.

Reference


Cdr C G Hodge and Cdr D J Mattick (MOD Bath) The authors would like to thank Mr Crook for his valuable contribution to the debate and the copy of his most interesting paper. Addressing his points individually:

Is 30 kn really necessary?
This is an operational decision and is part of the information provided by central defence staffs, and, as with so many fundamental decisions, top speed is not a simple parameter to determine. Accordingly, when assessing such requirements for future warships, a combined operational effective-
ness and investment appraisal is undertaken, which establishes the cost of the requirements and balances this against the operational gain. For example, an escort needs a special advantage over the ship it escorts. If one operational requirement is to escort a multinational task force to a littoral warfare arena, the speed of advance is determined by the fleet train at, perhaps, 20 kn.

However, if the convoy includes an aircraft carrier which regularly reverses course to achieve adequate wind over the deck for flying operations and then rejoins the group at 28 kn, then the protecting escort accompanies it or there is an increased risk of loss of the carrier whilst it is unprotected, or the whole group slows down and the arrival in area is delayed. Such operational assessments could lead to a maximum speed being defined between 22 and 30 kn. This paper addresses a 30 kn ship as this was considered a ‘worst case’, the biggest and most expensive machinery fit likely to be required!

**Mechanical and electrical transmission**

Due to the way Government financing is undertaken there is inevitably a higher concentration on ‘first cost’ than on ‘total cost of ownership’. Accordingly, the fewer prime movers installed, the cheaper the bill to the shipbuilder.

The selection in the paper is based on 2 x WR21s to provide boost propulsion to meet the 30 kn requirement and 1 x 7 MW generator to provide cruise propulsion over 75% of the operating profile. The emerging generation of complex cycle gas turbines have a flat specific fuel consumption over a wide power range. Thus running one or two engines consumes much the same amount of fuel, but running two does commit a greater maintenance burden. Accordingly, a smaller number of larger engines also reduces total cost of ownership.

However, as the question identifies, the smaller number of engines are more prone to action damage. The authors believe that because electric propulsion brings the opportunity to disperse the prime movers more widely than in a classic mechanical transmission system – where they are tied to the shaft line – then the likelihood of action damage interrupting propulsion is reduced despite the smaller number of prime movers. Studies are in hand at the moment to quantify the balance.

**Motors**

Whilst high temperature superconducting motors are being developed (an 80kW machine has recently been announced), these are not at ‘room temperature’ (the 80 kW machine operated at -245°C, liquid neon temperatures rather than liquid helium). Superconductivity has been demonstrated at liquid nitrogen temperatures but not for power applications – yet (as the power goes up the temperature goes down)

Once the materials are available to support power machines at liquid nitrogen temperatures (nitrogen is freely available from the air and is relatively easily liquefied), then the major task of transferring science through demonstration and development and into production can begin.

It seems likely that higher temperature, higher power, superconducting machines will be developed but commercialisation at marine propulsion power levels is considered to be at least 30 years away. Furthermore, they show all the signs of being rather more expensive than a synchronous or induction motor.

On the other hand, permanent magnet machines have been around at low power levels for many years, the bicycle hub dynamo being an early example. The breakthrough that enables their application to marine propulsion is the increase in field strength of modern rare earth magnets. To date, several machines in the megawatt range have been built and demonstrated. They are thus ready for commercialisation now and can be expected to be ready in time for the next generations of warships. First estimates also indicate that permanent magnet machines will be similarly priced to existing conventional machines.

**Variable speed drives**

Cyclo and synchro converters utilise the thyristor power electronic device which can only be switched slowly (in electrical terms where one cycle of 60 Hz is some 17 milliseconds), and requires a reverse voltage to be switched off. In the face of these limitations the cyclo and synchro are virtually the sole contenders at warship propulsion power levels and significant harmonic distortion is the result, along with a large volume of equipment to clean up both the supply and the supplied waveforms.

However, the Insulated Gate Bipolar Transistor (IGBT) is now becoming available at the required power levels and there are other future generation devices on the horizon. These devices switch much more quickly and can be utilised in pulse width modulated variable speed drives. The result is much less harmonic distortion and much less infrastructure to clean up the waveforms.

**Harmonic distortion**

The reduction of harmonic distortion is agreed to be a major design driver for an electrical propulsion system – not only is the distortion conducted into all connected equipment, the high order harmonics can generate EMI and be transmitted into the receivers of weapon equipment.

However, as described above, the IGBT and future generations of power electronics will impose a much reduced harmonic distortion burden and, by adapting currently available technologies, the authors are confident that control will be neither costly nor voluminous.

**Bearings**

High speed generators directly connected to gas turbines are currently being developed at several universities. The fact that these are the rotational speeds of gas turbines indicates that the technology exists now to provide bearings for such machines. The authors also consider that active magnetic bearings could be harnessed for these duties.

**Distribution**

The dc distribution is only a vision at present and studies are being undertaken to establish the cost and disadvantages of such a distribution system. Given that proviso, the authors’ vision is:

**Question a:** The dc system is seen as distribution only, thus the motors are likely to be ac squirrel cage induction motors fed by static electronic controllers, the output stage of existing variable speed equipment.
Question b: The lighting is seen as being fed from 115V 60 Hz derived at the zone power supply unit.

Question c: The battery is seen as the standard 8800 Ampere Hour cell widely used in submarines. To achieve a 480V nominal dc busbar, the battery’s volume and weight are 37m³ and 118t.

General
Point a: The questioner’s approval of the removal of all hydraulics is welcomed. The authors feel that taking hot, pressurised oil into a war zone is something that should be avoided.

Point b: The reliability and maintenance of power electronic equipment has certainly improved over recent years; there are so many dc, cyclo and synchro driven ships around that confidence grows all the time.

Conclusion
Point b: With or without the dc ring main, the MOD sees a need to undertake a shore test of any ‘first of class’ propulsion system before it is committed to a major warship. Furthermore, from the experience of Exmouth and the introduction of gas turbines, there is a senior school of thought that there should also be a demonstration at sea. Whilst the authors agree that simulation should be sufficient to validate the electrical design, some form of testing is likely to pay dividends by enabling integration and identifying weak ‘ARM’ links.

Point c: Fortunately, and as a result of the Type 23 and merchant service experience, times have changed. It is now widely accepted that electric propulsion can and does work, indeed such cries as ‘why was the Type 23 designed with a gearbox’ are often heard; the culture is entirely different from the early Type 23 days, and the authors believe that the vision outlined in the paper is far less radical than the CODLAG was, when the questioner was involved. Moreover, the first question these days tends to be: how much? The authors believe that their vision can deliver a ship that is cheaper than the Type 23 or Type 22 (without weapons anyway!).

Point d: Some of the factors influencing maximum speed were outlined earlier. However, and philosophically, there are a number of occasions in war where the equipment carried to provide 30 kn has allowed operation to continue after sustaining considerable damage. Perhaps if it were a 25 kn ship then limping home rather than operation might be the result?

Point e: The point is well made. The authors feel strongly that the end of the paper chase is in sight; we now need to develop hardware.