# Geared Electric Propulsion

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The use of an electric machine with a gearbox is not a new phenomenon. They have been used to provide a compact propulsion solution with motors which operate at standard industrial speeds. When used in Z-drives they provide the same compact solution for an azimuthing drive with the minimum size pod.

Usually asynchronous motors are used with variable speed drives and fixed pitch propellers to provide high torque and thrust at a range of ship speeds without the fixed speed need for a controllable pitch propeller (CPP) and the related need for propeller blade pitch angle control and the hydraulic actuation that this requires. However modified geared electric and other similar solutions are explored to assess their potential benefits for an 80m research vessel. A solution with two twin-wound fixed-speed motors with CPP was explored to understand its potential benefits and to identify any performance shortfalls it may present. The study considered the issues involved in the trade of efficiencies between motor converters and the CPP losses at different blade angles. The study also considers a range of sea states including the sensitivity of the combinator curve.

## INTRODUCTION

For many years, electric motors have been used as Power Take-In (PTI) drives for slow speed operations to avoid low engine loads and poor combustion in the mechanical drive comprising the two or four stroke engines. For warships and research ships, direct electric drive has also allowed for a quieter drive with no gear noise and much reduced noise from the acoustically isolated DG sets.

As ships have grown in size and top speeds have increased, both to meet for commercial pressures, the size, weight and cost of direct electric drive motors has also grown. The size of electric motors is roughly proportional to their torque rating and there is a challenge to fit ever increasing diameter motors in the fine after hullforms for faster vessels. Although the motors can be moved forward to benefit the longitudinal weight balance, this makes the propulsion system consume more internal space which is less efficient in ship design and operating terms.

A large motor is made of copper (conductor), iron (flux connector) and steel (frame and strength bearing members). The price of copper has fluctuated with the global economy but there is a definite historical upward growth trend whereas the price of iron ore has followed a falling trend.
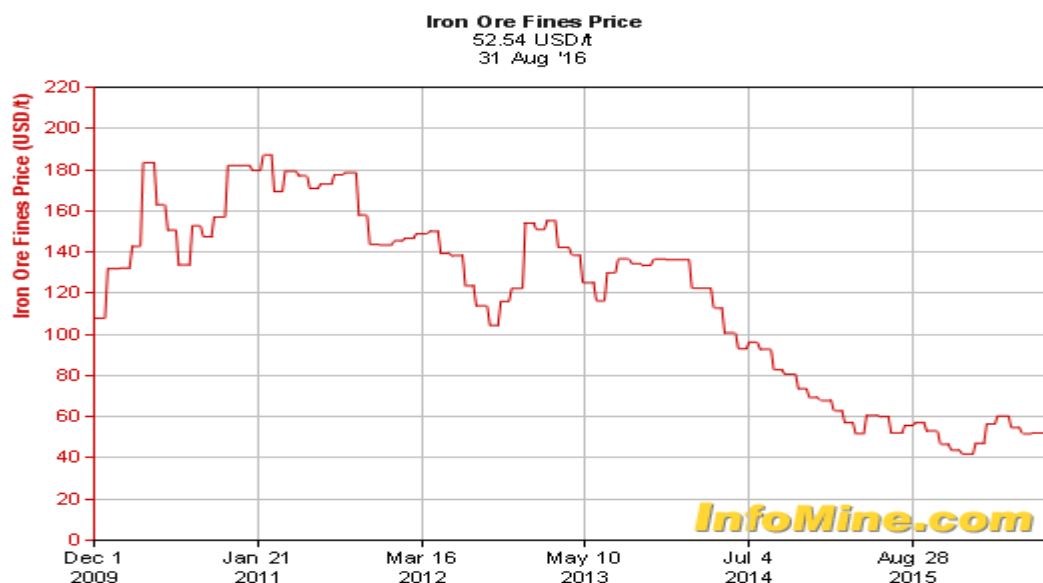
**Figure 1. Iron Price since 2009 (Ref InfoMine.com  (Ref 1) )**

To address the cost and ship-fit implication of large slow-speed motors, geared motors have been considered for some time, both as Z-drive prime movers and as dives through a standard reduction gearbox to a conventional propeller arrangement. Such a design allows standard marine motors to be employed, one or two into a reduction gearbox.

## GEARED-ELECTRIC

Maillardet (Ref 2) makes a strong case for the use of standard affordable medium speed motors to drive propellers through reduction gears on the basis of acquisition cost, size, weight. He addresses the reliability issues that are often associated with gearboxes and observes that an electric motor-gearbox arrangement does not require clutches, actuators and interlocks which are often the source of unreliability.

The use of gearboxes introduces tooth contact noise at a frequency which may easily propagate through the propeller shaft to the propeller and provide a source of underwater radiated noise. Although flexible shaft couplings can be used to manage this, a noise-reduced gearbox probably would add to the acquisition costs contrary to Maillardet's counter claim.

Maillardet discusses the scope for the use of epicyclic gearboxes which offer a more compact solution than parallel shaft designs. They also offer scope for greater reduction ratios as per the cited application of steam turbine drive reduction in the steam driven tankers. Epicyclic gearboxes were used for the steam turbine generator to save space in the NS Savannah.  Budd (Ref 3) describes how epicyclic gearboxes (EGB) could be used for steam-driven contra-rotating propeller (CRP) applications. However CRP and EGB are seldom used at sea due their considerable costs and currently they would be used for specialist applications where space was at a premium.

**PROPELLER SHAFT-MOUNTED MOTORS**

For many years, propeller-shaft mounted electric machines have been used for synchronous power generation. The two or four stroke engine runs at a steady speed and the machine acts as a generator to supply electrical power at the required frequency.  With the introduction of variable ship speeds to meet commercial pressures and the opportunity to use power electronics, the machine can now act at any shaft speed as a generator and due to the four quadrant nature of the power electronics, it is also feasible to use them as motors for slow speed manoeuvring in areas where full thrust is not required.  Companies such as GE, Rolls-Royce (Hybrid Shaft Generator system (HSG)) (Refs 4 & 5) ), MAN and The Switch of Finland offer such systems with The Switch offering P/M solutions.

More recently P/M machines have been used instead of conventional motors and a more comprehensive explanation of the benefits is provided at Ref 6.

**GEARED ELECTRIC NAVAL SHIPS**

Geared electric propulsion is employed in the French FREMM class warship, the German F125 frigate and the UK MARS tanker.

**French FREMM**

The French FREMM warship (Ref 7) employs permanent magnet (P/M) motors with a GT engine in a CODLOG configuration as shown in Figure 2.
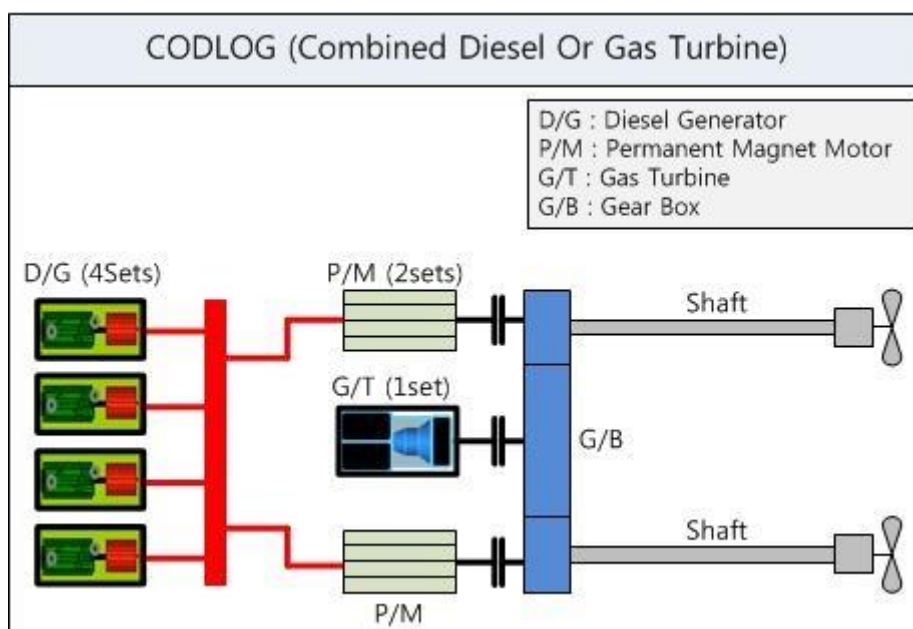


**Figure 2. FREMM CODLOG Arrangement**

Figure 2 shows the 2,100kW motors driving through a reduction gear. They are used for speeds up to 15 knots.  Qualizza et al (Ref 8) provide a short commentary on the

design intent of the FREMM including an explanation of the nominal operating modes or configurations of the CODLAG-come-hybrid propulsion system.

For medium speed designs, i.e. 1,000rpm to 10,000rpm P/M motors offer significant benefits over standard AC squirrel cage asynchronous and synchronous motors. In general they have twice the torque density leading to designs which are half the size and weight, (Ref 2).

**German F125**

The German F125 P&P configuration is CODLAG delivering power to the CPPs either by two Siemens electric motors providing 4,500kW each and/ or a single cross-connected GE LM2500 GT engine (20MW).  Electrical power is provided by four MTU 20V4000M53B DGs, each providing 3,015kWe.

The presence of CPP with electric motor gives an opportunity to use these together to optimise propeller and motor efficiencies.



**Figure 3. Frigate type F125 of the German Navy (copyright Bundeswehr/Dennis Kramer)**

**Royal Fleet Auxiliary MARS Replenishment Tanker**

The MARS tanker (Ref 9) has two shaftlines each with a geared electric machines and a medium-speed diesel engine drive (Ref 10) . The MARS tanker is arguably one of the largest hybrid four-stroke vessels afloat. The design allows the main engines to drive the ship mechanically and supply power to the ship via the gearbox-mounted electrical machines operating as generators at higher ship speeds. At lower

ship speeds, the DG sets supply power to the ship and drive the ship via the motors, (Ref 11) .

**RENK AED**

More recently the Renk gearbox company have offered their Advanced Electric Drive (AED) (Refs 12 & 13) )  which is an integrated reduction gearbox and medium speed motor on a common raft. It is designed to be a cost-effective alternative a slow speed motor. This concept was initially introduced by Hoppe in 2012 (Ref 14) ) where, using conceptual ship designs, it was combined with direct drive engines to provide a hybrid design.
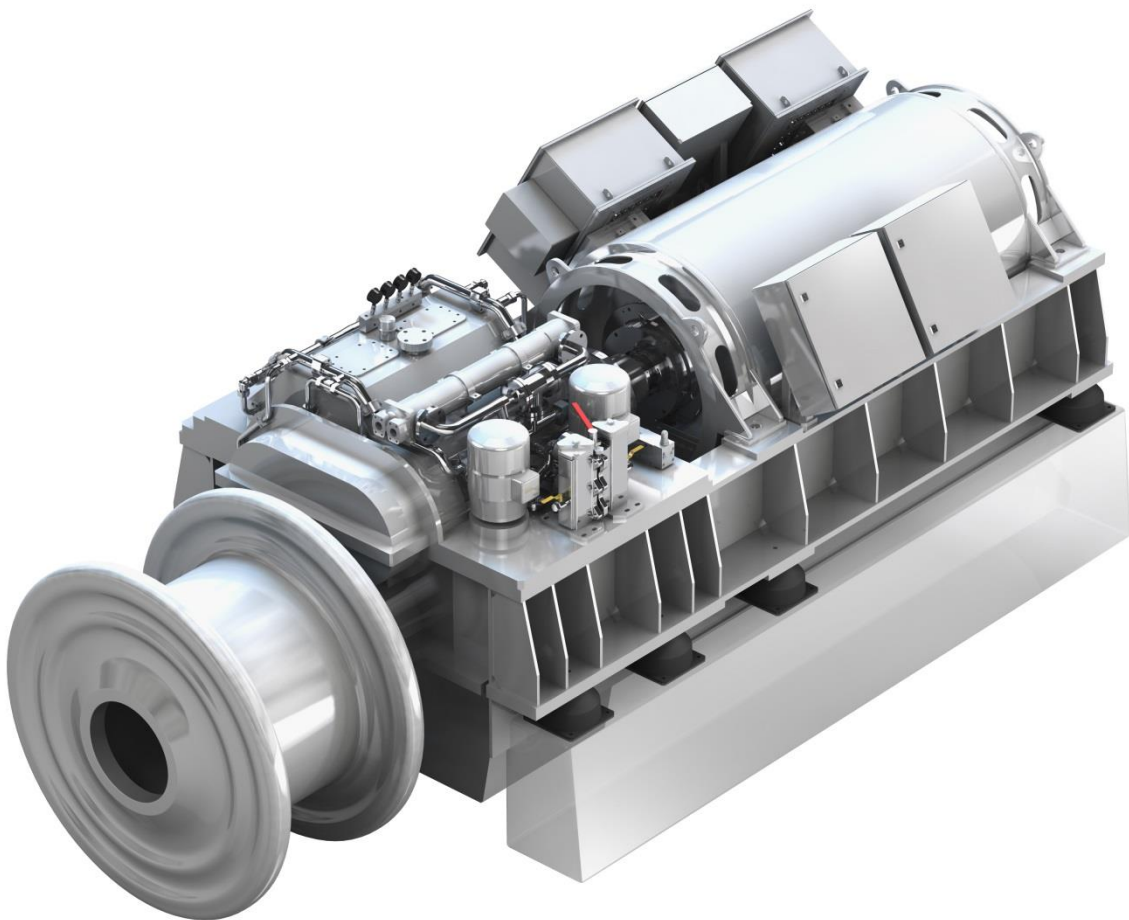


**Figure 4. Renk AED. (copyright Renk)**

The use of an AED design has since been more fully reviewed as a product for use in hybrid designs superyachts by Brealey 2015 (Ref 15).  The quietness of the AED is an attractive feature in a noise-sensitive vessel and its compact features also

enable it to be installed in the limited space set aside for main machinery. The speed control of the AED employs PWM converters which take the ships main switchboard frequency and voltage and modify it to suit the requirements for the motor's speed and torque output. Typically these are silicon –based thyristor devices which take the rectifier supply and use high frequency switching methods to manufacture the required motor supply. Such switching leads to losses which manifest themselves as heat which lowers the efficiency of the conversion process and requires the provision of cooling systems.

## MECHANICAL-ELECTRICAL HYBRIDS

One of the most notable earliest mechanical-electrical hybrids **is** the Type 23 frigate (Ref 16). designed in the 1970's, it employs propeller shaft-mounted dc motors with a GT engine drive through a reduction gearbox (Ref 17). At speeds between 15 and 22 knots or so the motors can operate with the GT engines to make the most of the DG set fuel economy whilst the balance of the required propulsion power is taken from the GT engines.
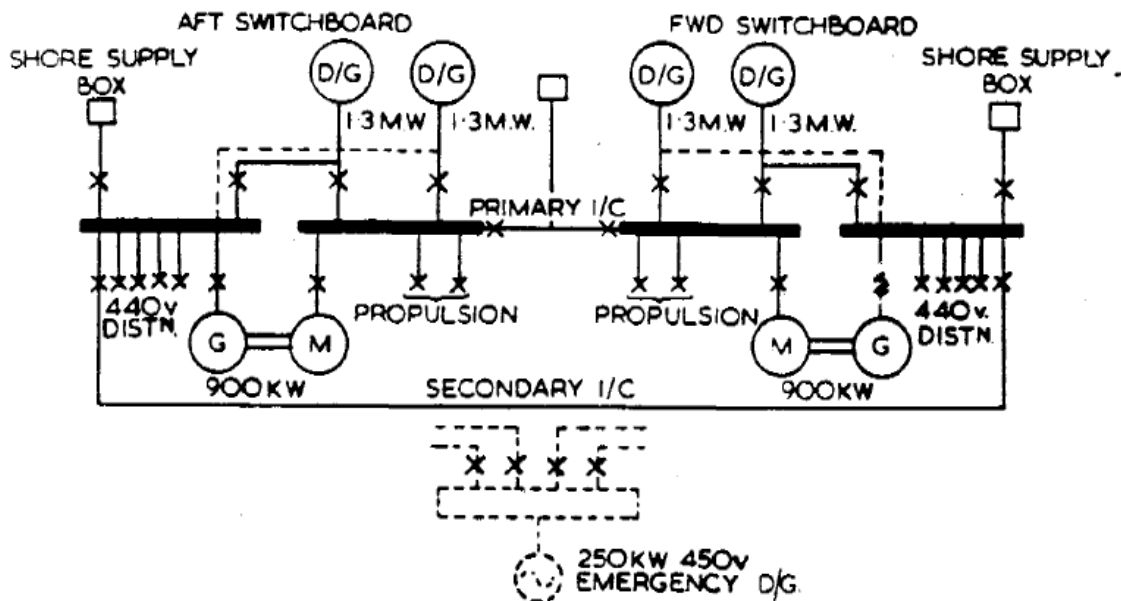


**Figure 5. Type 23 frigate electrical block diagram**

Figure 5 (Ref 18) ) shows the single line diagram for the Type 23 electrical power system. Power is generated at 600V and is converted to 440V via two motor-generators each rated at 900kW. The combination of shared propulsion between engines and motors and the ability to share electrical load from parallel generators, the first time in RN service, has shown to be flexible and effective. This arrangement enables the DG sets to be kept at higher loads which avoids the low loads issues which can lead to increased maintenance and coking.
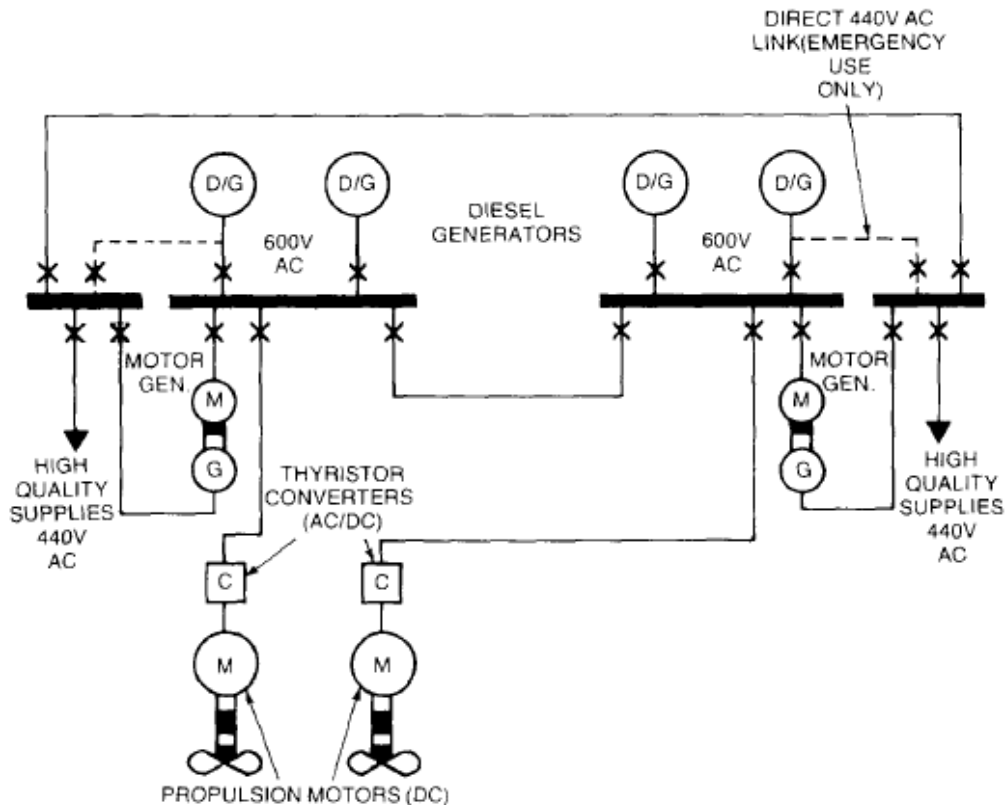
**Figure 6. Type 23 Electrical Power Generation & Distribution**

Figure 6 (Ref 19) shows the use of thyristor converters (ac/dc) to vary the supply from the main switchboards to provide the required power and voltage to the motors so that they turn at the required speed.

Dannatt ( Ref 20)  further describes the electrical power and propulsion systems. The three phase thyristor-converter provides a maximum dc output of 810V. Allowing for losses this gives a usable 750V dc which is suitable for the design of dc motor employed.  The protection of the Type 23 electrical system is described in more detail by Scott ( Ref 21) .

Although modern motor control systems employ different switching strategies and make use of more modern solid-state switching technologies, they still represent an energy transformation where there are losses and thus a reduction in the overall propulsion efficiency.

## TWIN-WOUND MOTORS

To address the losses with converters, the Norwegian company, Stadt (Ref 22) introduced geared electric motors which were twin-wound such that the motor has two sets of windings. A supply to one winding with a given number of pole pairs provides one synchronous speed, which the supply of power to the other winding gives a different synchronous speed. Such a design in essence has a simple make-break switch isolator between the switchboard and the selected motor windings with

a sinusoidal waveform power supply with no losses associated with the PWM rectifier-converter (Ref [23]) .

However such a design would mean that the ship could only operate at one of two speeds in a given speed-resistance situation, where that is defined by displacement, sea state and hullform fouling amongst other possible factors. To achieve variable thrust and thus variable speed, a controllable pitch propeller (CPP) is used. By varying the propeller blade pitch angle for a given shaft speed, a range of thrust and thus ship speeds can be achieved. Thus the losses are "transferred" from the PWM to the CPP with the additional efficiency loss between CPP and fixed pitch propeller (FPP) which is assumed to be 1% across the whole pitch range.

## SANCO STAR

The Stadt propulsion system was initially applied to the research ship the Sanco Star, one of a series of research vessels which are still employed for underwater seismic exploration in the oil and gas industry.



**Figure 7. Sanco Star – copyright Sanco Shipping AS**

The Sanco Star has the following principal characteristics.

| Parameter | Value |
|---|---|
| Length | 80m |
| Beam | 16m |
| Draught (transit) | 6m |
| Maximum contracted speed | 14+ knots |

| Parameter | Value |
|---|---|
| Ship's non-propulsion electrical load | 150kWe |
| Daily fuel consumption | 24m$^3$/day @ 14 knots |
| Displacement | 4,660 tonnes |
| DE gensets | 3 x 1,582 kWb |
| Propulsion | 2 x 2,500kW geared motors |
| | 315kW low power |
| | 1,500kW medium power |
| | 2,500kW full power |
| Propellers | 2 x 3.1m diameter, |
| | 150rpm medium power |
| | 190rpm full power |

**Table 1. Ships Main Particulars**

The Sanco Star has two CPP, each propeller shaft is driven by a twin-wound electric motor rated at:

- Low rpm. 315kWb
- 720rpm 1,500kWb
- 900rpm 2,500KWb.

A reduction gearbox reduces the motor speed from 900rpm to 190rpm propeller shaft speed. Three DG sets provide power to the ship and the propulsion.

The ship's assumed operating speed profile in sea state 4 is shown in Figure 8. This profile will vary slightly at higher sea states as the increasing resistance leads to speed loss at the top end. The extra resistance due to wind and wave at all sea states is based on the Holtrop & Mennen method, (Ref 24), which is as inaccurate an estimator as any other.
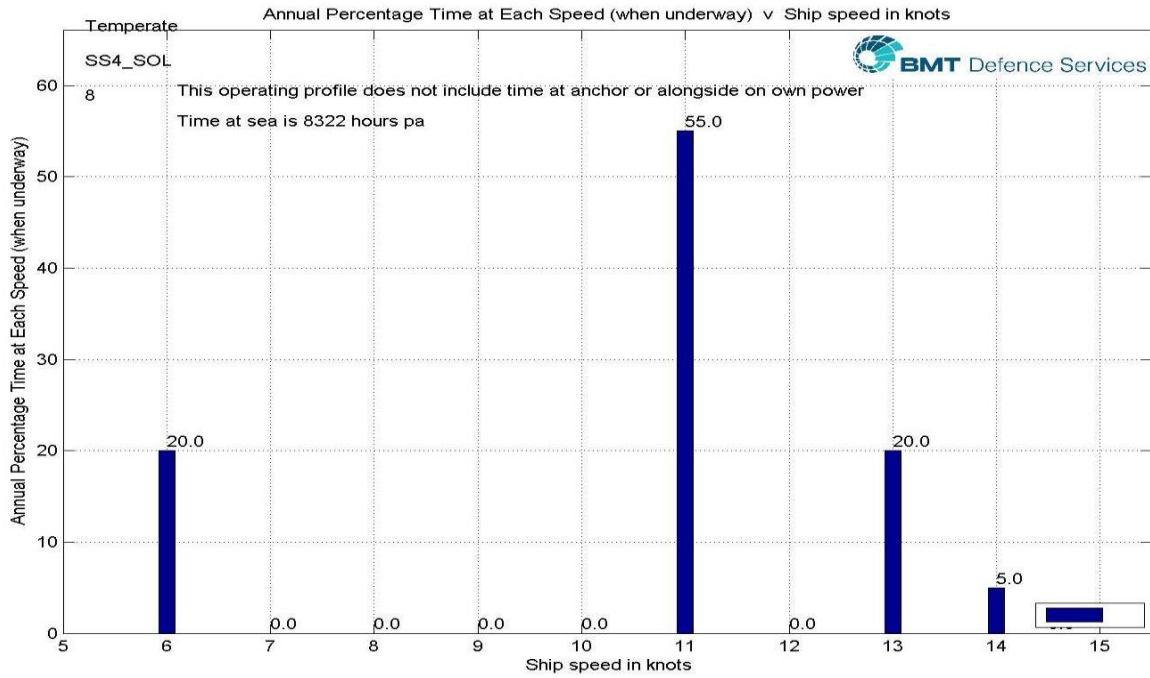
**Figure 8. Assumed ship-speed operating profile**

Using the BMT proprietary marine power and propulsion analysis tool, Ptool (Ref 25), a comparison has been made with a standard FPP, variable speed design using the same propeller size with the same nominal maximum pitch ratio. The same DG sets are used and importantly the motors are controlled by standard marine power electronics. Motor behaviour models use the standard and Stadt-supplied data.
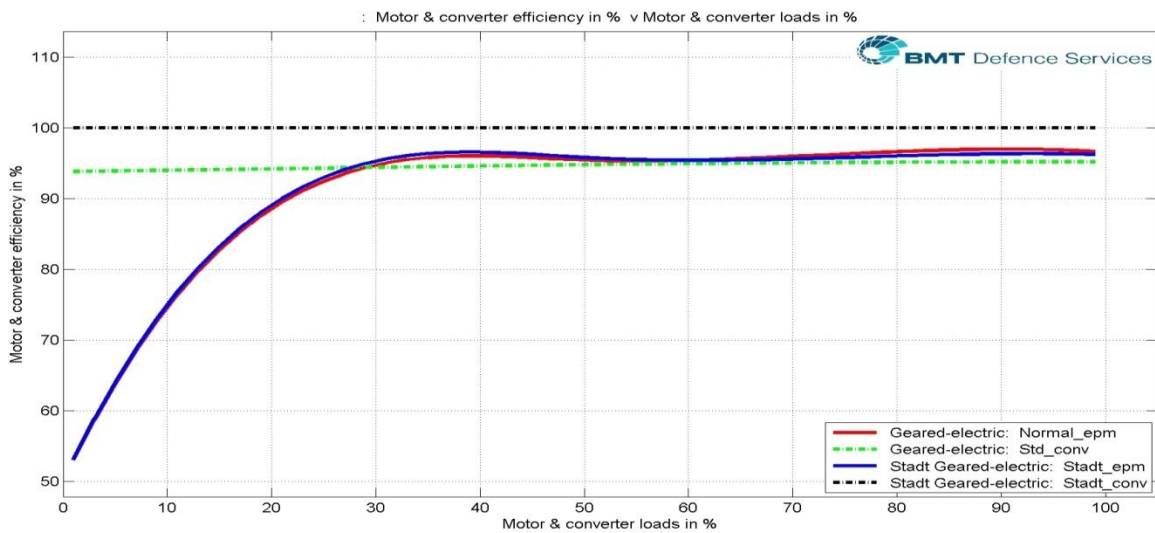


**Figure 9. Motor & converter efficiencies**

Figure 9 shows the small efficiency difference between the standard and Stadt motors and the assumed standard converter efficiency versus load. The Stadt

converter is 100% efficient as there is no power conversion equipment (Ref 26) . The analysis uses a fixed value gearbox efficiency for the assessment of both designs.
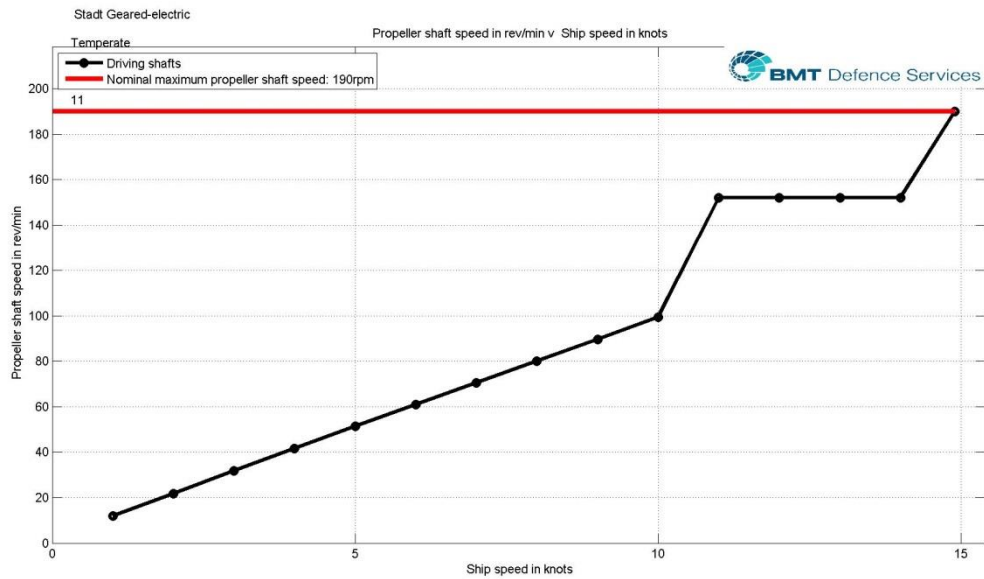


**Figure 10. Propeller shaft speed v ship speed**

Figure 10 shows how the propeller shaft speed increases steadily up to 100rpm at the lower rated power setting before it jumps to the constant speed regime of 150rpm at 11 to 14 knots for powers up to 1,500kWb . At 14.5 knots the shaft speed is at the second steady speed condition of 190rpm for all powers up to 2,500kWb.
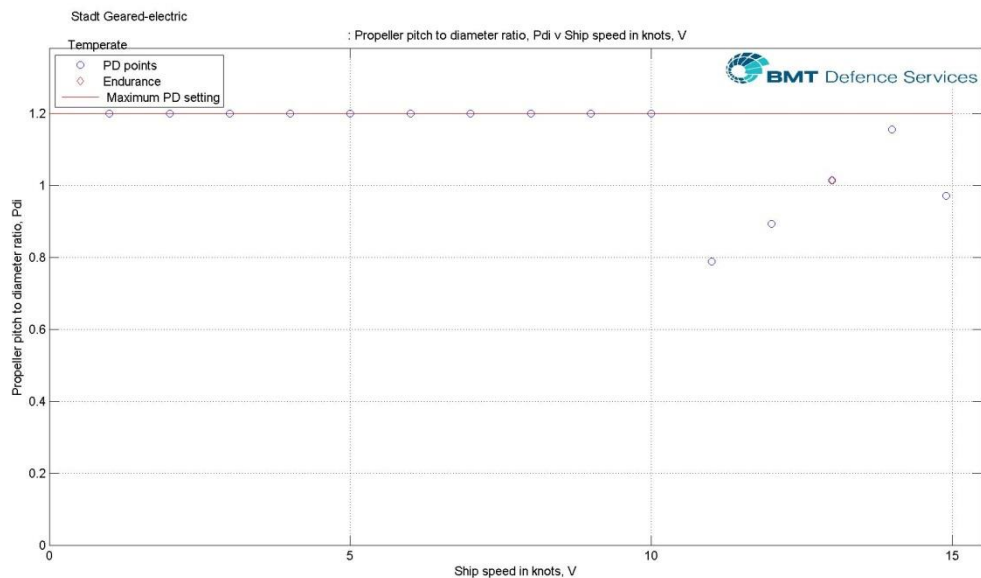


**Figure 11. Propeller blade pitch angle to diameter ratio v ship speed**

Figure 11 shows how the propeller blade pitch angle ratio to the diameter (PDR) is fixed for lower powers before it is varied to create the correct thrust for high powers and ship speeds. To generate the same thrust, a finer (i.e. lower) PDR leads to a

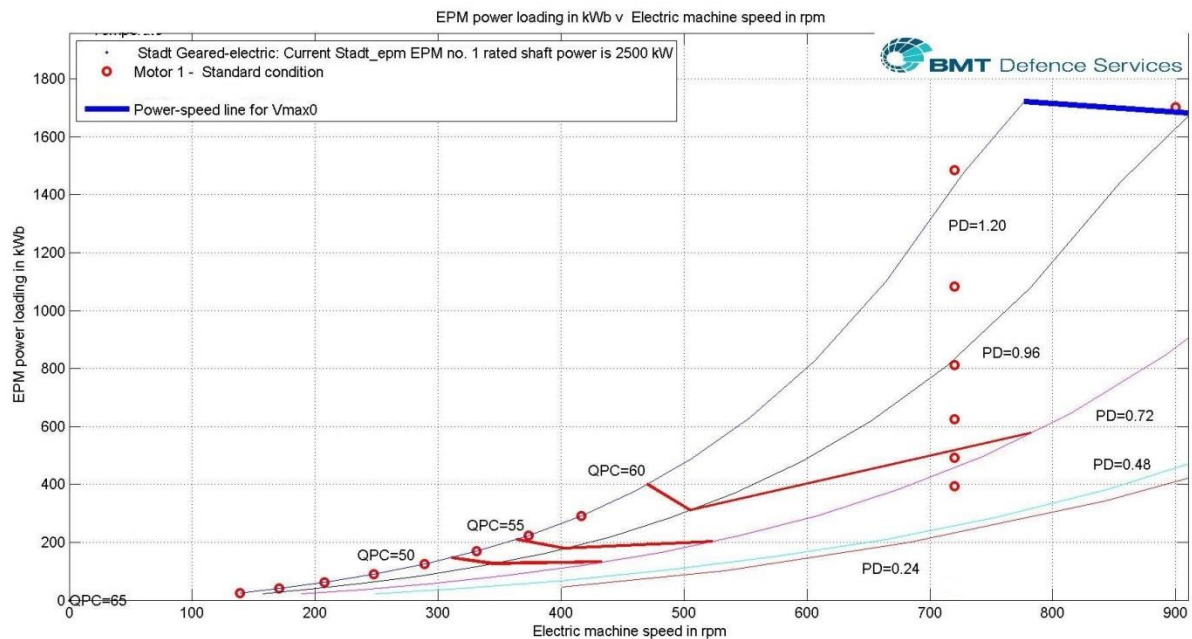lower efficiency due to the propeller turning faster with high viscous blade friction losses.



**Figure 12. Motor power v speed with propeller pitch ratios**

Figure 12 shows operation of the Stadt design with the fixed pitch operations in red circles at powers up to 315kW before the first set speed operations are used between 315kW and 1500kW per shaft. At full speed (14.5 knots, sea state 4) the second fixed-speed is used for powers up to 2,500kW per shaft. Lines of constant Quasi-Propulsive Coefficient (QPC) are shown in red. A comparison of the open-water propeller efficiencies in Figure 13 shows a slight disadvantage to the CPP due to the hub losses and the off-design point pitch angles.
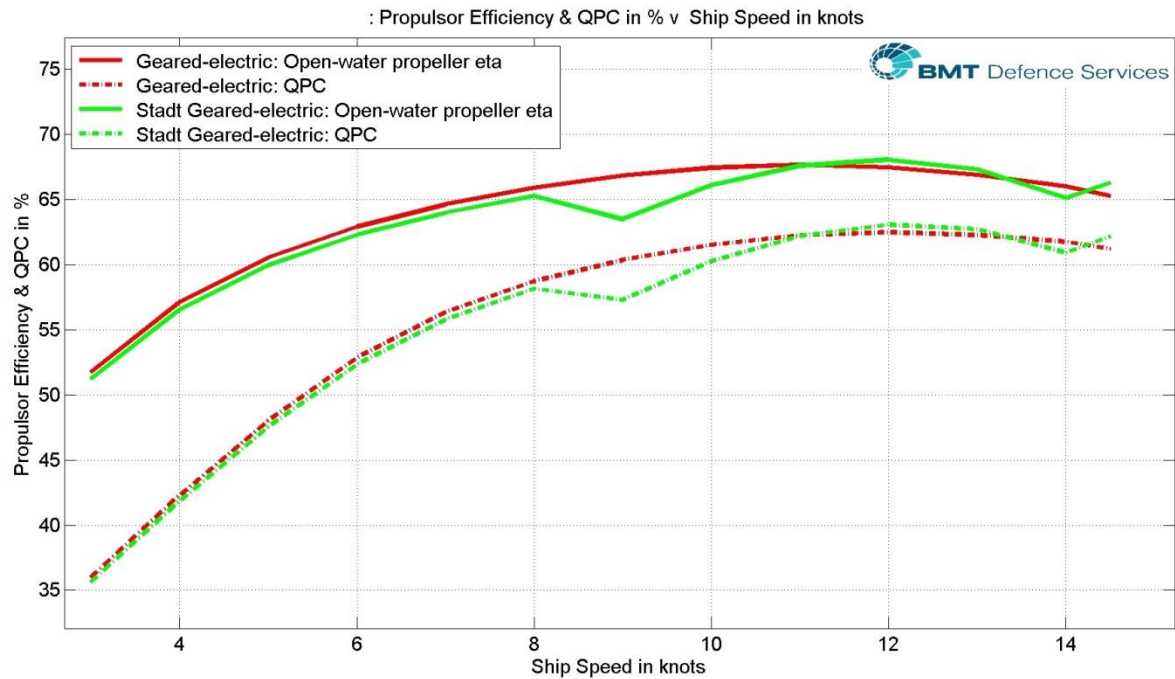
**Figure 13. Propeller open-water efficiencies & QPC**

Figure 13 shows the open-water efficiencies and QPC of the two propellers compared. The propeller model gives the CPP an additional 1% inefficiency compared to the FPP.  The other differences are due to the change in blade angle and thus pitch. The greater CPP efficiency in one region is due to the propeller over-pitching in some cases due to the speed-power restrictions of the twin-wound design.
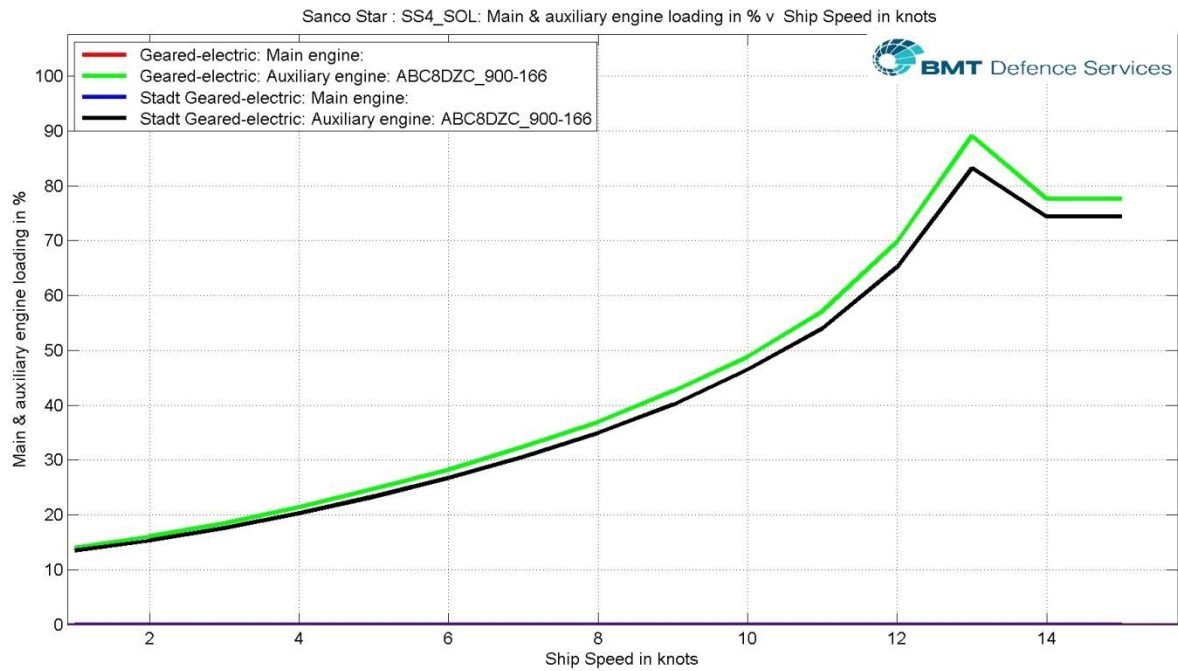
**Figure 14. DG Set loading**

Figure 14 shows how the DG sets in the Stadt design have a lower loading due to the absence of converter losses.  This leads to a lower fuel consumption rate as shown in Figure 15.
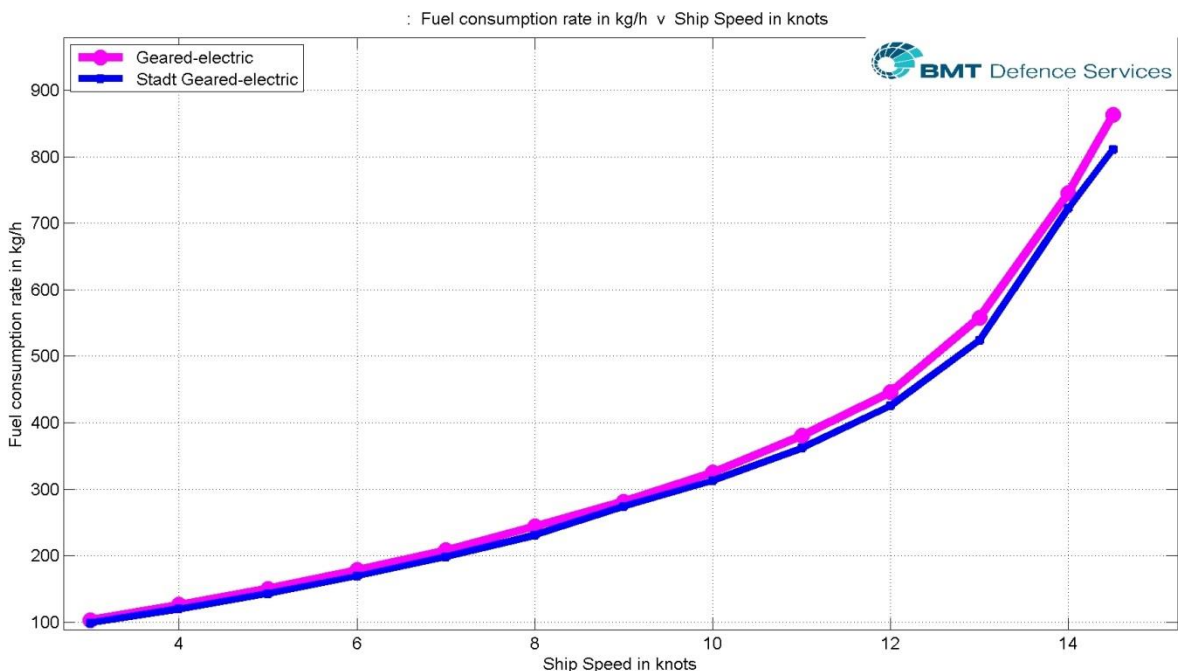


**Figure 15. Fuel Consumption Rates**

Figure 15  shows how the twin-winding design offers a lower fuel consumption across the speed range for this sea state.  For the given operating his leads to a 5%

annual fuel saving.  When the whole set of sea states are considered on a weighted total, the savings are over 4% with there being a saving of over 3% at each sea state.

## CONCLUSIONS

This study has explored the use of geared electric propulsion and specifically has assessed the use of twin-wound motors with CPP versus the use of the standard motor-converter solutions with FPP employed in most such applications.  The study on one ship that actually operates at sea indicates that the losses due to CPP pitch angle changes are not greater than the savings due to the omission of the need for a converter.

The use of a twin-wound motor drive with thrust control via CPP, reduces the need for electrical power transformation equipment and offers a potentially cheaper design solution with an indication that fuel consumption is either better or no worse.

## ACKNOWLEDGEMENTS

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