NAVAL ECONOMY AND FLEXIBILITY

John Buckingham
Chief Mechanical Engineer
BMT Defence Services Ltd
Email: JohnB@bmtdsl.co.uk

1. Abstract

Coastguard vessels, offshore patrol vessels and corvettes typically have a basic design which comprises a two-shaft propulsion system with each shaft driven by one medium-speed (i.e. 500 to 1,000 rpm) Main Diesel Engine (MDE). Conventional propulsion arrangements such as this are compared with a four-MDE design and a hybrid design to assess the scope for energy savings through better fuel economy and propulsion and power generation redundancy. Suitably used, the alternative designs allow for operations where the running engines are better matched to the power generation demand at any given mix of ship speed and ships power demand.

Keywords: Economy, energy efficiency, hybrid propulsion

2. Context

Conventional government-owned vessels which patrol inshore and sea areas, with a displacement of 1,500 to 3,000 tonnes typically have a twin-shaft propulsion arrangement with each propeller driven by a medium-speed MDE through a reduction gearbox. Just one engine can drive the vessel at cruising speed, with the other trailing, either with a stationary shaft and feathered propeller or with a non-driven rotating propeller: there will always be a drag effect exercised by the non-driven propeller. If the single engine is to be run up to full revolutions when at cruise, then a reduction ratio is needed that is different to that required for full revolutions at full speed. This calls for a double-path gearbox. Such vessels typically employ high-speed DG sets to provide electrical power to the ship.

If a single gearbox reduction ratio is adopted, the propeller blade is at full pitch and the engine is running at a point on the torque-speed curve which is away from the full-power point. If the engine is not sequentially turbocharged this will usually lead to a worse specific fuel consumption and thus worse economy. If the engine blade angle is fined off to move the engine speed to better economy point, this leads to worse propeller efficiency. In either case, there is a worse outcome for either engine or propeller efficiency at cruise speed.

A Basic Design comprising two 3,000kW MDE was defined to allow comparison with alternative concepts.

A four-engine concept seeks to avoid the shortcomings of the basic design. Each propeller shaft is driven by two 1,500kW high-speed engines through a single- or double-reduction gear. For this application, Each propeller shaft is driven by two high-speed engines through a single- or double-reduction gear. An example power-pack comprises four high-speed engines. This performance of this arrangement was considered against that of the typical medium-speed engine design.

The two designs each have four 600kWe DG sets for power to the ships services.

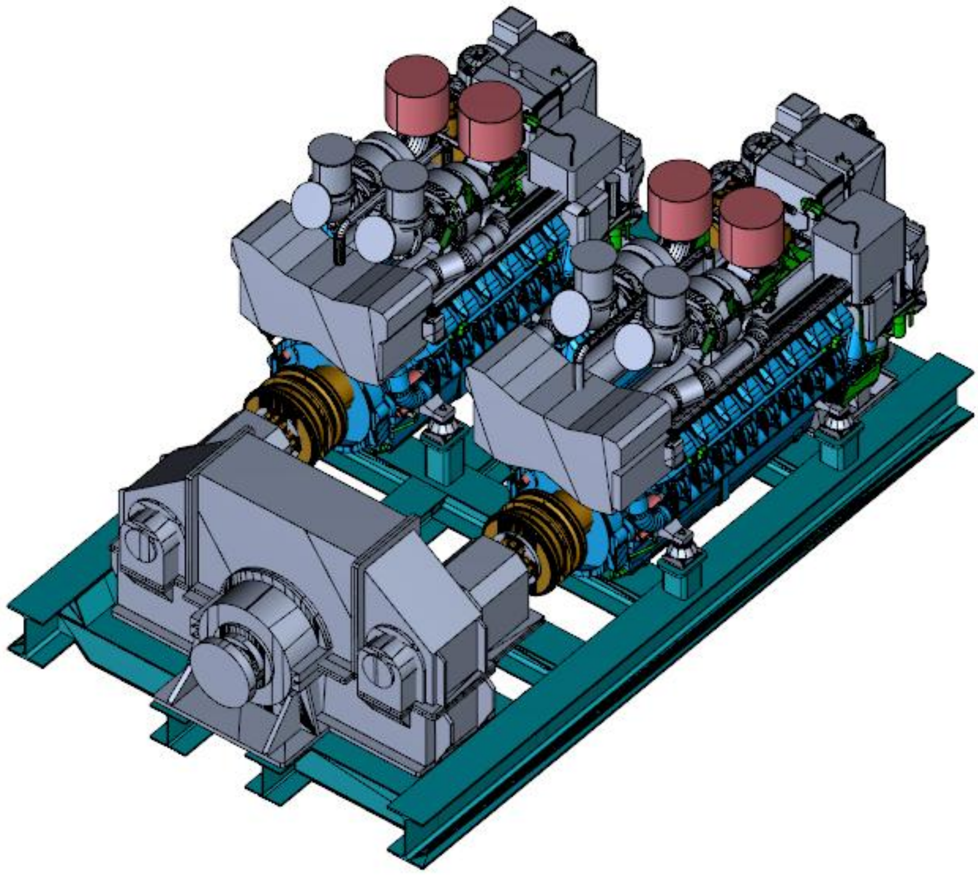

Figure 1: The Renk-MTU Power-Pack Arrangement

3. Power-Pack arrangement

The Power-Pack concept attempts to offset the trailing-shaft drawback of the conventional arrangement. The higher gearbox reduction ratio may involve slightly higher losses but at cruise speed, one engine would run on each shaft thus avoiding the need to trail a shaft.
The high-speed engines are Sequentially Turbo-Charged (STC) and allow for good economy and better maximum torque capability across the whole engine speed range. Thus at cruise speed the engine can be located away from the smaller optimum load range as per the conventional design and can run at a good part-load efficiency. This allows the propeller pitch to be optimal for this speed.

Although they have good part-load efficiency (i.e. specific fuel consumption) relative to its full load performance, the high-speed engines' efficiency at full load is not always as good as that of a slower-speed engine, so the overall benefit is affected by the balance between propeller and engine efficiency.

4. Comparison: two- and four-engine options

4.1 General

A theoretical comparison of the different arrangements reveals how each of different options can be most suitable depending on fuel costs, engine support costs and the ship's operating profile.

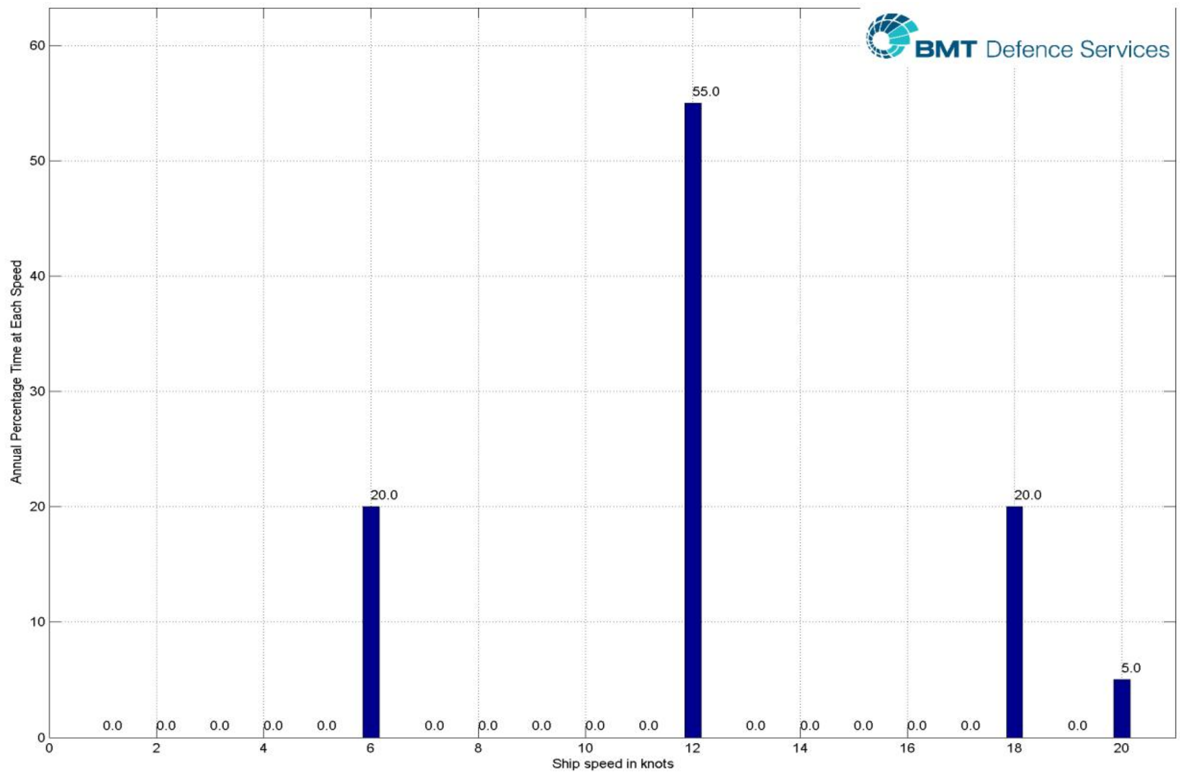

Figure 1: Ship Speed-Time Operating Profile

Figure 1 shows the assumed ship's operating profile. About half the time is spent at 12 knots cruise with periods at a boost speed of 18 and 20 knots. There is also a significant time spent at the loiter speed of 6 knots. However it is also recognised that the ship‘s profile often reflects the optimised speeds for the machinery installed.

4.2 Space and Weight Savings

It is estimated that the four-engine design is about 30 tonnes lighter than the two-engine design. This is principally due to the 44 tonnes for the smaller high-speed engines versus the 73 tonnes for the larger engine. The four-engine design is estimated to have a smaller volume as the engines are both lower and shorter than the twin-engine design although the raft as a whole will be wider. Since almost all the auxiliary components are onboard the raft, upkeep on the smaller engines can be carried out by engine exchange. Components such as cooler, filters, hydraulic valves, sensors, controls, and pumps are mounted on the gearbox. The larger torque envelope of the STC engine allows for more engine operating flexibility and fewer restrictions on low-speed operations. The bespoke gearbox provides scope for engine input forward or aft.

4.3 Engine Costs

For the assumed ship speed profile, the four-engine design consumes 3.8% more fuel per year or 165 tonnes. This is £83k or €94,000 at £500/tonne. For this study, engine support costs are related to the engine rating through the factor £10/MWh. Thus an 8,000 kW engine costs £80/hour to run and a 4,000 kW engine costs £40 per hour. Whilst this figure is much higher than quoted by engine suppliers it does go some way to reflect the factored cost of infrastructure for the ship owner in terms of spares, ILS and the staffing required ashore. The figure is clearly representative yet would need to be subjected to sensitivity analysis. It does not consider the impact of higher running speeds on the Time Between Overhauls (TBO) or the relative ease of maintaining smaller engines in-situ or through upkeep by exchange. The two engine design has annual engine support costs of £0.711m compared to £0.504m for the four engine design. This does not include a factor for the markedly different number of engine cylinders.

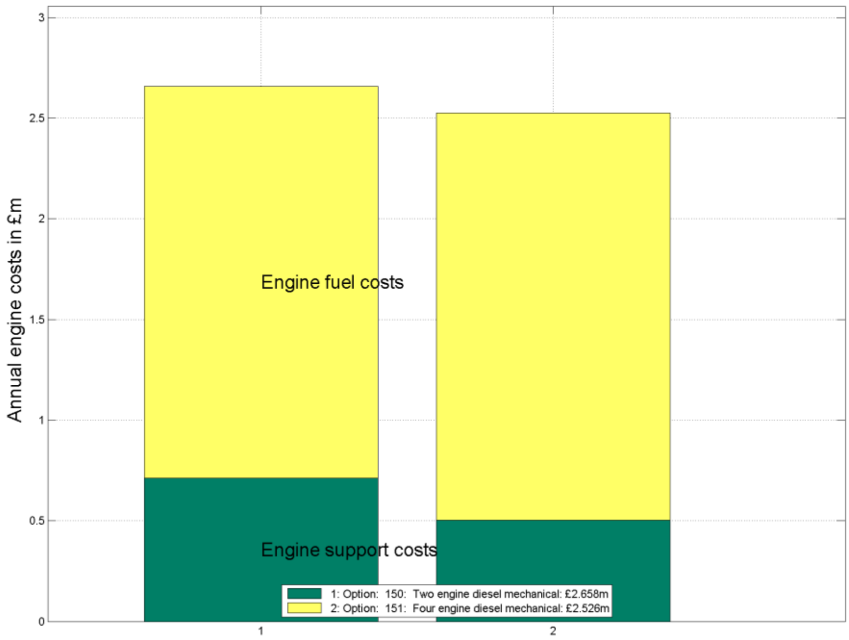

Figure 2: Annual Engine Costs for each Option

Figure 2 shows the total annual engine costs for both options showing how the adoption of four engines can lead to a lower overall cost with a comparable fuel consumption.

5. Hybrid Designs

The introduction of affordable high powered electronics has allowed a greater flexibility to be achieved with the use of electrical power between power generation and propulsion onboard ships.

Hybrid designs appear to be best suited to those vessels which have a range of ship system power demands. The higher peak demand is usually for a specialist case (i.e. Replenishment-At-Sea winch and pumping duties or the recovery of a towed array). With an installed set of four alternators three sets are to be able to cater for this peak even if most of the time the normal cruise load can be met by two sets alone at 60 to 70% MCR. This surfeit of onboard power generation capacity means that there is scope for the DG sets to provide motor propulsion at slow to medium speeds where the MDE would be too lowly loaded. This facilitates the use of motors for loiter and slow cruise modes saving running hours on the MDE which thus avoids maintenance hours and the costs that this incurs.

Such motors would drive into the gearbox, without a clutch, through the PTO shaft and allow both the MDE to be shut-down and de-clutched.

A propulsion motor will require a Variable Speed Drive (VSD) to allow for speed and torque control. It will also require some facility to absorb power generated by the inertia of the propeller shaftline during manoeuvres. This can be discharged into a brake resistor as heat and cooled by sea water or can be re-generated back into the ship's network. If this last approach is used then it is a small step to the use of a four-quadrant Active Front End to generate power from the motor machine at variable speeds with MDE drive. In such an arrangement the two MDE drive the propeller shaftlines and also drive the motors which are acting as alternators. Most medium-speed MDE allow for a generous torque-speed characteristic in the mid-speed range: this allows the MDE to provide the propulsion power on the cubic-law propeller curve and also provide the ships services power at an offset to the propeller curve.

Ships power from the MDE means such power is being generated from a bigger engine with typically a better Sfc than the smaller DG sets. For most of the range of interest, if the ratio of engine cylinder sizes is greater than 1.5 then the 6% losses due to the AFE and the gearbox transmission are on parity with the use of the DG sets with the motor and DG sets alternator losses assumed to be equal. This ratio is however very dependent on engine selection and hence a hybrid solution needs to be tailored to each ship and its usage for it to realise energy savings.

The feasibility of the motor option is essentially down to the ratio of the peak power demand to the cruise demand . If three gensets need to supply the peak load at 85% MCR and two are sufficient at the same load for cruise then essentially the cruise load needs to be less than two-thirds the peak load for this to work. The lower this ratio the more power available for motor propulsion.

In a hybrid solution the motor machine needs to operate as a genset rated near or at the same rating at the two DG sets. Therefore the hybrid machine is going to be rated higher as an alternator than as a motor due to the limited power available from the two DG sets for motor use after they have supplied the ships services.

If the difference between two-thirds peak power and the ships services cruise demand is 400kW or more then two 200kW motors can be used. The greater this difference the larger the motor capacity can be and the faster the ship can go in motor propulsion mode. With speeds between 5 and 9 knots this is very effective for many operations undertaken by naval vessels.

When operating as a hybrid genset each of the two MDE provide half the required mechanical power to the machines which is an offset to the propeller curve. At some lower ship speeds this may require the MDE speed to be increased to allow the load to be in a valid part of the engine‘s power-speed characteristic. The engine speed is increased by fining off the propeller blade angle so that the engine can develop the demanded power and stay below its stall point. This does lead to some propeller inefficiency which is have accounted for in the overall performance.

A key requirement is for the motor machine to be able to operate as a fully rated hybrid genset in the full range of applicable engine speeds which is consistent the ship‘s propeller speed and not just rated at full electrical power at full speed.

6. This Hybrid Design

6.1 Description

The Hybrid Design which matches the functionality of the Basic Design comprises an arrangement whereby two of the high-speed 600kW DG sets are removed and replaced with two Hybrid Machines (HM) driven by the MDE through the gearbox PTO shafts.

Each HM machine can operate as a 200kWb motor drive with its speed controlled by a four-quadrant power converter configured as an Active Front End (AFE). The same converter can treat the power generated when the HM is acting as a PTO-driven alternator to supply 600kWe 60Hz, 690V to the ship’s bus.

With a Hybrid Design here may be design issues relating to the ability to generate sufficient current to allow a fault to be detected but this can be handled in a number of ways.

There is also a tighter design challenge with the ship fit issues relating to the constraint of having to locate the HM machine adjacent to the MDE. Therefore a Hybrid Design does save the footprint and downtakes and uptakes of two DG sets but it does introduce a more constraining ship fit arrangement.

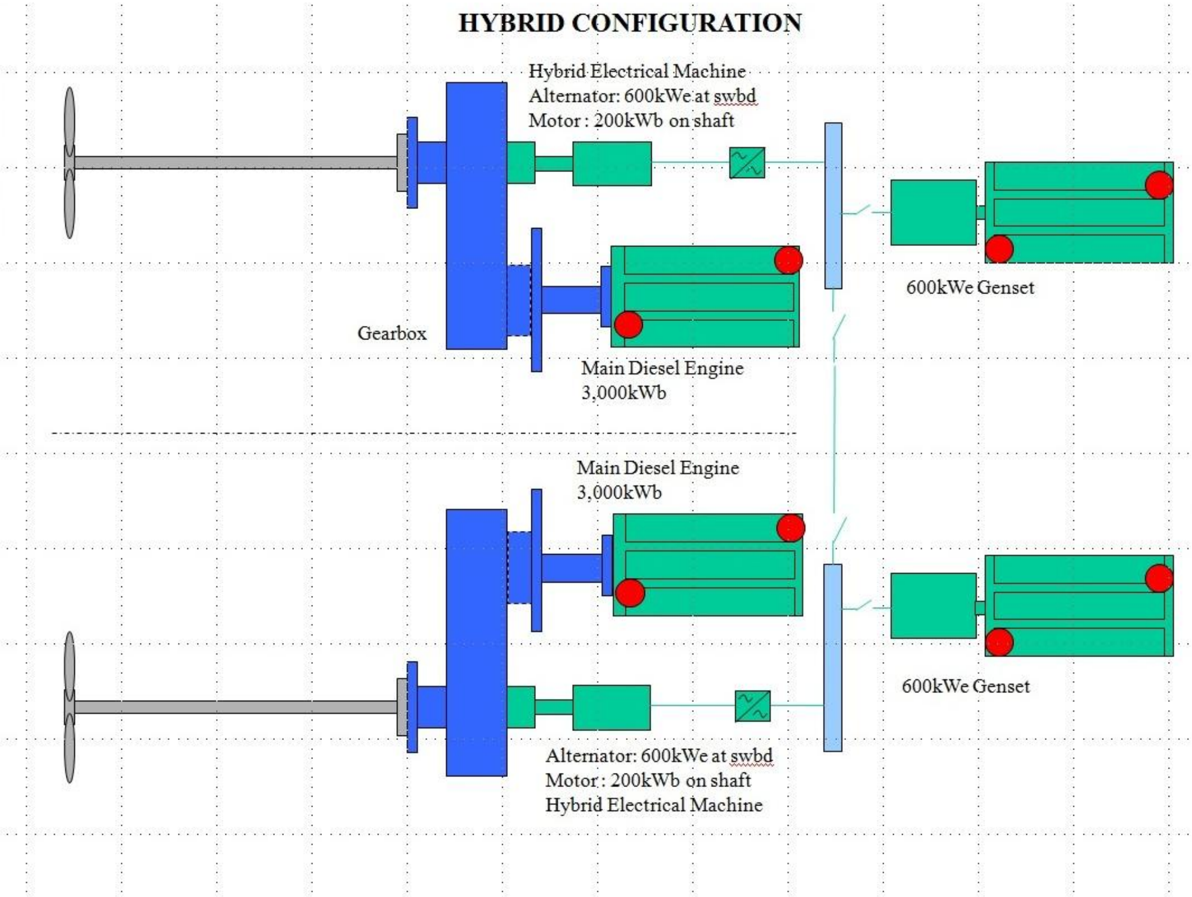

Figure 3: Hybrid Arrangement

6.2 Benefits

In a good Hybrid Design the MDE are more efficient (say by 10% or more) than the smaller higher-speed DG sets so that the same electrical power is provided by a more efficient means at the prime mover level. . The MDE are thus used to provide both propulsive and electrical power thus saving fuel and saving engine running hours and engine procurement costs.

The mechanical and electrical losses through the gearbox and the AFE, respectively will reduce the benefit of the MDE's better efficiency but the secondary benefit is that the electrical take-off is making the MDE load, and thus its efficiency, better than it would otherwise be.

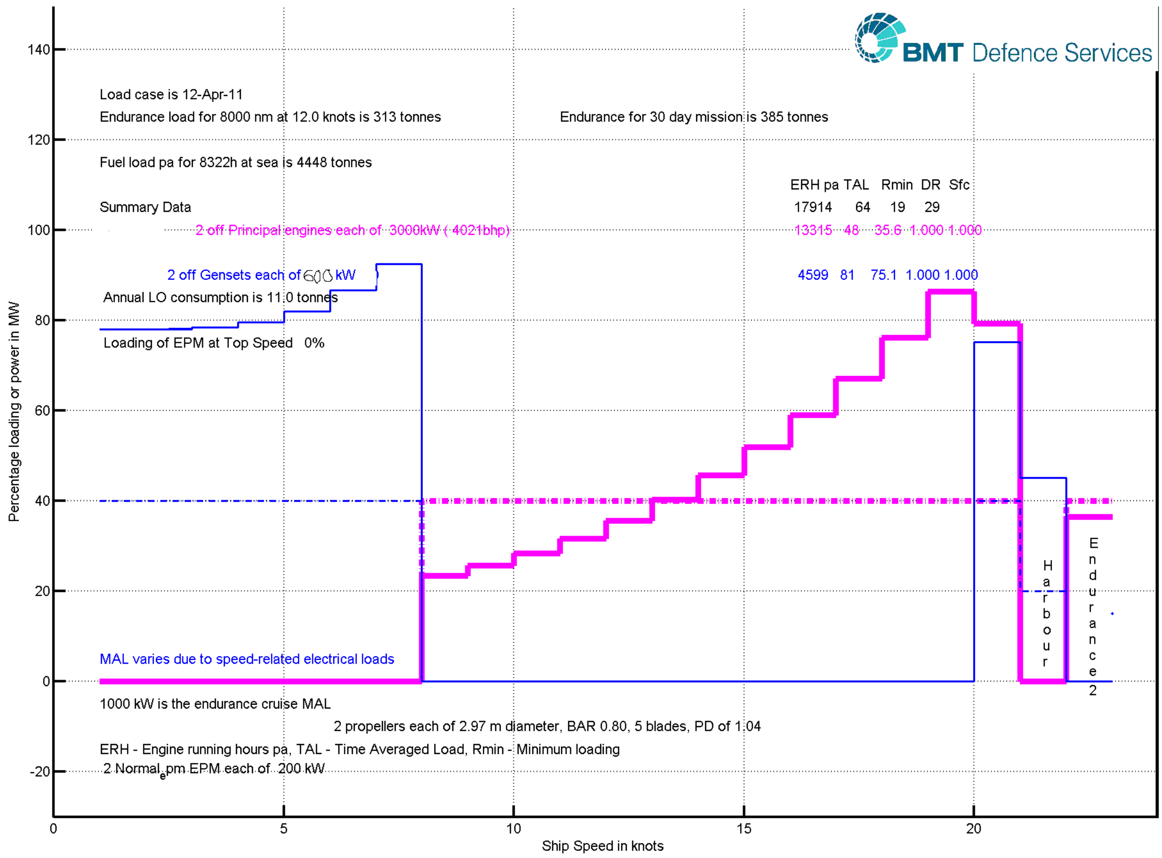

Figure 4: Hybrid Engine Loadings

6.3 Operations

The two 600kW DG sets allow for HM motor drive to 7 knots to provide a useful continuous loiter capability. This avoids single main engine operations and the issue of losses from a trailing shaft.

Between 8 and 19 knots, the two main engines drive the propeller shafts and their respective HM generator to supply ship's power. This covers the major element of the operating profile and employs the full torque-speed capability of the main engines. At 20 knots, the main engines simply drive the vessel and the two DG sets supply ships power.

A hybrid design leads to fewer engine running hours with a 2% lower fuel consumption. The actual difference will vary greatly with the operating profile and the extent to which the trailing shaft in the conventional design provides propulsion drag.

There is also a greater reliability of propulsion power supply as there are four prime movers which can provide propulsive drive and not two.

The two motors provide the capability of a continuous slow speed for loitering but the nature of the design also allows one main engine to provide power to its own shaft and some power to the other to allow a zero-drag trailing shaft. This is a half-way house between full electric loiter drive and main engine drive. The benefit of using this mode is closely associated with the trailing shaft drag, and the balance between propulsive and electrical loads. It is also usual to have a DG set running in such a case to ensure there are two independent sources of electrical power.

6.4 Resilience and Flexibility

The Hybrid Design offers a diverse and resilient source of electrical power as the HM machines are less vulnerable system faults and they can absorb energy from regenerative devices on the bus or from the HM motors when they act to brake the ship. (CPP is retained for a full speed crash stop capability).

A key aspect is the flexibility offered by the ability to load the main engines with a combination of propulsive and electrical to suit their best efficiency point. In this way the design can accommodate changes to the electrical load chart through life and yet maintain an economic means of operating.

The Hybrid Design provides four independent source of motive power for the propulsion function compared to two for the Basic Design. Both designs have a common reliability issue with the gearbox and the CPP.

Both designs have four independent sources of electrical power and for some ship designs it is likely that the HM sets will provide more power than the DG sets they replace. This could be due to the standard rated capacity and the ratio of MDE to the DG set sizes.

6.5 Full Electric Propulsion (FEP) design,

In an Full Electric Propulsion (FEP) design, the propulsion motors need to be fully rated for the top speed but operate for most of the time at a much lower power. This can lead to poor efficiencies in both the DG set alternators, the motor and the VSD for the motors. At top speed, the Hybrid Design has fewer losses due to energy transformations and is thus more efficient than the FEP Design. . The HM motor would be expected to operate near their peak rating when in the range 5 to 7 knot and thus offer a better efficiency to the larger motors in the FEP Design.

7. Conclusions

The four-engine Power-Pack has footprint benefit in terms of length and on the basis of the assumptions in this study, an overall engine support cost benefit. There are no discernable differences in the endurance fuel requirement though the four-engine design has a worse range above the endurance speed.

The provision of four engines will make for a more available propulsion arrangement even if there is a high chance of any one engine failing. The choice of the four-engine design needs to reflect the ships operating profile as this can have a major bearing on the match of main machinery to ship usage and the fuel economy achieved. Where necessary a father-son arrangement may be more suitable than four of the same engines.

Hybrid designs are a relatively new phenomenon, being advanced through the benefits of cheaper and robust power electronics modules. They typically allow the removal of two DG sets from the ship and offer more flexibility at the cost of a more complex operating control strategy. Used judiciously they offer fuel savings through the use of the MDE's better inherent fuel efficiency but they also future-proof a design as there is greater flexibility to achieve main engine running nearer its optimal efficiency point.

A hybrid design allows the main engines to be better loaded at their cruise speed, the speed at which they operate much of the time at sea and avoids costly the accumulation of DG engine running hours.

8. Acknowledgements

It is BMT's intention to claim copyright for this work. The kind permission and resources granted to the author by BMT are acknowledged with thanks. All findings, ideas, opinions and errors herein are those of the author and are not those of BMT Defence Services Limited.