THE GEARED MEDIUM SPEED INDUCTION MOTOR

A VIABLE ALTERNATIVE TO PERMANENT MAGNET MOTORS FOR FULL ELECTRIC PROPULSION

BY

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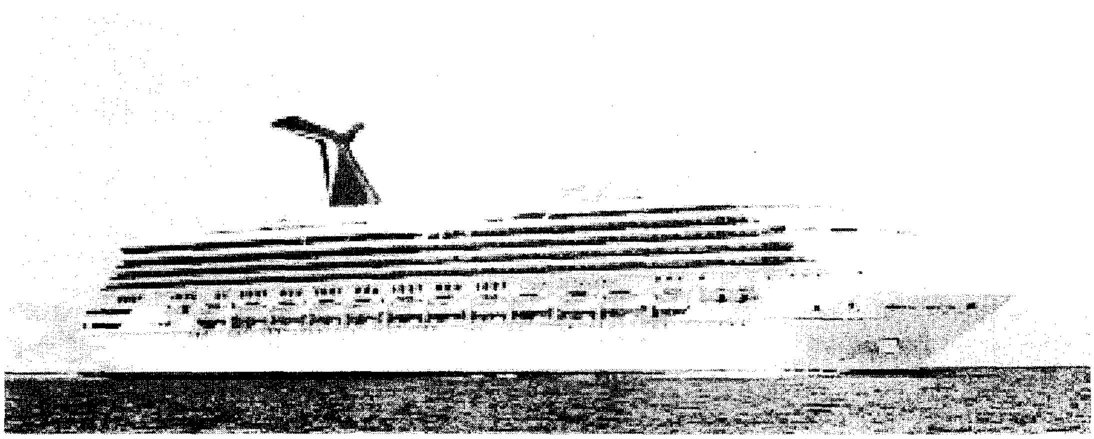
This is an edited version of the paper that was first published by the Institute of Marine Engineers at the Marine Engineering challenges for the 21st Century *Conference held at Hamburg from 14 – 16 March 2000.*

ABSTRACT

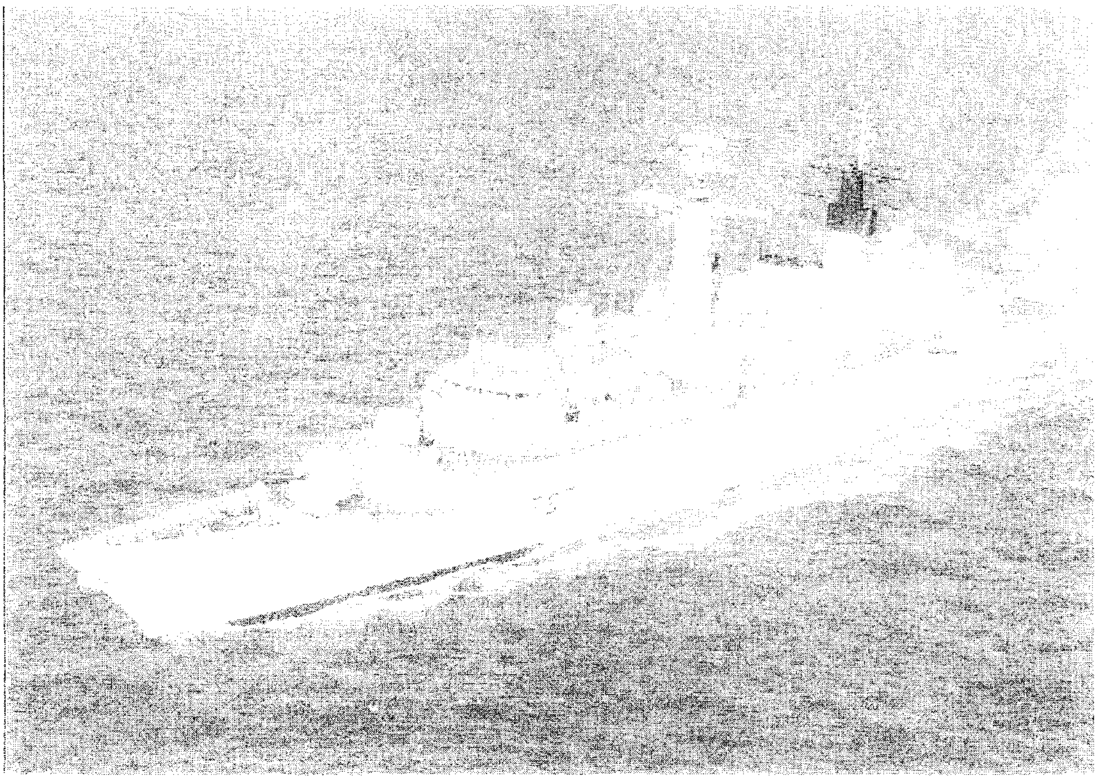
To implement integrated full electric propulsion (IFEP) in warships requires propulsion motors with three times the torque density of conventional synchronous or asynchronous machines. Permanent Magnet (PM) motors to meet the need for high torque density direct drive warship propulsion are being developed, but have yet to be proven in warship applications. This article examines an alternative to the PM motor, the medium speed induction motor with a gearbox. The power requirements for typical warships are summarized, and the motor performance boundaries of PM and induction motors outlined. Other performance criteria such as gearbox noise and reliability are considered, and some alternative drive configurations are evaluated for an escort sized ship. The relationship between drive system configuration and gearbox layout is explored, and related to the operational profile of warships. The size, weight, and cost of direct drive and geared electric motors is compared, and the efficiency of motors and control system is considered. The arrangements of geared motors for escort and carrier sized ships are presented. It is concluded that geared motors are a viable alternative to PM propulsion motors, with minimal development risk, high reliability and low maintenance, having both UPC and TLC significantly lower than any direct drive motor.



Introduction

Integrated Full Electric Propulsion (IFEP) is becoming common in ships such as cruise liners. These characteristically operate at variable speed, with long periods of low speed cruising, and transport a power hungry cargo – holidaymakers with a demand for high standards of heating, air conditioning and entertainment. In these applications IFEP can:

- Increase the life of the prime mover (mainly medium speed diesel engines).
- Reduce fuel consumption and emissions.
- Provide flexibility in machinery space layout.



Warships also operate at variable speed, typically for 70% of operational time at less than 20% of maximum shaft power, and for only 5% of time at sea close to full power. Modern weapons systems are also a 'power hungry cargo', for which up to 2MW must be provided on a frigate and up to 8MW on a carrier. The benefit of IFEP for fuel consumption and machinery life can also be expected to apply to a warship with a single 'Power Station' providing for both 'hotel' and propulsion power. However, the implementation of IFEP on warships is challenging. In addition to rigorous requirements for high shock capability and low noise signature naval vessels must be capable of operating at high speed. In frigate sized ships this requires a machinery installation of high 'power density' and particularly a propulsion motor of very high 'torque density'. The implementation of IFEP in warships has been frustrated by the large size of conventional, direct drive synchronous and asynchronous motors. Permanent Magnet (PM) motors are being developed, to achieve the required torque density, but are as yet unproven for warship applications.

This article proposes an alternative to PM propulsion motors. The combination of a medium speed electric motor, based on well proven current motor technology, and a simple single or two stage gearbox, is examined as an alternative to the shaft speed motors.

Power requirements – Escort and Aircraft Carrier

Escorts and aircraft carriers are typically designed for a maximum speed of around 30 kn. Escorts typically displace 5,000 to 8,000t while small aircraft carriers will displace 40,000 to 50,000t. For comparison, typical cruise liners displace 40,000t and are designed for a maximum speed of about 22kn, requiring a shaft power of about 30MW.

The displacement, maximum speed, shaft power and hotel load for typical examples of these ships is summarized in Table I, which also shows the specific power, that is the ratio of shaft power to displacement, and the ratio of 'hotel load' to shaft power.

TABLE 1 – *Typical ship parameters and powers*

	Ship class		
	Cruise ship	**Escort**	**Aircraft Carrier**
Deep displacement (t)	40,000	5,000	40,000
Maximum speed (kn)	22	50	30
Shaft power (MW)	30	50	80
'Hotel' power (MW)	10	2	7
Specific power (kW/t)	0.75	10	2
(Hotel power + shaft power)% (at rated shaft power)	33%	4%	9%

From Table 1 it is noted that:

- The specific power requirement (in kW/t) is some 13 times greater for an escort than for a cruise ship, while the specific power for an aircraft carrier is only some 2.7 times greater.
- The ratio of 'hotel' power to propulsion power is very much greater in a cruise ship (33%) than in an escort (4%) or aircraft carrier (9%), when related to maximum shaft power. However, when related to average power used when at sea, the ratio of hotel load to average shaft power in a warship will be more similar to that in a cruise liner.

Motor performance boundaries

The operating envelope of any variable speed electric motor is limited by two performance boundaries, viz:

1. The achievable torque density, i.e. the torque per unit volume, which is a function of the maximum practicable field density and current (ampere-turn) density.
2. The power density limit, i.e. the power per unit volume, which is a function of the internal losses of the motor, the maximum motor temperature and the motor cooling system.

These boundaries are shown schematically in (FIG.1), where the torque density (kN/m^3) and the power density (MW/m^3) are shown as a function of speed. To utilise fully the capability of an electric motor, the propeller characteristics and the motor characteristics should be such that at full speed the 'system' operates at the ideal speed 'a' where the torque and power density limits are simultaneously reached. This is impossible to achieve in a slow speed, direct drive motor, which will always be limited by the achievable torque density, and will operate well below the achievable power density limit.

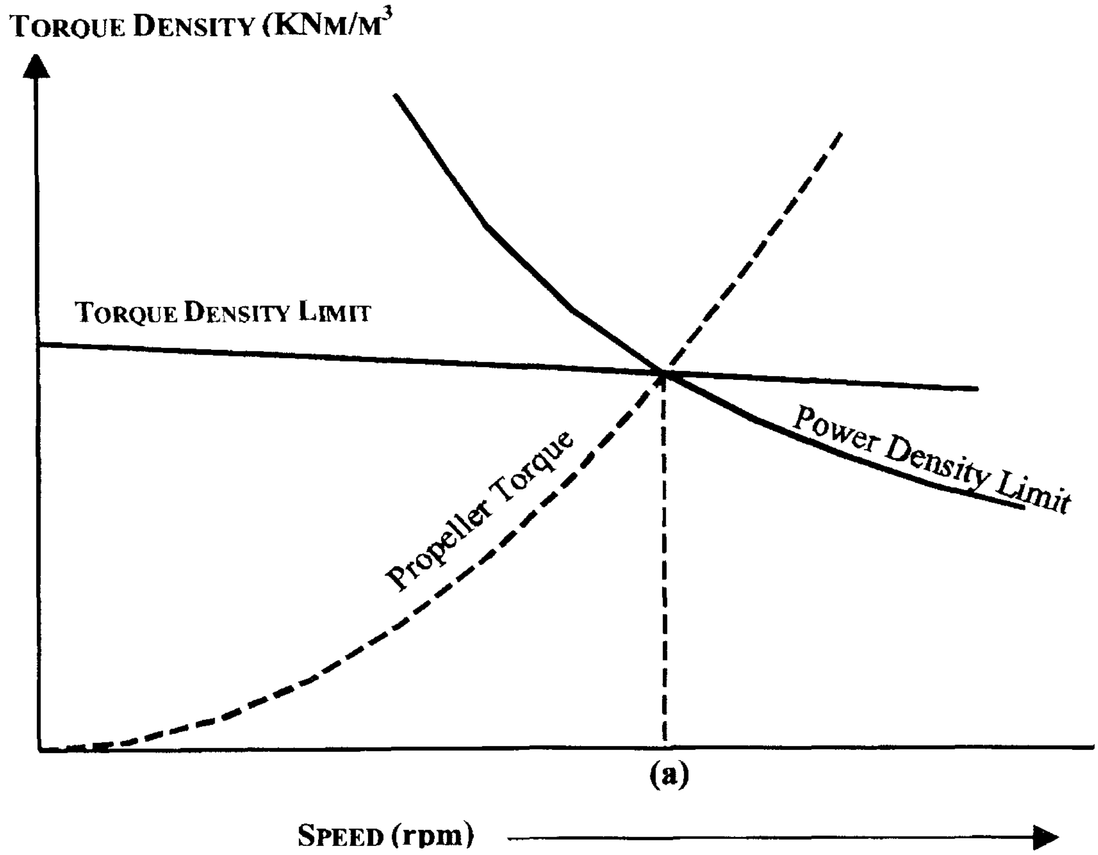


FIG.1 – TORQUE/SPEED CHARACTERISTIC

When considering the relative performance of different motor types for a marine propulsion system, it must be recognized that large variable speed Commercial Off The Shelf (COTS) motors are designed to be low cost, high efficiency machines for a very competitive market. They are also generally designed to achieve high torque (70-80% rated torque) at low speed. Such motors are not design optimized for marine propulsion where the drive requirements are unique.

Firstly

The motor torque characteristic follows the propeller law, that is, torque is proportional to the second or higher power of speed. The very low torque at low speed simplifies motor and cooling system.

Secondly

Although cost is important, it is less so than in commercial and industrial motors, so that high performance water cooled stators can be used.

Thirdly

The motors must have good shock resistance, which can best be achieved with short, large diameter motors. This is also a configuration that provides high torque capability (T □ d^2l).

No medium speed COTS motors are available which have been specifically designed for high torque and high power density and to meet the special needs of naval propulsion applications. However, the technology for such motors is well established and well proven, particularly in demanding applications such as rail traction. Following protracted discussions with leading motor manufacturers, the torque and power densities appropriate to medium speed AC squirrel cage motors for naval propulsion have been calculated based on current AC motor technology.

Table 2 summarizes the practicable torque and power densities and optimum speed, as well as weight and specific weight (T/MW), for two sizes of medium speed squirrel cage induction motor based on water cooled stators and air cooled rotors. Also included is a best estimate for the performance that could be achieved with a radial flux PM motor (it should be noted that the torque and power density are based on the stator outside diameter and overall length not on the motor casing cross section).

TABLE 2 – *Comparison of medium speed electric motor performance*

Motor type	Power rating	Torque density (kNm/m^3)	Power density (MW/m^3)	Optimum Speed (rev/min)	Weight (t)	Specific Weight (t/MW)
AC squirrel cage motor (8 pole)	5MW	14	3.6	2,455	5	1
AC squirrel cage motor (8 pole)	20MW	15	3	1,910	18	0.9
Radial flux PM motor	5MW	30	10	3,183	2.8	0.6

Typical torque and power densities for implemented low speed propulsion motors, both synchronous and squirrel cage induction, and a prototype PM motor are summarized in Table 3. It should be noted that the power density is the power density of the particular motor, it does **not** represent the maximum power density that could be achieved with this type of motor.

TABLE 3 – *Comparison of low speed motor performance*

Motor type	Power rating	Torque density (kNm/m^3)	Power density (MW/m^3)	Optimum Speed (rev/min)	Weight (t)	Specific Weight (t/MW)
AC Synchronous motor	6MW	19.5	0.31	150	51	8.5
AC squirrel cage motor	19MW	20	0.32	150	117	6.2
AC Synchronous motor	44MW	23	0.32	144	285	6.5
AC PM transverse flux motor	20MW	60	1.1	180	65	3.2

In Table 3 it is noted that the torque density of the conventional low speed motors ranges from 19.5 to 23 kNm/m^3 and that the power density is almost identical for all three examples. The PM motor achieves three times the torque and power density, and has a specific weight (t/MW) about half that of the induction motors.

Direct Drive and Geared Motor Power Density

Considering just the motors alone, a comparison of medium speed electric motor performance (Table 2) with that of the low speed motors (Table 3) shows that:

- The power density achievable with a medium speed induction motor is over 9 times greater (at 20MW) than is achievable with a low speed induction motor.
- The power density achievable with a PM Transverse Flux motor is less than 40% that of a medium speed induction motor based on existing technology.

It is thus clear that significantly better utilisation of the capability of a motor is achievable if the 'optimum' motor speed can be matched to the speed of the propeller. At the powers being considered, the best propeller speed will lie in the range 160 to 220 rev/min. To match the optimum motor speed of typically 1900...2450 rev/min to this propeller speed will require a suitable gearbox. Such arrangements are investigated in greater detail below.

Drive reliability

Most large marine propulsion systems have used direct drive motors, that is motors directly coupled to the propeller shaft and thus operating at propeller speed. The perceived advantages of this arrangement are:

- Simplicity.
- Reliability.

There is no doubt about the simplicity of shaft mounted motors, or, in the case of synchronous or asynchronous motors, their inherent reliability. However, the reliability of very large PM motors is yet to be proven in a naval propulsion application.

In a drive system using medium speed motors, the system reliability depends on both motor and gearbox performance. Medium speed induction motors are known to be extremely reliable, and can achieve long lives without failures. The gearboxes required for a medium speed AC motor are not COTS items, but are based on well developed, well established technology. Such gearing will benefit from past and current generic research into gear reliability and gear noise, in particular the work described below.

Gear reliability has received considerable attention over the last 10 years, with much MoD(N) research into gear material fatigue strength, and the cause of pitting, micro-pitting and tooth breakage. In parallel with this, techniques are being developed for better NDT of gears after heat treatment and gear grinding, which will assure the highest possible steel fatigue strength. Better understanding of gear fatigue combined with a refined 3D Finite Element stress analysis developed specifically for gears[1] means that these can be designed and manufactured with confidence to achieve very high reliability. It is now possible to specify gears with a realistic mean life between failure of the gear elements of 50,000 hours, without incurring significant cost increases. New gearbox assembly techniques and more rigorous type testing will ensure that the design performance is achieved in service.

Gears are, of course, not the only components that can fail in gearboxes. Historically, the most unreliable components have been multi-plate friction clutches, actuators and interlocks. The gearbox for an electric drive, however, does not need clutches of any sort, since the electric motor can remain permanently coupled to the gearbox. Since the motors are bi-directional they do not require reversing arrangements necessitating more components and usually fluid couplings. As a result, the gearboxes for an electric drive are smaller and less complex than current naval gearboxes, and can be designed to achieve a probability of failure (of any gearbox component) of less than 0.75% over a 30 year life (4,000 year MTBF). The reliability of the gearbox is thus expected to be better than that of the electric propulsion motor.

Drive noise

Electric propulsion is seen as a 'quiet' drive system. However, to achieve the very low noise and vibration levels required in warships will require extremely careful design of motor stators, otherwise significant vibration of the motor casing will occur at pole passing frequency. This can generate excessive vibration and noise over the critical frequency range. Power conversion machinery can also contribute to noise vibration.

Naval experience with electric propulsion has been principally with DC motors in submarines. In surface ships the Type 23 frigate uses DC motors of relatively low power, which would not be considered for current IFEP. Thus, although this class is quiet in electric propulsion mode, it would be unwise to extrapolate from its performance to that of large AC propulsion motors, and infer that these will meet the very stringent underwater noise and vibration requirements of future naval ships. The vibration levels generated by very large, multi-phase PM propulsion motors have yet to be demonstrated at sea.

In a geared electric motor, noise will be generated both by the motor (at pole passing frequency) and by the gears at tooth contact frequency. The smaller size, and the lower air gap forces, will make control of motor stator vibration easier than for the larger, direct drive motors. It would also be practicable and relatively inexpensive to soft mount the high speed motors, should this be necessary.

To meet the most stringent gear noise requirements, the Royal Navy has, over the last 10 years, commissioned a wide ranging programme of theoretical and experimental research to:

- Improve understanding of the fundamental kinematic and dynamic behaviour of gears which results in 'gear noise'.
- Investigate experimentally the relationship between gear design and gear noise.
- Develop tools for the design of quiet gears.

This research has perfected a 3D Finite Element based calculation procedure[1] which optimizes the design of the micro-geometry of gears for minimum excitation and thus minimum noise. This technique has been exhaustively validated against measurements of the Royal Navy's 8MW Marine Gear Research Rig[2], which has confirmed excellent correlation between theory and practice[3,4,5]. The tools are therefore now available and proven to optimise gear design for low noise and reduce gear noise at tooth contact frequency by as much as 20 dB relative to current naval gearing. This improvement in gear noise can be achieved without any increase in gearbox costs.

Drive system configurations

Many different IFEP system configurations are possible. Two will be considered here to illustrate the impact of the drive system on the motor and gearbox layout and system cost and efficiency.

The most basic drive concept for an escort sized ship assumes two advance cycle Gas Turbine driven Alternators to power propulsion and ships services, with a smaller diesel or gas turbine alternator for harbour duty and back up. The two propulsion motors are controlled and powered through static frequency converters. In this case because of the relatively flat specific fuel consumption characteristic only one motor per gearbox (and shaft) is required. To control shaft speed, two 22MW static frequency converters are also required. This arrangement is shown schematically in (FIG. 2).

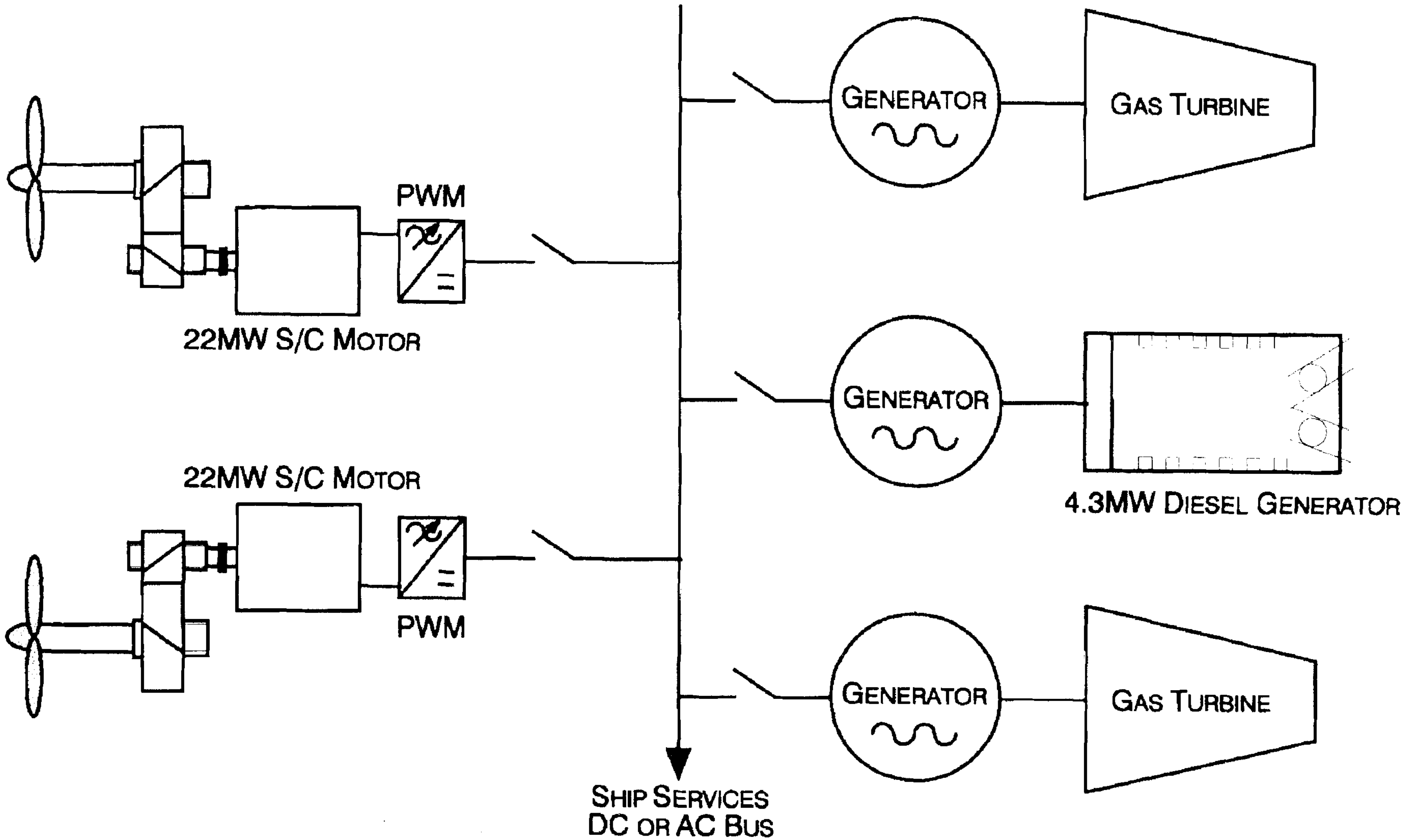


Fig.2 – One motor per shaft IFEP

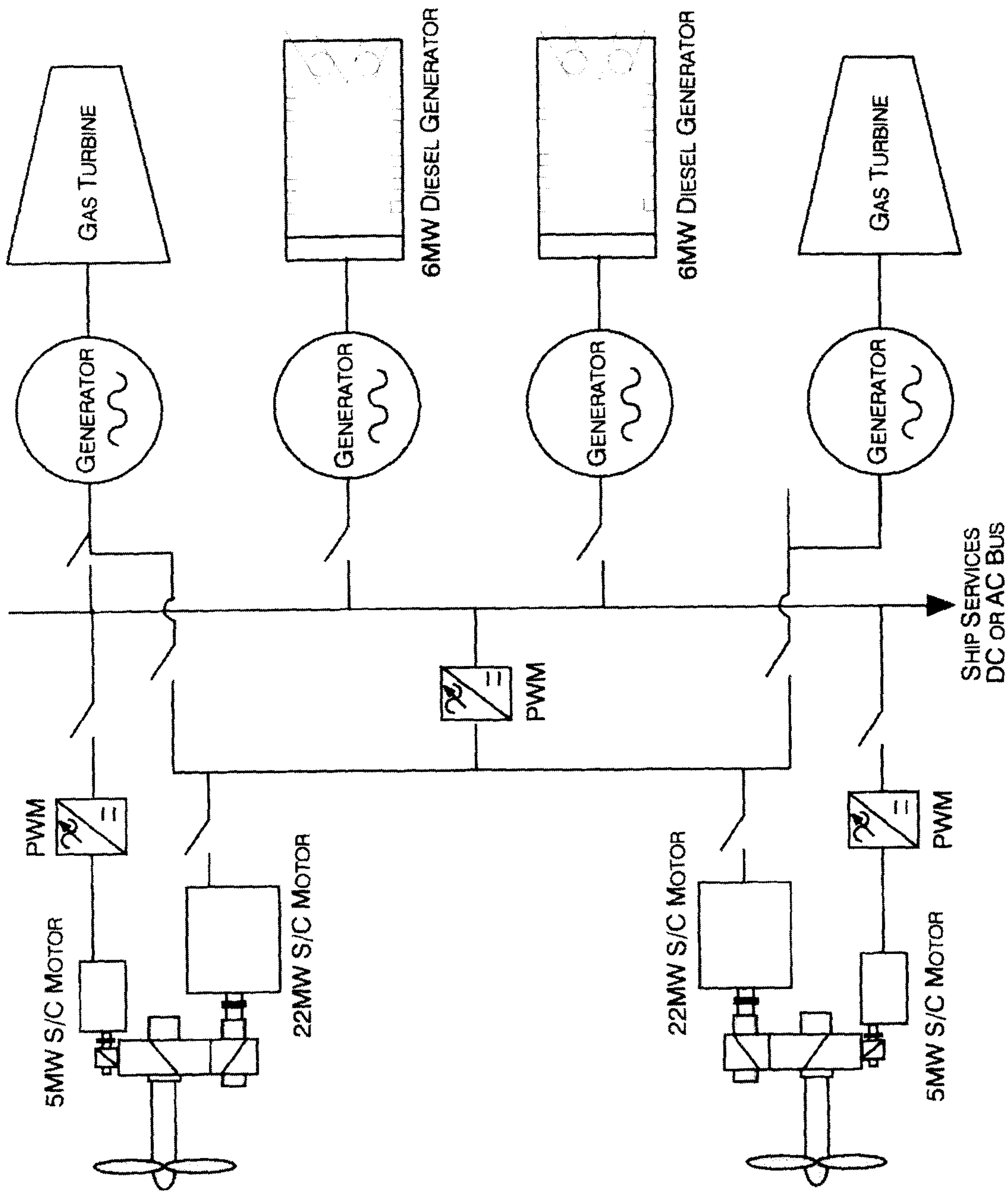


FIG.3 – TWO MOTORS PER SHAFT IFEP

An alternative drive and control concept, which has some merit, is to separate 'cruise' and 'sprint' operation of the vessel. This is particularly advantageous to offset the relatively poor fuel consumption characteristics of the simple cycle G gas turbine at low power. The cut-off point for 'cruise' will depend on the ship mission profile. Most vessels however primarily operate below 18...22 kn, which can be considered a typical limit of normal cruise operation. For a twin shaft escort, to be operated in 'cruise drive' up to 22kn requires 5MW per shaft, with a further 22MW to achieve a sprint speed in excess of 30kn. The concept of separate cruise and sprint drives with two motors per shaft is shown in (FIG.3) for an escort sized ship.

In cruise mode the propulsion motors are operated through static frequency converters from the main ship's bus. Diesel or turbine generators of 2 x 6MW supply power to propulsion and ships services. In sprint mode, that is in the speed range 22...31kn, variable speed gas turbine generators are directly connected to the sprint motors, which operate as asynchronous motors on a variable frequency supply. In this system, the static frequency converters for propulsion are only rated at 2 x 5MW, although a further static frequency converter may be required to provide fixed frequency AC power for ships services. Compared to an equivalent single motor system with full static frequency converter control, this can represent a significant reduction in cost, size and weight and can also achieve improved efficiency.

Alternative gearboxes

Figures 2 and 3 show the two basic configurations of drive system, that is:

- One geared motor per shaft.
- One cruise motor plus one sprint motor driving through a common gearbox onto each shaft.

There are many different gearbox designs that could be used in this two drive configuration, but these can be considered under the main heading of:

- Epicyclic gearboxes.
- Parallel shaft gearboxes.

The Royal Navy has not used epicyclic gearboxes for main ship propulsion. However they are used in some other navies, and have been used widely some decades ago in steam turbine (De-Laval) driven tankers. The reliability of these epicyclic gearboxes has been good, but the noise performance is less well understood than parallel axis gearing. The epicyclic gearing option is included here primarily for comparison of size and weight of the gearbox and motor combination.

The Royal Navy has wide experience of parallel axis gearing of two and three reduction stages, in both surface ships and submarines. For this article a relatively simple two stage gearbox design is considered which combines the drive from the cruise and sprint motors. Different gear ratios are proposed for cruise and sprint to allow both motors to operate close to their optimum speed.

Epicycle geared motor

An epicyclic gearbox offers a compact arrangement for a single motor drive system configuration as outlined in Figure 2. In this case a single stage gearbox is considered, which limits the gear ratio to 6.5:1 and gives a motor speed of 1,170rev/min at 180rev/min propeller speed. This motor speed is significantly below the optimum speed of a 22MW induction motor (1,910rev/min) but the simplicity and small size of the single stage epicyclic gearbox compensates in part for the larger motor size.

Table 4 summarizes the major parameters for the epicyclic geared motor, that is motor and gearbox size and weight and gearbox component sizes. The motor dimensions are based on the torque and power density and weights summarized in Table 2. The gearbox design is based on very conservative stressing (substantially lower than current Royal Navy gearboxes) to achieve high reliability and very low through life cost.

TABLE 4 – *Parameters for 20MW epicyclic geared motor*

MOTOR			GEARBOX		
Motor type		Induction 8 pole	**Gear ratio**	u	6.5
Rated power	MW	22	**Pinion diameter**	mm	341
Rated speed	Rev/min	1,170	**Wheel diameter**	mm	1,892
Rated torque	kNm	179.5	**Facewidth**	mm	430
Torque density	KNm/m^3	17.1	**Centre distance**	mm	-559
Power density	MW/m^3	2.1	**Length**	mm	800
Length	mm	2,500	**Width**	mm	2,300
Diameter	Mm	2,300	**Height**	mm	2,450
Weight	t	27.5	**Weight**	t	24

It is noted that the weight of the three planet epicyclic gearbox is almost identical to that of the motor, giving a total 'Geared Motor' weight of 51.5t, and that motor and gearbox are of identical diameter and width, 2300mm. The general arrangement of the 22MW, 180rev/min geared motor is shown in (FIG.4). A standard Allen gears 'Stoeckicht' epicyclic gearbox design has been adopted, close coupled to the hollow shaft induction motor.

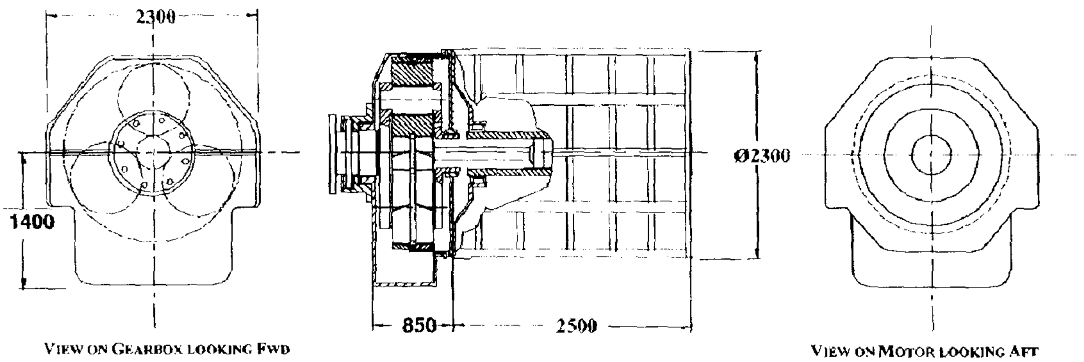


FIG.4 – SINGLE STAGE EPICYCLIC AND 22MW PROPULSION MOTOR

Two motor parallel shaft geared drive

The drive concept with separate 'cruise' and 'sprint' motors as shown in Figure 3 can be realised with many different gear arrangements. (FIG.5) shows one such arrangement with the minimum possible number of gears.

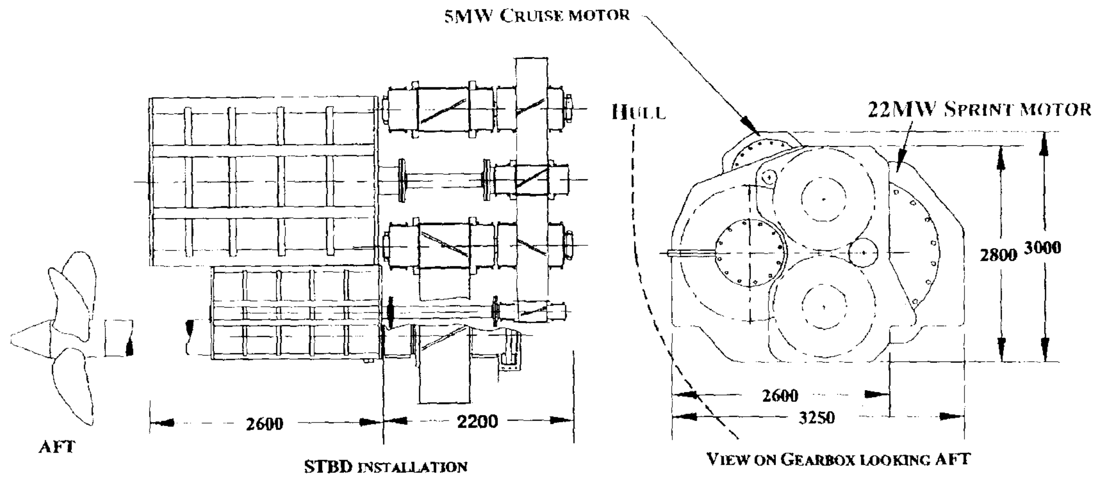


FIG.5 – TWO MOTOR (CRUISE AND SPRINT) DRIVE

The 22MW 'sprint' motor drives an input pinion which meshes with two 1st stage wheels, which in turn drive the 2nd stage pinions that mesh with the main wheel the 5MW cruise motor is connected to its own pinion which meshes with one of the 1st stage wheels. The gear ratio for the two stage sprint gearing is 10.61:1, giving an optimum motor speed of 1,910rev/min at 180rev/min propeller speed. The maximum 1st stage ratio for the cruise motor is limited by stressing considerations to 5.33:1, giving an overall ratio of 16.15:1. As a result the cruise motor will be running at only 1,875rev/min at 20kn rather than at its optimum speed of 2,455rev/min. Above 20kn the cruise motor can be operated as a constant power variable speed drive with a maximum motor speed of 2,906rev/min at 180 shaft rev/min. The main motor and gearbox parameters for such a drive are shown in Table 5. Both motors are permanently coupled to the gearbox through diaphragm type couplings. With only seven gear elements and no multi-plate or SSS clutches the gearbox is simpler than any current naval boxes.

TABLE 5 – *Two motor geared drive*

Motor			
Motor type		**Induction cruise**	**Induction sprint**
Rated power	MW	5	22
Rated speed	Rev/min	1,875	1910
Rated torqu	kNm	22.5	110
Torqu density	knm/m^3	15	15
Power density	MW/m^3	2.94	3
Length	mm	1,902	2,600
Diameter	mm	1,965	1,900
Weight	t	4.5	19

Gearbox – 2 stage 16.16:1 and 10.61:1				
Gearbox stage		Induction cruise	Induction sprint	II
Gear ratio	u	5.33	3.5	3.03
Pinion diameter	mm	235	358	549
Wheel diameter	mm	(1,253)	1,253	1,663
Facewidth	mm	(358)	358	549
Centre distance	mm	744	805.5	1,106
Length	mm		2,200	
Width	mm		2,600	
Height	mm		2,800	
Weight	t		32	

Size and weight comparison, geared and direct drive motors

A comparison can now be made between the direct and geared motor drives.

The overall sizes and weights of the two geared motor arrangements are compared in Table 6 with the size and weight of direct drive induction motors of the same power rating. For comparison purposes, the data for a projected transverse flux PM propulsion motor is also included. To underline the difference in static frequency converter requirements, the weight of this is also included in the last line.

TABLE 6 – *Size and weight comparison of geared and direct drive motors (per shaft)*

		22MW epicyclic gearbox	5MW cruise 22MW sprint dual tandem gearbox	22MW 180rev/min Induction Motor	22MW 180rev/min PMPM
Length	mm	3,350	4,800	4,300	2,900
Width	mm	2,235	3,250	4,000	2,900
Height	mm	2,550	2,800	4,000	2,900
Weight (motor+gearbox)	t	51.5	55	113	71
Weight (motor+gearbox+ converter)	t	70.5	60	132	90

In Table 6 it is noted that the epicyclic geared motor arrangement is the lightest, with a weight 45% that of the direct drive induction motor and 72% that of the PM propulsion motor. However, when the weight of the static frequency converter is included, the configuration with separate cruise and sprint motors has the lowest system weight, 60t compared to 90t for the PM and 132t for the induction propulsion motor drive system. For the complete ship propulsion system, this represents weight savings of 60t relative to direct drive PM or 144t relative to a slow speed induction motor drive.

When comparing the space envelope of the 'two motor' geared arrangement with that of the low speed induction and PM motors, a possible advantage is that the motors could be positioned alongside the prop shaft so that the actual build space requirement is less than the tabulated space envelope would suggest. The dual motor configuration also has 27MW installed power per shaft rather than 22MW as is the case with the other options shown.

Although rather long, the small diameter of the epicyclic geared motor (22MW at 180rev/min) means that the total build volume is small, representing only 78% of the PM, and only 28% of the low speed induction motor.

Drive system losses and efficiency

One of the advantages of IFEP is a reduction in overall fuel cost for propulsion and 'hotel' power. The generation of 'hotel' power is outside the scope of this article. However, the losses in the static frequency converter, and propulsion motor and gearbox (when fitted) are compared for the major options. It should be noted that only gearbox, motor and converter losses are considered. It is assumed that prime mover and generator efficiency at a given power is the same irrespective of the type of motor used.

Gearbox losses are well understood and have been accurately measured on the Marine Gear Research Rig. They can be broken down into:

1. Windage, churning and bearing losses, where $P_w=C_1 n^2 + C_2 n^3$. The constants C_1 and C_2 are a function of gear diameter and facewidth. For the relatively slow gearing being considered here, $C_2 n^3$ is negligibly small, and the churning losses are then:

   1st Stage $P_{w1} = 32.7 n^2$ watts per mesh

   2nd Stage $P_{w2} = 65.2 n^2$ watts per mesh

   where n is speed in rev/sec.

2. Mesh friction losses. These are a function of transverse contact ratio, slide-roll ratio, oil film thickness and transmitted power. For these gears, mesh friction loss is:

   $P_f = (0.524\% \pm 0.02\%)$ x transmitted power.

The losses and efficiency for three different propulsion systems are summarized in Table 7.

TABLE 7 – *Losses and efficiencies*

Propulsion system							
		22MW direct drive		22MW geared epicyclic (single stage)		5MW + 22MW dual tandem gearbox (two stage)	
Transmitted power	MW	5	22	5	22	5	22
Total gearing losses	KW	0	0	38	160	59	248
Total motor losses	KW	260	940	158	552	135	552
Converter losses	KW	150#	460	150#	460	110*	0
Total losses	KW	410	1,400	326	1,172	304	800
Efficiency (motor + gearbox + inverter)	%	91.8	93.63	93.48	94.67	93.92	96.36

\# – 22MW inverter   * – 5MW inverter

In each case the losses in motor, gearbox, and static frequency converter are given for cruise (5MW for 20kn) and sprint operation (22MW for 31kn). Three propulsion systems are considered:

- 22MW direct drive with induction motor and static frequency converter.
- 22MW geared motor with static frequency converter as shown in Fig 4.
- 5MW cruise, with 22MW spring two motor installations as shown in Figure 5.

The comparison of motor plus converter efficiencies shows that at both 5 and 22MW, the low speed motor is the least efficient. There is little to choose between the single motor epicyclic and the two motor dual tandem gear drive at cruise speed (5MW) but at sprint speed (22MW) the two motor drive, which does not require a static inverter for sprint operation, is more efficient.

It should be noted that at sprint (22MW) the gearing loss is only 248 of the 800kW total losses in the two motor geared drive. At 22MW the total losses in the low speed motor and inverter are 1,400kW – resulting in a significant increase in cooling load.

Cost comparisons

Cost comparisons are always difficult if the components are not COTS or, as in this case, no identical motors have been built. Nevertheless, cost comparisons are important in evaluating the ranking of alternative propulsion systems, and an attempt at realistic costing is made below.

The induction motor designs used in this study are based closely on current industrial motor technology but the proposed 8 pole large diameter machine is not an off-the-shelf product for which costs are established. For the purpose of this study it has therefore been assumed that the medium speed motors required for the geared drive, with a specification to meet naval shock and noise requirements, will be 50% more expensive than equivalent industrial traction motors. The cost of gearboxes is based on executed naval gearing of similar size. The true cost of large PM machines is still conjecture and for the purpose of this paper it is assumed that a low speed PM motor will cost 50% more than an induction motor of the same speed and rating. This cost estimate for the PM motor with static frequency converter agrees fairly well with the estimate given by Rahn[6] who quotes a cost of DM0.7M/MW which would give a cost of £5.7M for the PM motor drive (at DM 2.70/£).

Static frequency conversion equipment is also crucial to the comparison particularly due to the fact that the rating and therefore cost for the twin motor cruise/sprint arrangement is significantly lower. The full cost analysis is presented in Table 8.

Table.8 – *Cost summary, geared motors and static frequency converter*

		Motor and gearbox type			
		22MW 180rev/min Induction motor	**22MW 180rev/min PM motor**	**22MW 1,170rev/min Induction motor epicyclic gearbox**	**5MW cruise (1,875rev/min) 22MW sprint (1,910rev/min) Induction motors Dual tandem gearbox**
22MW motor cost	£K	1,200	1,700	760	485
5MW motor cost	£K	–	–	–	148
Gearbox cost	£K	–	–	510	820
Motor and gearbox cost	£K	1,200	1,700	1,270	1,453
SPC – PWM cost	£K	1,800	1,800	1,250	525
Total cost per shaft	**£K**	**3,000**	**3,500**	**2,520**	**1,978**

Even with the proviso that all costs in Table 8 are only best estimates, there are nevertheless significant differences in total system cost, that is the cost of motor + gearbox + static frequency converter. In particular a significant cost saving is effected in the two motor geared drive which requires just a 5MW rather than 22MW static frequency converter. The result is a drive system that is significantly less expensive. Considering this concept with cruise and sprint motor as representing 100% cost, then the relative costs of the drive options are:

Dual Motor (Cruise and Sprint) System:	100%
Epicyclic Geared Motor System:	127%
Direct Drive Induction Motor System:	157%
Direct Drive PM Motor System:	177%

Geared motor installation – Escort

(FIG.6) shows the epicyclic geared motor of Figure 4 installed in an escort sized ship. The small diameter of the gearbox and motor (∅2300) allows these to be positioned well aft with a short main shaft. With a height of only 2550mm, the installation also requires less height in the machinery space than any other drive.

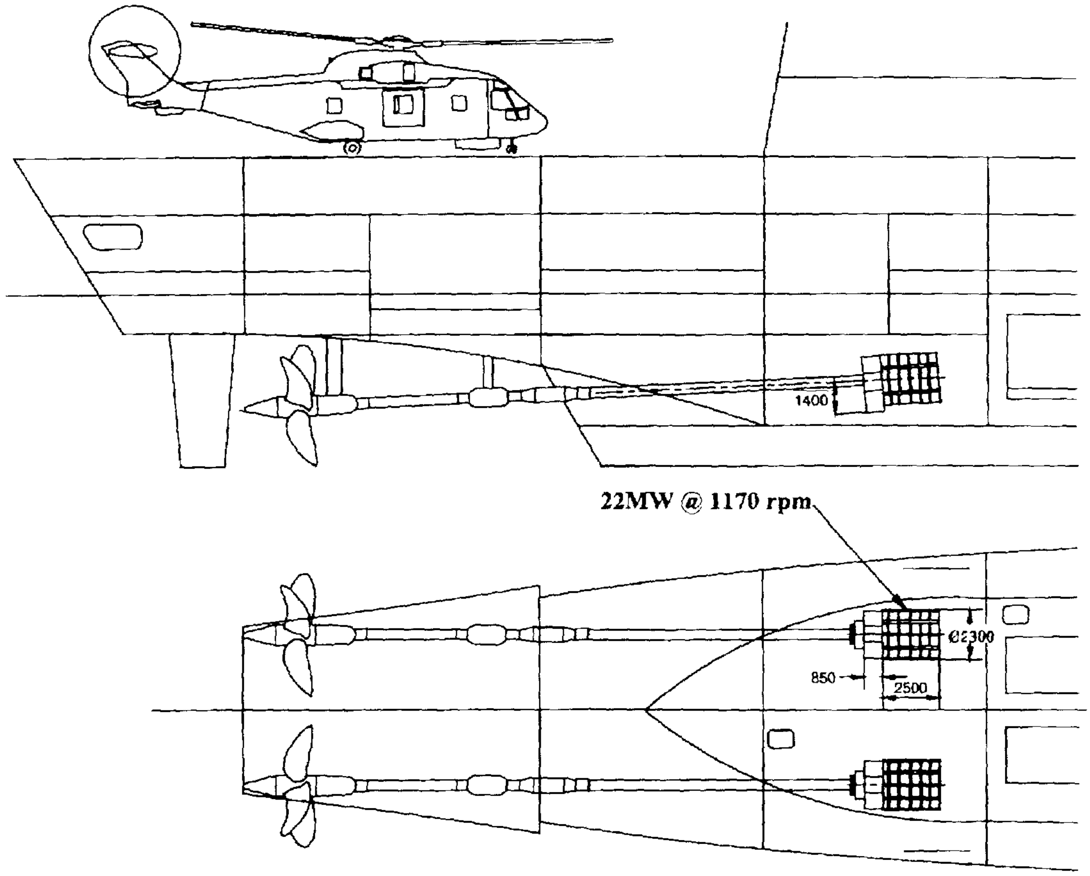


FIG.6 – EPICYCLIC GEARED MOTOR INSTALLATION

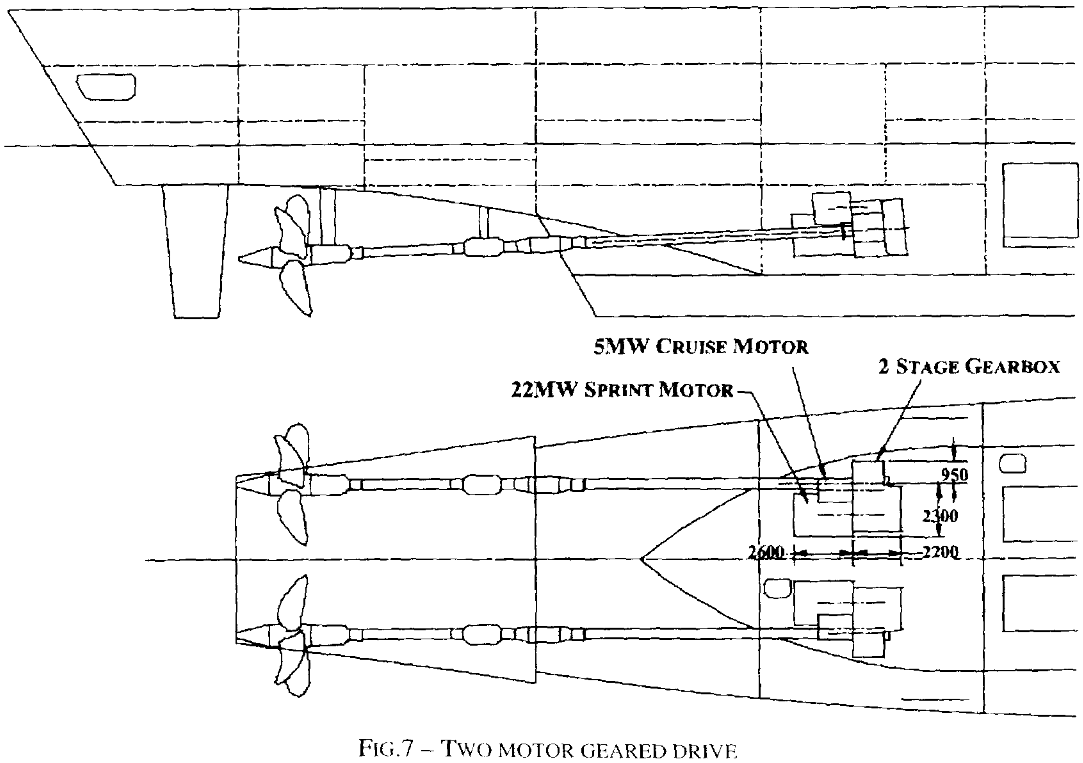


FIG.7 – TWO MOTOR GEARED DRIVE

(FIG.7) shows the parallel shaft gearbox with cruise and spring motors installed on an escort. The relatively small main wheel diameter (1663mm PCD – see Table 2) results in a narrow gearcase (960mm) which allows this gearbox to be moved even further aft than the epicyclic. The dual motor layout offers flexibility in positioning the motors, either forward or aft of the gearbox, depending on the machinery space layout and access required for servicing.

Geared motors for larger ships

To complete the picture, the use of a gearbox to facilitate IFEP in larger ships is also considered. An aircraft carrier, for example, will require an installed shaft power of about 90MW, that is 45MW per shaft. A 45MW, 180rev/min induction motor would typically weigh 230t, and have overall dimensions (excluding bearings) of 5800 x 5800 x 5800mm.

An alternative 44 MW drive for one shaft is shown in (FIG.8). This uses two 22MW induction motors identical to the proposed medium speed motors for an escort sized ship. If appropriate, a smaller cruise motor could also be fitted to the gearbox. By using two motors for each shaft, each with its own primary gear train and second stage pinions, the main wheel and all other gearing remains identical in size to that used on the escort propulsion gearbox. This could have advantages in terms of first cost and spares. This arrangement results in overall dimensions 4,630mm wide, 2,400mm high and 4,800mm long. The weight of the 44MW geared motor assembly would be about 90t. In other words the weight of the geared motor is 40%, and its overall space envelope only 27% of the equivalent direct drive motor.

Discussion

It is generally considered that there is insufficient space available in a small escort sized ship to fit a conventional direct drive AC propulsion motor of adequate power. Larger escort vessels could benefit from advances in polyphase induction motors. However, in order to realise IFEP on these smaller warships, the development of low speed, high torque density motors is being undertaken.

The required torque density of about $60kNm/m^3$ can, in principle, be achieved with transverse flux PM machines, or circumferentially magnetized external rotor machines[7]. However, motors of these types have not yet been built for 22MW power output, and pose a development risk, not only in terms of achievable performance and weight but also in terms of vibration and noise. Further aspects which must be addressed for these radically new machines are the difficulties of identifying potential risks and all possible modes of failure particularly in respect of bonded permanent magnets and the prediction of fatigue and creep life.

An alternative to the use of slow speed, high torque motors is the use of a conventional AC motor in conjunction with a gearbox. As shown in this article, motors and gearboxes based on current well proven technology are smaller than PM motors and can be easily accommodated in an escort sized ship. Such a drive does not pose any development risk or incur R&D costs. The failure modes for induction motors are well understood, as are those for gears, with substantial experience of both over many decades, so that performance over the life of the ship can be predicted with some confidence. A further advantage of the medium speed geared induction motor is the lower cost, potentially saving some £7.8M UPC per ship installation over an equivalent PM motor drive.

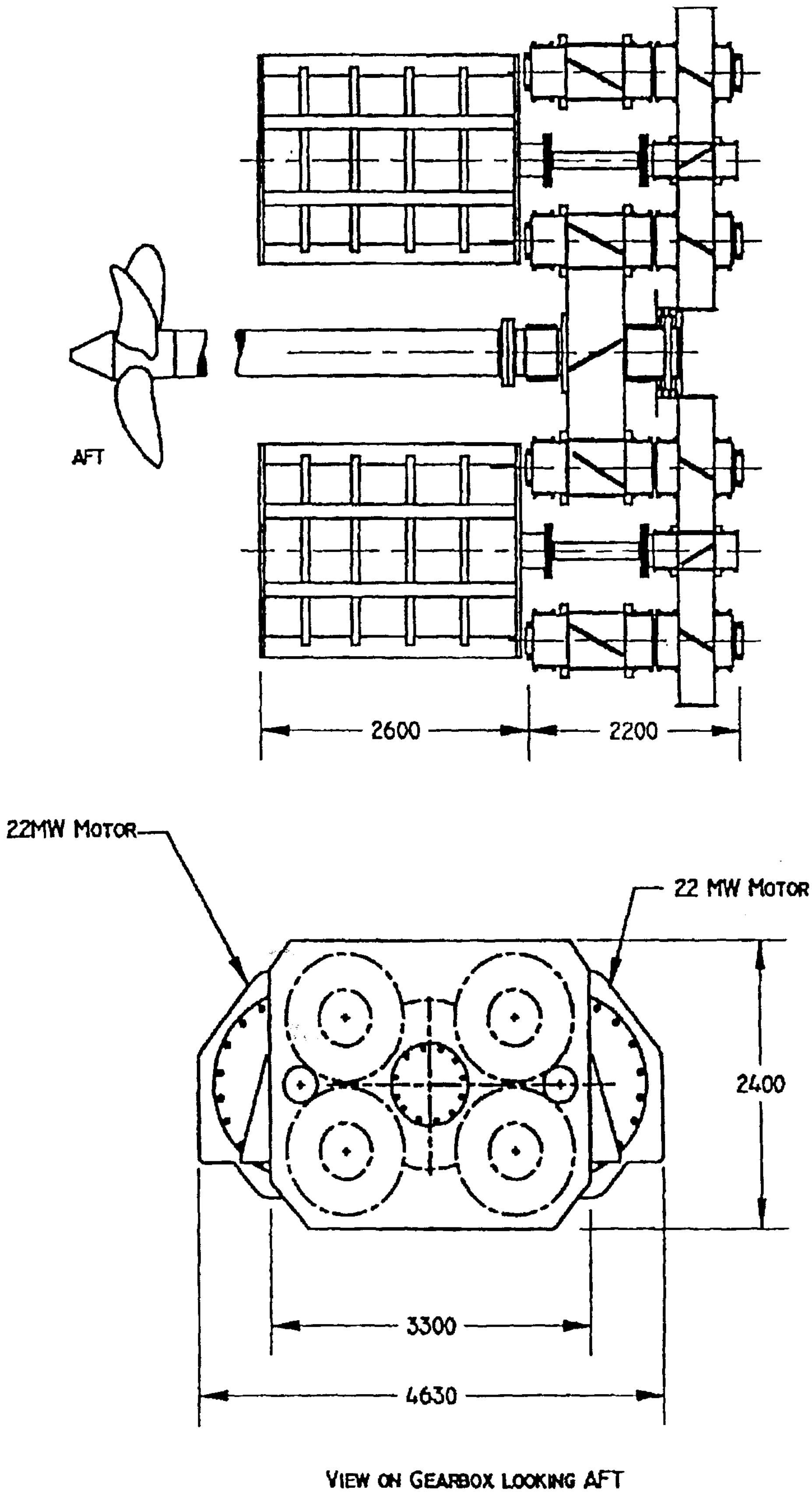


FIG.8 – 44MW GEARED ELECTRIC PROPULSION

In the event of motor repairs or servicing being required, the smaller size and weight of medium speed motors makes their removal from the ship relatively easy, thereby reducing maintenance and service costs.

Geared medium speed propulsion motors are also a viable alternative to both conventional low speed, direct drive, induction motors and PM motors for larger naval vessels such as aircraft carriers with cost, weight and efficiency advantages. With a gearbox it is possible to provide separate cruise and sprint drive of adequate power, based on conventional medium speed AC machines, in a package about one quarter the size of a low speed AC machine. Such a propulsion system is yet another possibility to add to the many arrangements presented by VOSPER[8] and would be comparable in weight and volume t the COGLAG fit with water jet.

Although the geared motor arrangement with a single stage epicyclic gear is the most compact, it has the disadvantage that it cannot be used with a separate sprint motor. The noise performance of epicyclic gears is also not as well understood as that of parallel axis gearing, in particular the dual tandem articulated gearbox configurations which have been used in all geared submarine drives and have been well researched and developed over the last ten years. For vessels with high installed power and stringent noise and vibration specifications, this type of gearing should be preferred.

Conclusions

Key features of direct and geared propulsion motors have been examined and the following conclusions can be drawn:

- There are no reliability concerns with medium speed induction motors.
- Noise and reliability concerns in respect of future geared motor propulsion drives are ill founded and based on experience with older gear technologies and designs directed to minimum weight rather than maximum reliability
- State-of-the-art parallel axis gearing can achieve very low noise levels, more than adequate to satisfy the most stringent naval radiated underwater noise specifications.
- Geared propulsion motors offer a low risk alternative to the use of advanced PM propulsion motors. High performance medium speed induction and synchronous motors and propulsion gearing are well established technologies which do not require substantial research and development.
- The small size and low weight of geared propulsion motors make them particularly attractive for use in smaller warships where high power and torque density is required.
- Geared propulsion motors are less expensive than direct drive synchronous and induction motors, and are significantly cheaper than equivalent PM machines, especially in a system where spring operation uses a variable speed, variable frequency generator without static frequency converter.
- The small width and height of a geared propulsion motor permits installation further aft. A very compact machinery layout is therefore possible with motors mounted alongside the main shaft.
- The ability to combine two or more geared medium speed propulsion motors in a geared drive makes these a low risk option for IFEP on larger vessels such as carriers requiring between 40 to MW per shaft.

- The use of a number of medium speed motors in a geared drive offers considerable flexibility in the control system and the possibility to standardise drive motors and gearing over a wide range of vessels – LPD, Escort, Carrier etc.

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