

HYBRID DRIVES FOR EFFICIENCY

John Buckingham

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

ABSTRACT

The introduction of affordable and reliable Active Front End (AFE) power electronics technology now enables the marine Power and Propulsion (P&P) designer to employ a hybrid design to achieve efficient electric drive for cruise speeds and cost effective mechanical drive for faster speeds. The electric drive allows the Main Diesel Generators (MDG) to provide power to Ships Electrical Load (SEL) and the propulsion motors whilst those same motors operate as alternators when running on the Main Diesel Engines (MDE) at higher speeds.

The design leads to fewer prime movers, fewer engine running hours and also fuel economy compared to the usual alternative designs: full mechanical and full electrical. BMT have recent experience of how such a design is achieved. In this paper a typical naval auxiliary vessel is used as an example to demonstrate the benefits of a hybrid design and some of the issues involved in its implementation.

Keywords: Energy efficiency, hybrid propulsion

CONTEXT

Auxiliary naval vessels such as tankers and stores replenishment vessels have often been driven by a single slow-speed engine. Increasingly twin shafts driven by medium speed engines are being adopted. Twin shafts allow better manoeuvrability and also offer a measure of propulsion redundancy. Twin-skegs vessels have been used for some time for LNG carriers and BMT now offers this propulsion arrangement within their Aegir range of auxiliary vessels for the reasons given above and because a two shaft design has been found to offer energy efficiency benefits (Ref 1) .

This paper presents the findings of an efficient auxiliary tanker study which used an Aegir variant (Ref 2)) that is not a design for a specific application. The paper describes the benefits of a hybrid P&P design for the fuel economy and addresses how sensitive this benefit is to changes in ship's resistance and the SEL which is baselined at 2,333kWe.

Three P&P design options are considered for a twin-skeg vessel, namely: Diesel Mechanical (DM), Diesel Electrical (DE) and Hybrid. Each design is defined by its Replenishment-At-Sea (RAS) role which can have a total electrical demand of over 4MWe. Therefore there needs to be a sufficient electrical generating capacity for this primary role even though it would be used for 10 to 20% of the time at sea.

Figure 1 shows the assumed ship's operating profile. The speeds have been centred on a cruise and RAS range of 12 to 14 knots with a top speed of 18 knots. The lowest continuous sustainable speed is 6 knots for steerage. There is also a significant time spent at the loiter speed of 6 to 10 knots.

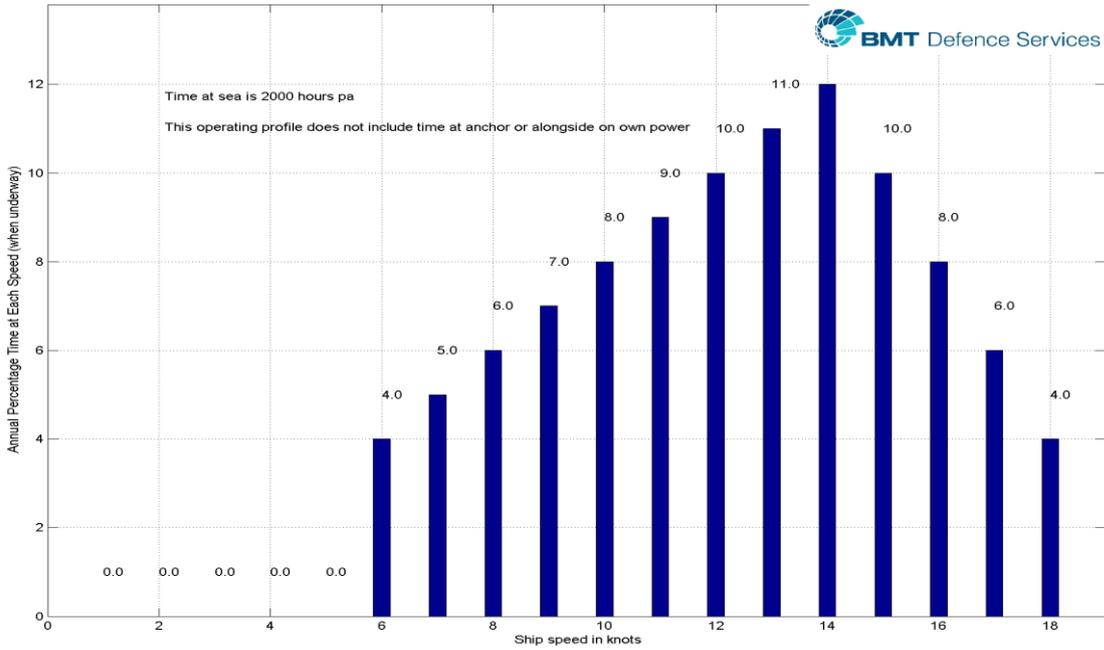


Figure 1: Ship's Operating Profile

THE DESIGNS

Diesel Mechanical Design

The DM design has each propeller driven by a 7,500kW 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 exerted by the non-driven propeller.

The DM design assumes that the two MDE drive the propellers at all speeds with single shaft trailing as a reversionary option. It is considered that the operational requirements will demand that the ship be fully manoeuvrable at all times: hence there is always a drive on each shaftline.

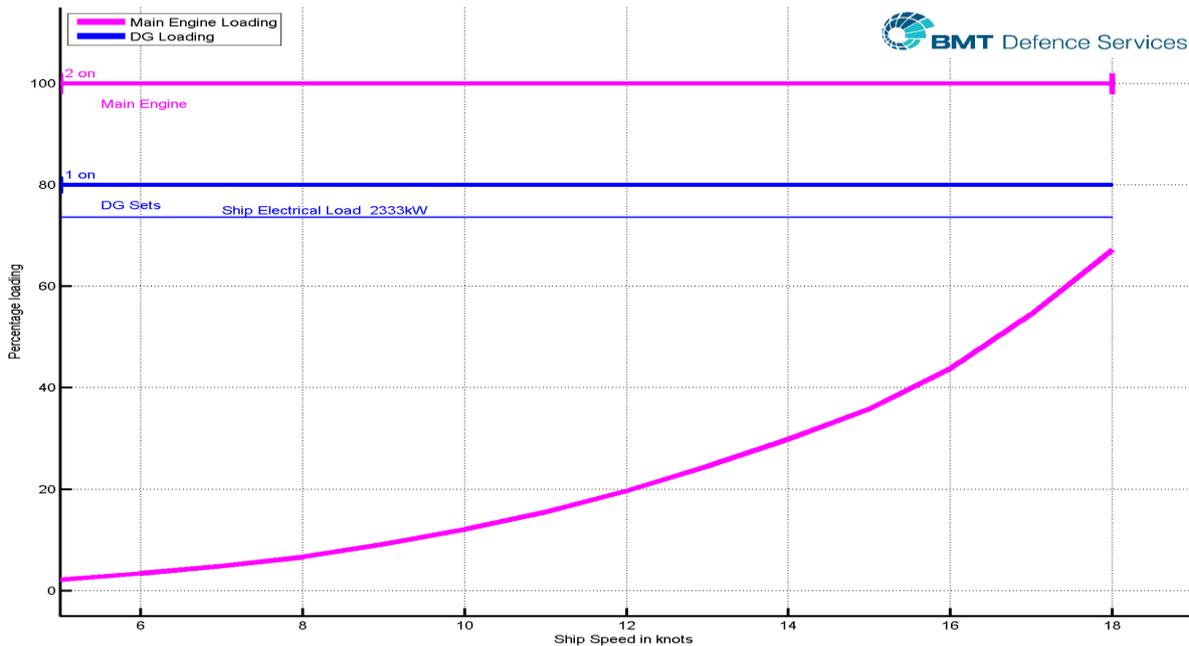


Figure 2: Mechanical Drive Engine Loadings

Any number of the four 3,300kW MDG can provide electrical power to the ship with the full SEL during RAS operations being met with three. Figure 2 shows how one MDG can supply the normal SEL. This may be adjusted to two MDG under “Action State” conditions to provide continuity of power should the single MDG fail. RAS operations are not shown.

Diesel Electrical Design

In the Diesel Electrical design the propulsion is full electric: the propulsion motors and the Variable Speed Drive (VSD) converters 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 the MDG alternators, the motor and the VSD.

The DE design comprises two 5,00kWb electric motors driven from the 690V bus via motor converters. The 690V bus is supplied from four DG sets: two rated at 8800kWb and two rated at 3360kWb. DG sets are brought in and turned off to suit the combined propulsive and SEL load at each integer ship speed. There is sufficient installed power to achieve top speed with one DG set down.

Hybrid Design

The hybrid P&P system is a COmbined Diesel eLectrical Or Diesel (CODLOD) arrangement. This comprises a twin shaft arrangement, where each shaft is driven either by a 7,500kWb MDE OR a Hybrid Machine (HM), coupled to a reduction gearbox to drive a Controllable Pitch Propeller (CPP).

The HM are asynchronous (induction) machines and can act as either a propulsion motor to drive the shaft or as a variable-speed shaft generator providing power to the Ship’s Electrical System (SES). When operating in motor mode, each HM provides up to 1000kWb of propulsion power to their respective shaft. The HM are driven through their power converters each supplied from the generating side of the SES which is supplied from the MDGs. It is envisaged this would be a 690V system or maybe a higher voltage. Such motors would drive into the gearbox, without a clutch, through the Power Take-Off (PTO) shaft and allow both MDE to be shut-down and de-clutched.

All variable speed AC propulsion motors have a Variable Speed Drive power converter to allow for speed and torque control. The requirements of power flow during manoeuvring lead the normal design to employ a four-quadrant power converter with an AFE and this is the case in the Aegir design. However the Aegir AFE is not used to allow power to be absorbed back through the HM to the SES such as during a crash-stop evolution on motors because the design makes use of the CPP to facilitate thrust reversal for braking. This avoids the need for Dynamic Braking Resistors and other means of handling regenerative power. But nevertheless the AFE has a critical use: operating in generator mode the HM generators are driven by the MDE through the gearbox and the AFE then allows up to 2400kWe of power to be passed to the SES.

Two 3,300kWe MDG provide electrical power to the SES and these can operate in parallel with the HM when they are operating in generator mode. This would be the case for RAS operations.

A hybrid design may have to address design issues relating to the ability to generate sufficient current to allow a fault to be detected. However this can be handled in a number of ways including the use of High Resistance Grounding.

The hybrid design seeks to make a virtue of the occasional need for a high generating capacity at cruise speeds. By using the MDE to generate power to the SES, the number of MDG can be reduced to two and thus the amount of machinery to be purchased and supported is also reduced. There are numerous other benefits too as will be shown below.

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 to supply the SEL 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 MDG. 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 MDG with the motor and MDG 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.

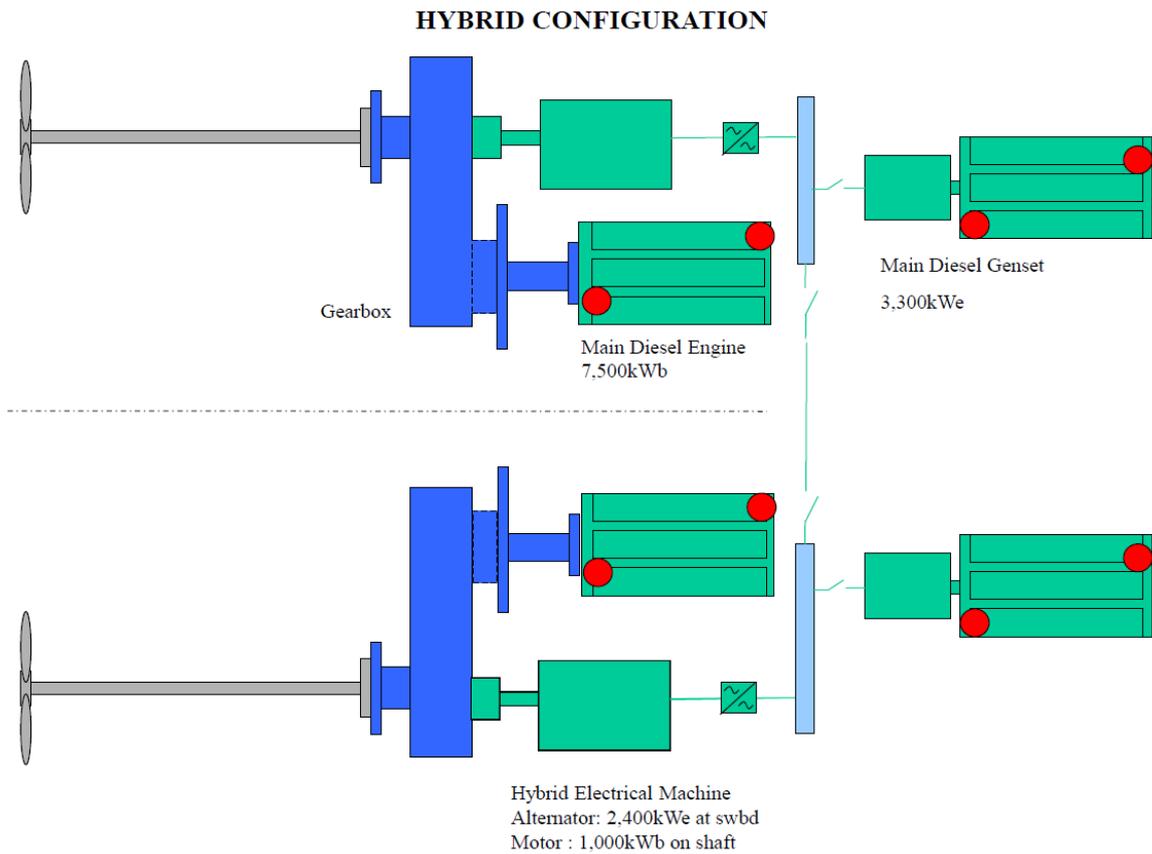


Figure 3: Hybrid Arrangement

Figure 3 shows a simplified schematic of the relationship between the MDE and the MDG.

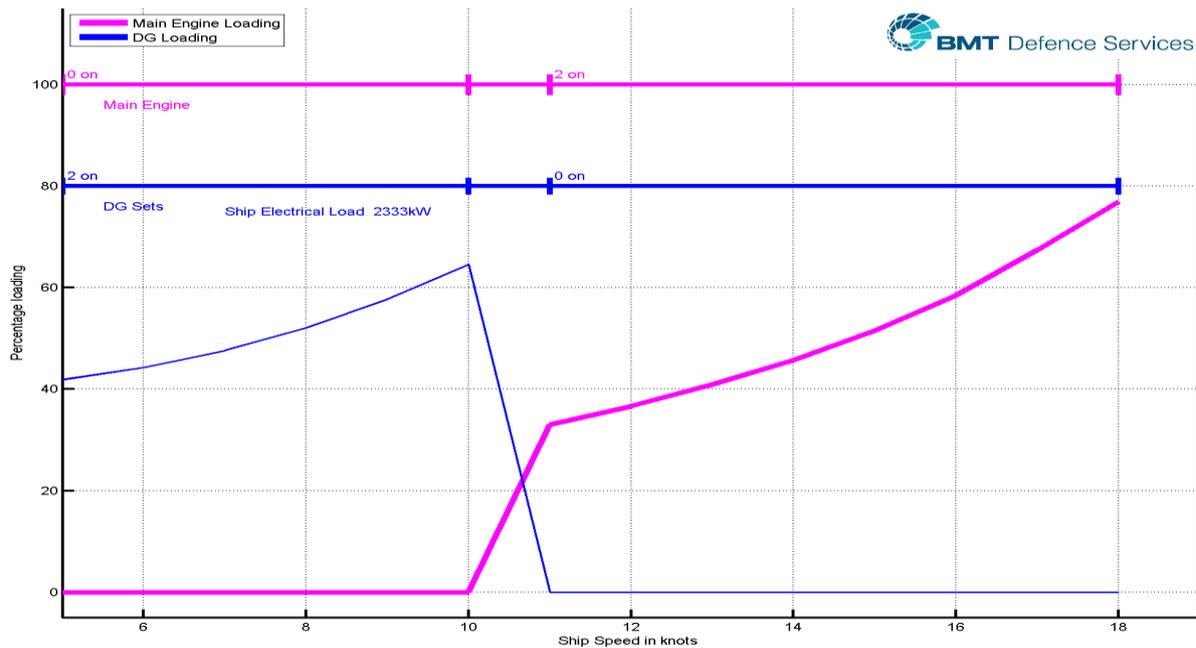


Figure 4: Hybrid Design Engine Loadings

Figure 4 shows the motors driving the ship to 10 knots before they are shut-down at higher speeds. For speeds above 10 knots the two MDE supply power to the propeller and the SEL.

Full Electric Propulsion (FEP) design

COMPARISONS

General

Engine Support Costs

For this study, engine support costs are those costs assigned to engine upkeep. They are assumed to be 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/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 and does include the use of both MDE for all speeds in the DM design.

The figure for the total annual engine-related costs is the sum of the annual cost of fuel and the annual estimated cost of engine support.

Fuel Consumption

The machinery definition and loading together with the fuel consumption at each integer speed has been identified using the BMT proprietary tool, Ptool (Ref 3). The results of this analysis are now presented with the fuel cost assumed to be £700/tonne for MGO or its equivalent.

At top speed, the hybrid design has fewer losses due to energy transformations and is thus more efficient than the DE design. The HM motor would be expected to operate near its peak rating when at 10 knots and thus offer a better efficiency than the larger motors in the DE design at this speed.

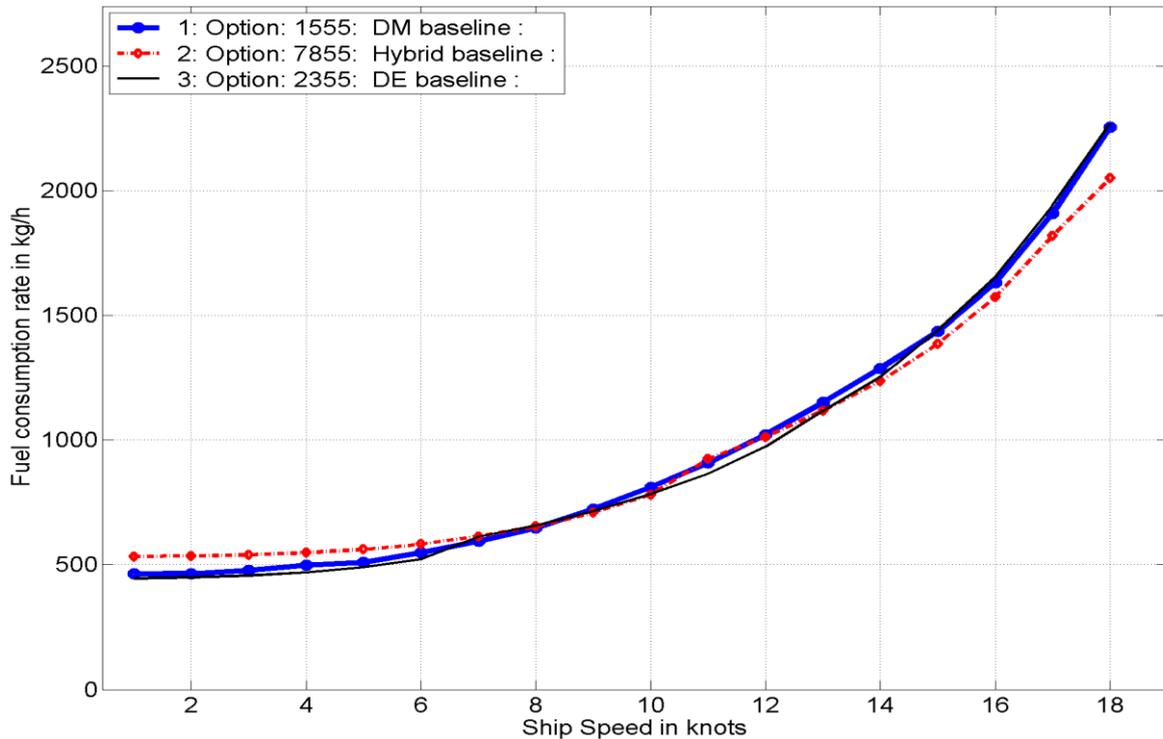


Figure 5: Fuel Consumption

Figure 5 shows how the hybrid has a slightly worse overall efficiency when operating in motor mode. However the MDE's efficiency and hence better specific fuel consumption (Sfc) is used to full effect at speeds above 13 knots. Between 9 and 13 knots the three designs have a comparable efficiency with the DE design being best in this range.

Figure 6 shows how the operating profile skews the trend in Figure 5 to allow the hybrid design create significant fuel savings at the higher speeds.

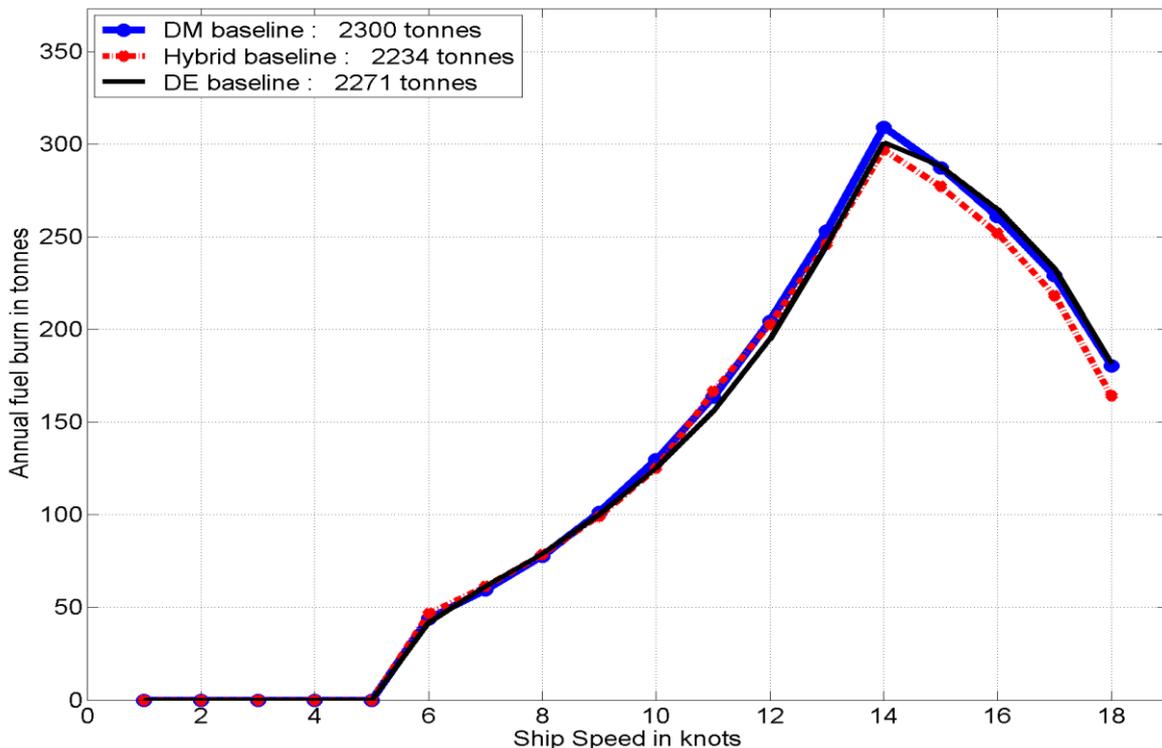


Figure 6: Annual Fuel Burn

When combined with the reduced engine running hours, and hence support costs, this leads to a reduced through life engine running costs as shown in Table 1.

The unit price costs and design development costs will vary between suppliers and shipyards. It is estimated that there is a greater effort in Design Definition for the hybrid design but with the hybrid design, the ship's general arrangement benefits from the removal of the two MDG.

Comparison Summary

The three designs have been compared for a range of parameters and the results are shown in Table 1.

Parameter	DM	Hybrid	DE	Best
Machinery weight	974	955		Hybrid
Machinery Volume	0	-150	+500	Relative in m ³
Annual Fuel Consumption	2,300 tonnes	2,234 tonnes	2,271 tonnes	Hybrid
Engine running hours	7,000	5,000	4,340	DE
Engine support costs based on engine running hours	£399k	£283k	£201k	DE
Total annual Engine-related costs	£2,282k	£2,118k	£2,068k	DE
Whole Life Cost (WLC)	£94.1m	£88.4m	£92.6	Hybrid

Table 1: P&P Comparison

Table 1 shows how the hybrid design offers fuel and WLC benefits as well as a lower ship impact due to the removal of two MDG.

Effect of Load Changes

It is recognised that the decision to adopt one P&P system or another may be made at a stage in the ship's design cycle when the full SEL and the full set of resistance data may not be known. It is therefore important to have an understanding of the sensitivity of the decision to the variation of these two factors. The SEL and ship resistance for the two baseline designs were varied by $\pm 5\%$ and $\pm 10\%$ and for each case the propeller definition was adjusted so that the comparison was fair and equitable.

The differences in annual fuel consumption between the operating performance of the DM and the DE when compared with the hybrid design were identified and plotted as a contour plot shown in Figure 7 and 8. The plot has some irregular contours due to the step changes of engine usage at key operating profile speeds.

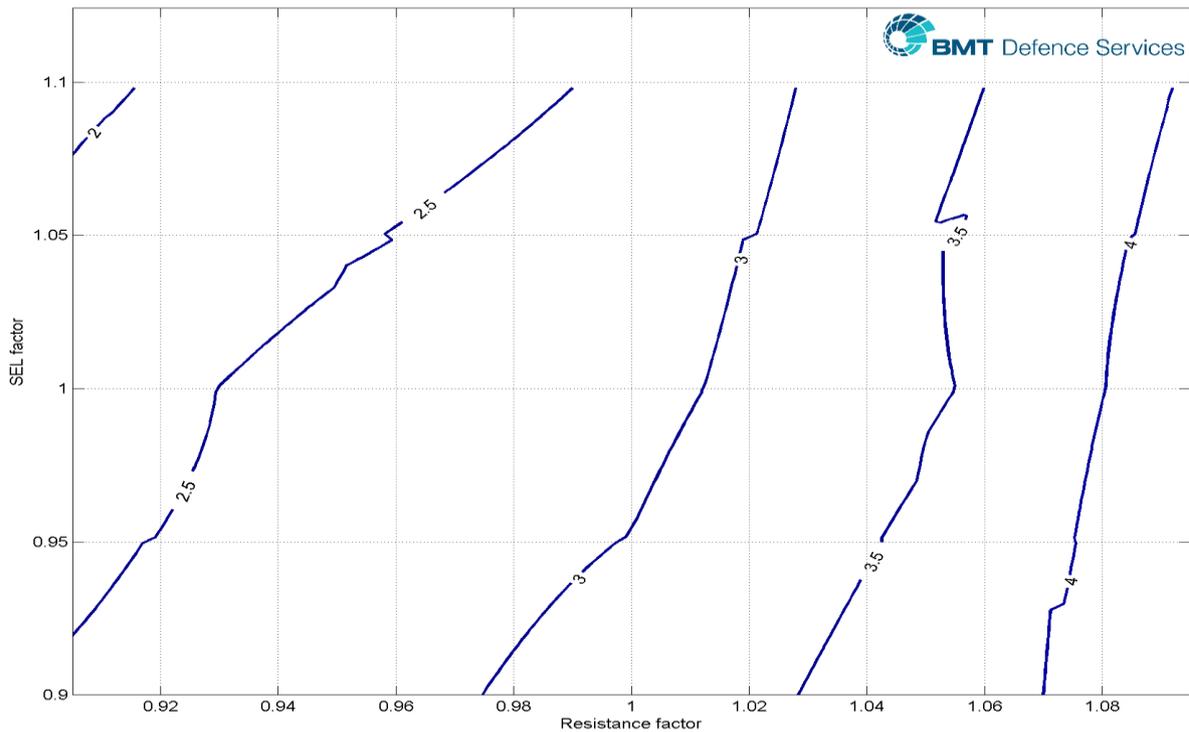


Figure 7: DM: Annual Fuel Difference

Figure 7 shows the percentage difference between the hybrid and the DM designs where a positive indicates a fuel saving due to the hybrid. The hybrid design offers the greatest benefit when the propulsion load is a higher proportion of the total load. When the propulsion load factor is lower the difference is less: this is partly due to the poor efficiency of the power electronics at lower loads. The SEL is about 26% of the propulsive power at the design point where both factors are 1.0.

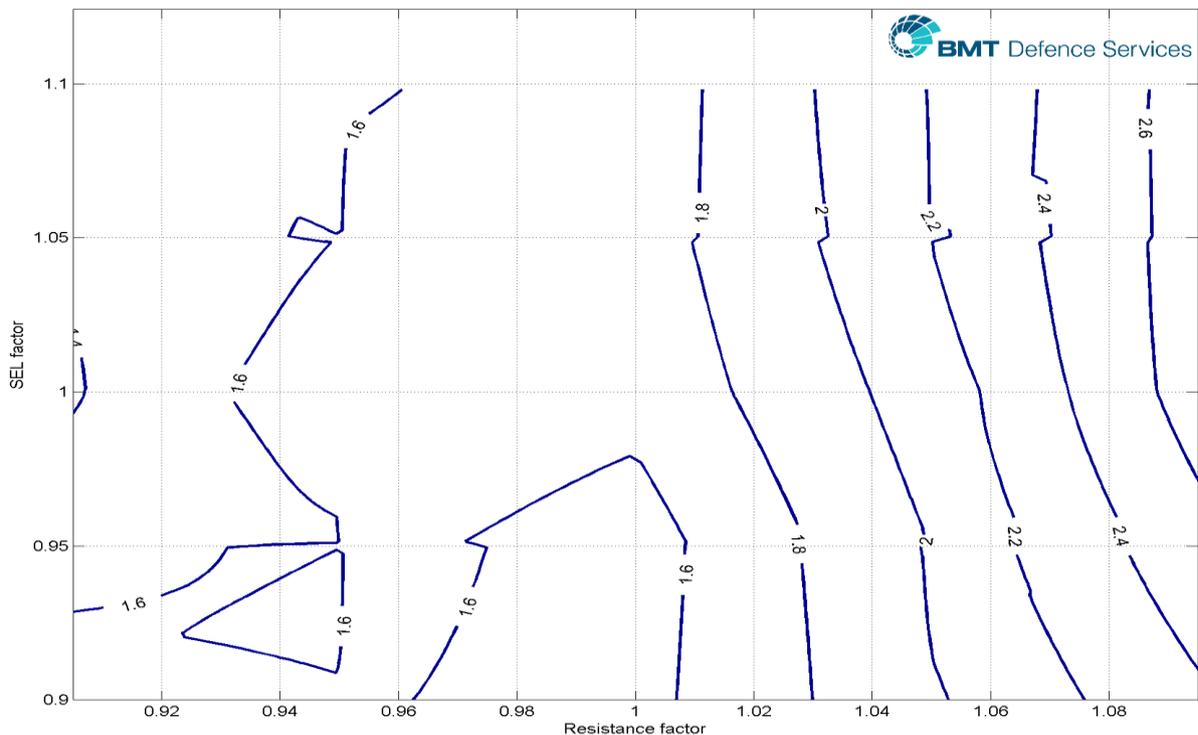


Figure 8: DE: Annual Fuel Difference

Figure 8 shows how the hybrid has the better performance at higher propulsive factors when compared to the DE design.

Hybrid Benefits

Hybrid designs appear to be best suited to those vessels which have a range of SEL demands. The higher peak demand (and hence the higher installed electrical generating capacity) is usually for a specialist case (i.e. RAS winches and cargo pumps or the recovery of a towed array) and usually occurs at cruise speed or below.

With an installed set of two MDE and two MDG, the combined use of the MDG and the hybrid alternators are to be able to cater for the range of peak demands at each speed. For most of the time the normal cruise load can be met by the two MDE alone at 60 to 70% MCR.

This surfeit of onboard power generation capacity means that there is scope for the MDG 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 these incur as well as a lower Underwater Radiated Noise (URN).

The feasibility of the motor option is essentially down to the ratio of the peak power demand to the cruise power 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 HM needs to operate as a generator rated near or at the same rating as the two MDGs. Therefore the HM is going to be rated higher as an alternator than as a motor due to the limited power available from the two MDG for motor use after they have supplied the SEL.

When operating as a hybrid genset each of the two MDE provide half the required mechanical power for the SEL to the hybrid machines. This generator load is an offset to the propeller curve and requires a specific combinator 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 away from its stall point. This does lead to some propeller inefficiency which is accounted for in the overall performance.

The HM generator is thus rated for a range of speeds so that the MDE and the propeller can operate between 10knots and full speed at the best speed as derived from the combinator curve. This involves the use of the two MDE to supply the total power demand and the propellers at the given speed to supply the total thrust. For this reason the HM generator is to be able to supply its full rated power in a range of shaft speeds, typically from 67 to 100%.

Thus a key requirement is for the electrical machine to be able to operate as a fully rated hybrid generator in the full range of applicable MDE speeds which is consistent with the ship's propeller speed, i.e. the HM generator is not to be just rated at full electrical power at full speed. The green dashed line in Figure 8 shows this.

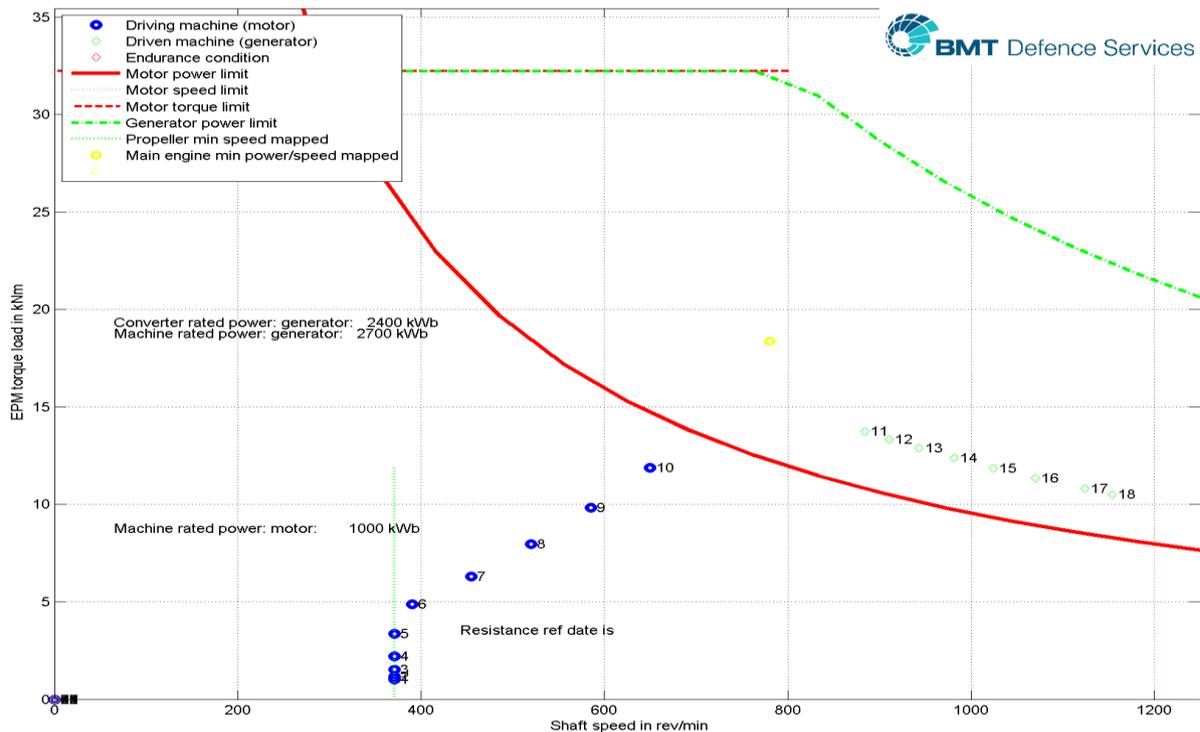


Figure 9: Hybrid Machine Loading

Figure 9 shows the loading of the HM for the range of ships speeds (knots) shown as numbers next to each circle. The blue circles show the motor operations and the green the generator mode.

Ship Fit

The HM design has a design challenge with the ship fit issues relating to the constraint of having to locate the HM machine adjacent to the MDE. A hybrid design does save the footprint and downtakes and uptakes of two MDG but it does introduce a more constraining ship fit arrangement.

In a good hybrid design the MDE are more efficient (say by 10% or more) than the smaller higher-speed MDG 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.

Operations

A hybrid design leads to fewer engine running hours and lower fuel consumption. The actual difference will vary greatly with the operating profile and the balance of SEL to the ship's propulsion load. There is also a greater reliability of propulsion power supply as the hybrid design has four prime movers which can provide propulsive drive, i.e. not just two as in the mechanical design.

The two motors provide the capability of a continuous slow speed for loitering but the nature of the design also allows one MDE to provide propulsive power to its own shaft and some power to the other shaft via the two HM to allow a zero-drag trailing shaft. This is a half-way house between full electric loiter drive and full MDE 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 MDG running in such a case to ensure there are two independent sources of electrical power.

Resilience and Flexibility

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

A key aspect of the hybrid is the flexibility offered by its ability to load the MDE 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.

Figure 10 shows how the hybrid design allows a better overall Sfc to be achieved for speeds between 13 and 18 knots: this covers the principal range of ship operations. The hybrid design provides four independent source of motive power for the propulsion function compared to two for the MD although both designs have a common reliability issue with the gearbox and the CPP.

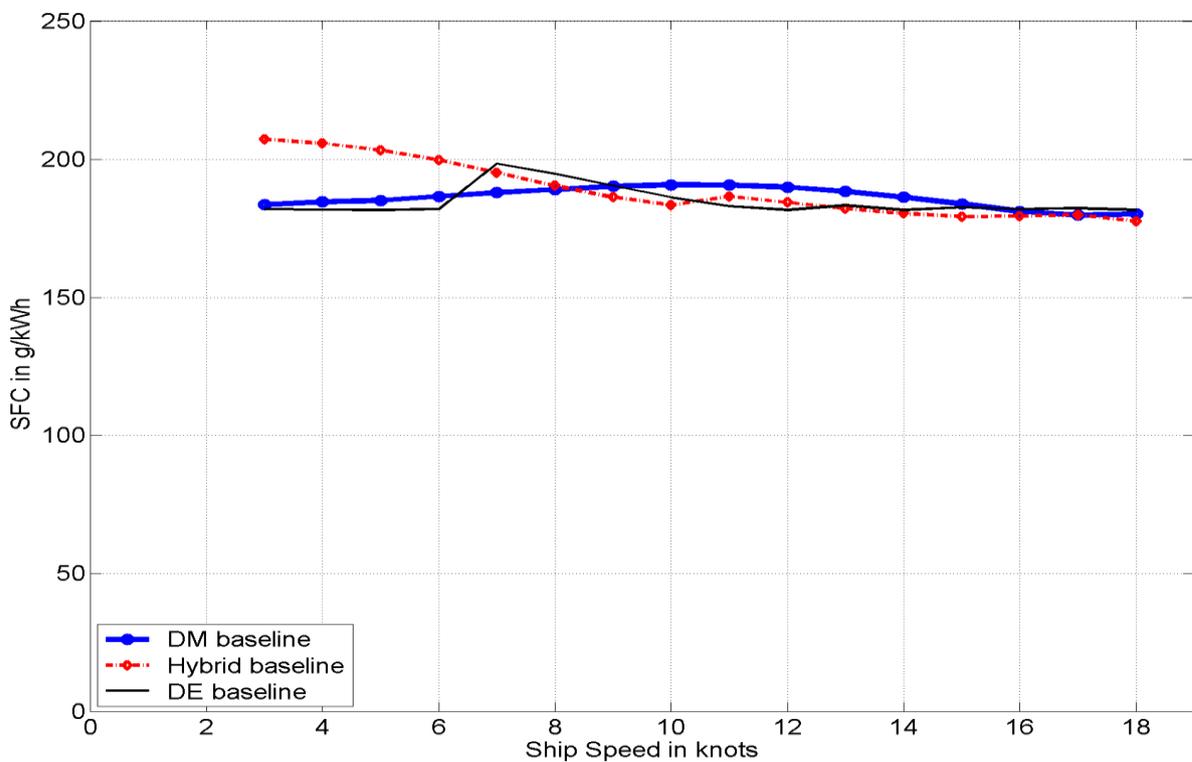


Figure 10: Overall Sfc

All 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 MDGs they replace. This could be due to the standard rated capacity and the ratio of MDE to the MDG sizes. The motor drive is also likely to provide a lower URN compared to operations in MDE drive.

CONCLUSIONS

Hybrid designs are a relatively new phenomenon, being advanced through the benefits of cheaper and robust power electronics modules. In BMT designs, they typically allow the removal of two MDG from the ship and offer more operating 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 running of the MDE nearer to 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. The hybrid is a cheaper alternative to the DE design and offers a lower fuel consumption and hence lower carbon dioxide emissions.

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