General Purpose Frigate Low-Speed Electric Drive - When does it Make Sense?

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Synopsis

Light Frigates (LFs), like many warships, will spend a reasonable amount of sea time at low speeds. By definition, the LF has to be capable yet affordable, a difficult balance to strike, but a dichotomy which has to be addressed particularly given the cost pressures our world's navies are under. Whilst low engine loading at loiter speeds may lead to fuel inefficiency and increased maintenance burden, a purely mechanical Combined Diesel and Diesel (CODAD) propulsion system is attractive from a simplicity perspective. Hybrid propulsion architectures, using electrical machines as motors for low-speed operations, can be employed as a way to address this part of the operating profile. This paper explores to what degree a hybrid solution is appropriate for a LF through the consideration of a number of factors.

Keywords: Warship; Frigate; Propulsion; CODAD; Hybrid; PTI; PTO; Spatial Integration; Cost.

Figure 1: Venator®-110 Light Frigate (VLF) Concept

1. Introduction

Light Frigates (LFs) are required to take part in a wide range of activities, from maritime security and boarding operations to providing credible combatant offensive and defensive capabilities globally. As such the LF's operational profile will see time spent at a range of speeds, but with quite a high percentage biased towards the lower-end. The LF has to be an affordable platform, yet needs a high installed power in order to sustain the high-speeds required to keep pace with the fleet. At a relatively compact typical overall length of just over 100m, internal space on a LF is at premium making propulsion machinery integration a challenge, not only for primary propulsion equipment but also ancillary systems such as the uptakes and downtakes, particularly when NOx emissions compliance is required.

Although such a varied operating profile can be effectively delivered with a purely mechanical-drive diesel propulsion system, hybrid propulsion in its various guises has been shown to offer benefits (Simmonds, 2016 & Buckingham, 2013) for certain Naval applications.

Hybrid propulsion may be as basic as small induction machines used as motors to allow low speed loitering without running the main engines, Power Take-In (PTI), through to more elaborate systems where electrical generation through Power Take-Off (PTO) is also employed using the same hybrid machines (HMs).

An existing LF design is used as the basis for this evaluation, Figure **1**: BMT's Venator®-110, (referred to henceforth as VLF), a variant of the BMT Venator Platform (Kimber et al., 2008). Holistic aspects including operational flexibility, physical integration and whole-life costs will be assessed to establish the advantages and drawbacks of a PTI-mode Low Speed Drive (LSD) for this application, whilst exploring the limitations of what is both practical and affordable.

Performance assessment has been carried out using a BMT proprietary tool, with cost comparisons have been carried out by using BMT and market data. Physical integration analysis has been carried out in Rhino 3D, by modelling the propulsion equipment within the LF hullform whilst recognising maintenance and access requirements.

2. VLF Requirements & Attributes

The VLF has the following key power and propulsion (P&P) requirements:

- Top speed- in excess of 25kts;
  - To keep up with the fleet & to cover large areas.
- Generator Redundancy "n+1";
  - Peak ship service electrical load satisfied with one diesel generator (DG) out of service.
- NO_x emissions compliance to MARPOL Annex VI;
  - For global capability.
- Shock Protection for Float, Move and Fight, with Shock Captivity for remaining functions;
  - To maintain key capabilities after a shock event.
- Lloyds Register (LR) PMR*: Propulsion System Redundancy in Separate Compartments, or equivalent;
  - To maximise survivability.
- No platform-level Anti-Submarine Warfare (ASW) requirement;
  - As this is a general-purpose frigate.
- No gas turbine engines;
  - The trade-off of a reduced top speed for a lower overall cost is appropriate for this platform.

VLF Attributes:

- Length (overall): 117m
- Length (waterline): 107m
- Draught: 4.3m
- Displacement: 4,000 tonnes
- Maximum beam: 18m
- Top speed: >25 knots
- Range: 6,000Nm at 15 knots

3. LF Operating Profile

Operating profiles are an estimate of intended usage based on a number of assumptions, and for multi-role vessels this estimation is made even more challenging due to the diversity of activities it will undertake. It is important to consider this when comparing modelled P&P system performance as the theoretical fuel consumption differences between mechanical and hybrid propulsion system options often differ by only a handful of percent, and are greatly influenced by the operating profile.

The speed-time operating profile used for the VLF is shown in Figure **2**, based on a vessel time at sea of 5,000 hrs/yr.

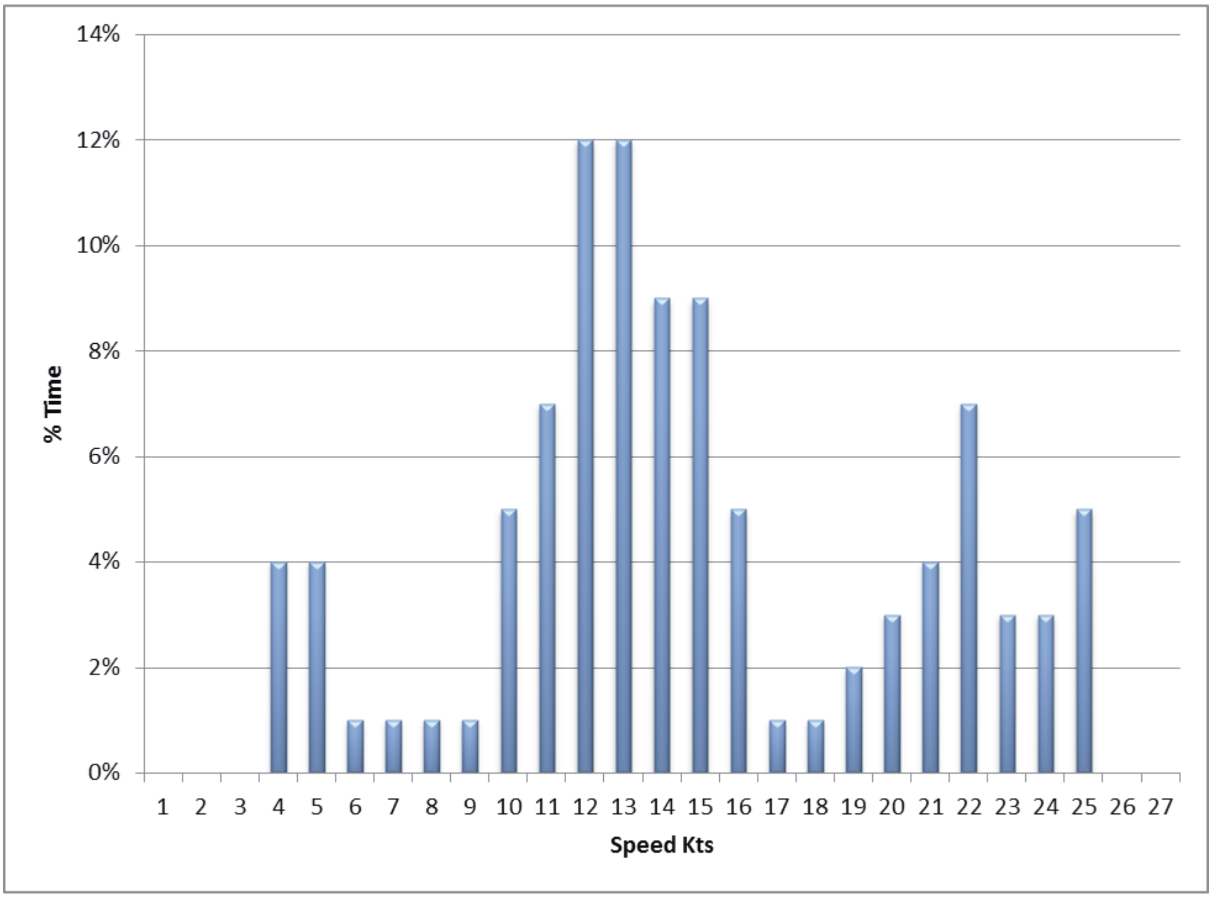

Figure 2: VLF Assumed Operating Profile

From the above, a target LSD speed of 12kts was chosen for the analysis, as the 4-12kt speed range makes up a third of the profile.

4. Power-Speed Curve

The assumed delivered power-speed curve can be seen in Figure **3**, developed from hullform tank testing, representing an average North Atlantic sea-state. The target LSD speed of 12kts under PTI operation requires a total delivered power (P_d) of 1,100kW (between both shafts).

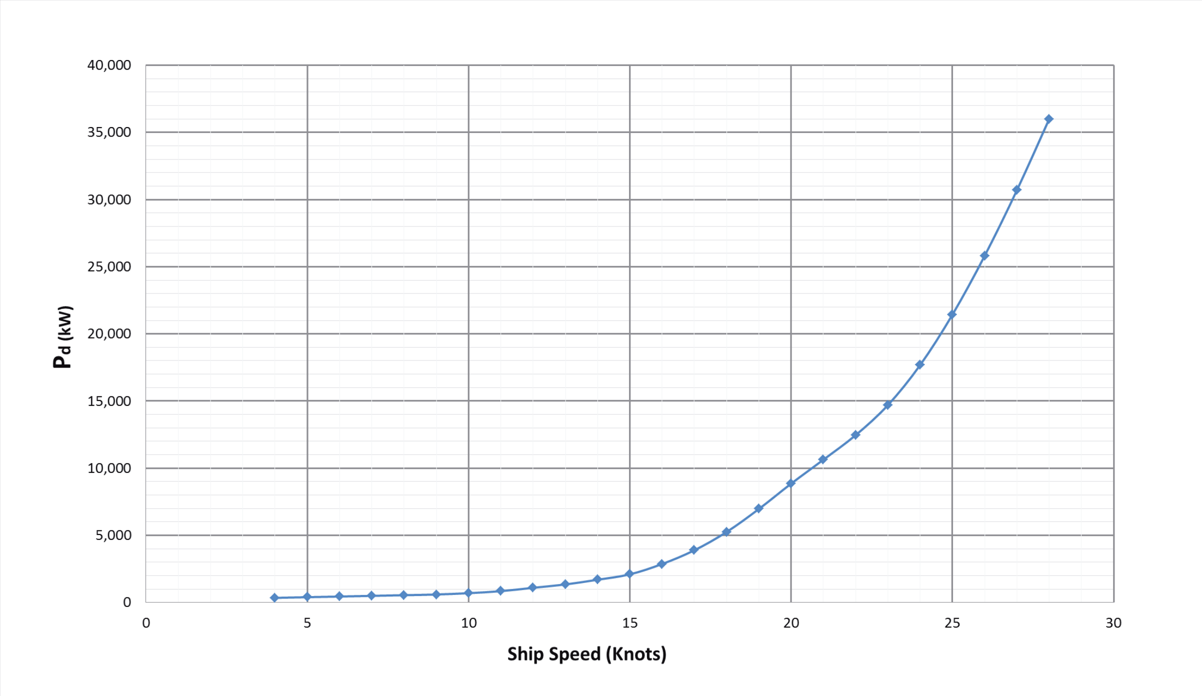

Figure 3: VLF Assumed Power-Speed Curve

5. VLF Baseline- Mechanical Propulsion System

A LF needs to achieve a useful top speed, i.e. in excess of 25kts in order to keep pace with the fleet and to cover large distances as a global warship. This high-speed performance demands a power-dense diesel engine propulsion package, however the VLF is a compact platform and so machinery space length is restricted. As Figure 3 shows, a propulsion package capable of delivering in excess of 24 MW is required, with four high power-density (circa >1000rpm) diesel engines of at least 6MW each needed. Candidate diesel engines for such a propulsion package are limited, but include engines such as MTU's 8000 series and MAN's 16V 28/33D STC.

Both of these engines are capable of extended low-load running. MTU's 8000 series shuts down a bank of cylinders at low loads for improved combustion conditions, and has proved extended running at less than 5% load as part of ABS Naval Vessel Rules testing. MAN's 28/33D STC can run at very low loads continuously for 12 hrs with just a 20 minutes period needed at 70% load to recover. (MTU/MAN literature- see references).

The VLF baseline propulsion system uses four MTU 16V8000M91L diesel engines, each rated at 8MWb at 1,150rpm, in a CODAD configuration. With two separate shaft lines combined with four prime movers and controllable pitch propellers (CPPs), the proven arrangement provides a significant level of flexibility whilst providing a high top speed:

- Power generation for ships services is from four MTU 16V2000M41B DGs, each rated at 0.9MWe, with only three of the four required (n+1 redundancy) to satisfy the peak ship-service load.
- The propulsion and power generation machinery is distributed over four longitudinal watertight compartments, and so satisfying LR PMR* requirements.

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- Shock compliance is delivered by shock-mounting the DGs and main engines. Flexible couplings connect the main engines to the propulsion gearboxes (GBs), which are shock-hardened along with the shaftline components.

Model renderings of the baseline system can be seen in Figure **4** and Figure **5**:

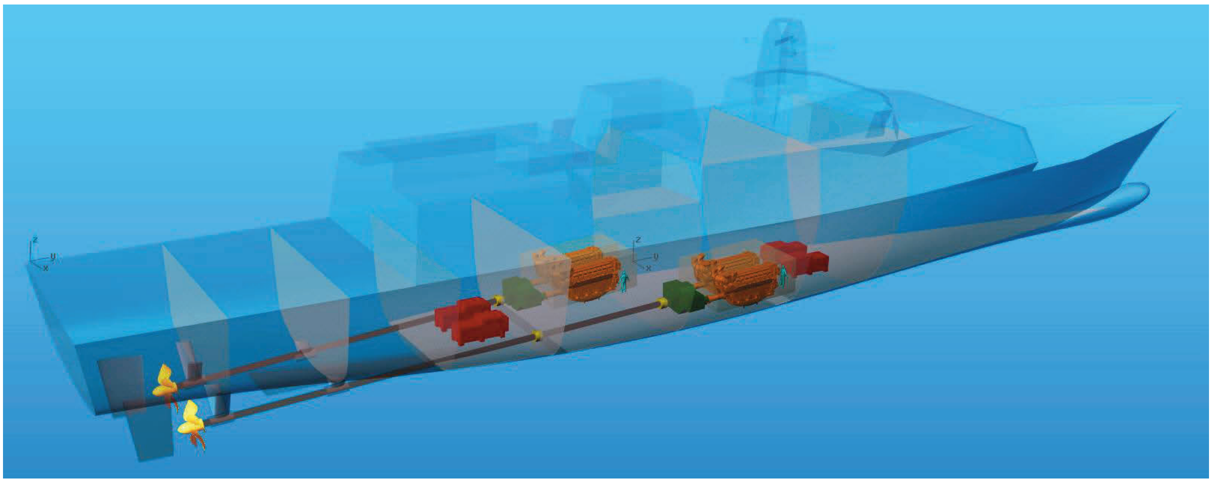

Figure 4- Baseline CODAD VLF P&P Arrangement

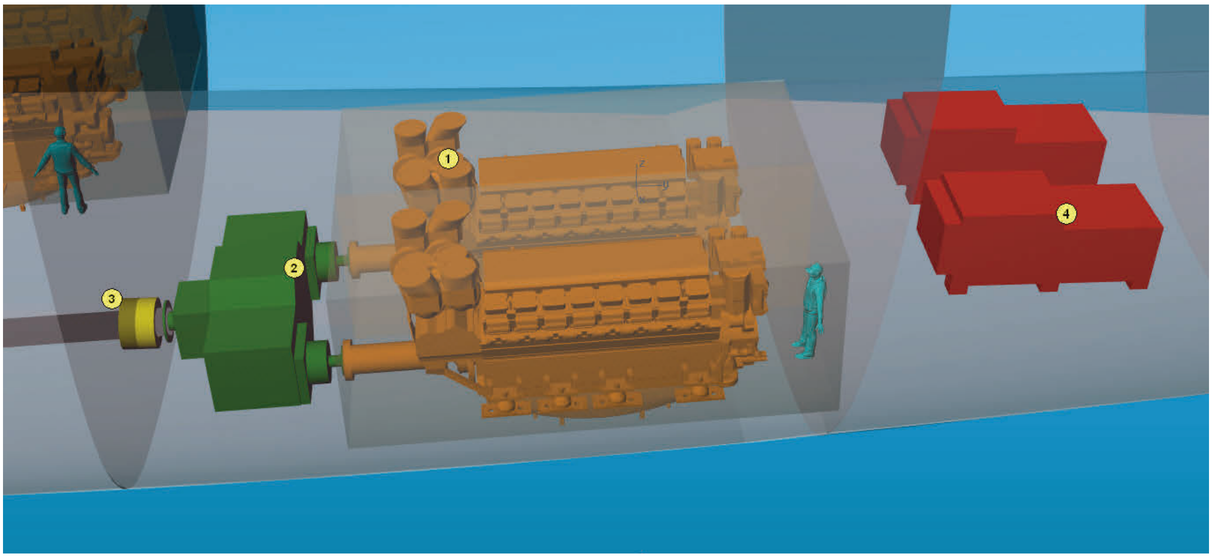

Figure 5- Baseline CODAD VLF Stbd Propulsion Train and fwd DGs

Referring to the labels on Figure **5**:

1. Main engines- MTU 16V8000M91L. Maintenance envelope shown as the surrounding translucent volume;
2. GBs (David Brown Santasalo shown);
3. Shaftline and bulkhead seal;
4. DGs- MTU 16V2000M41B.

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6. Hybrid Propulsion Systems

In recent years there has been a marked shift towards hybrid propulsion systems and currently various types of hybrid system are available. The focus of this paper is on a **CO**mbined **D**iesel e**L**ectric **O**r **D**iesel (CODLOD) hybrid arrangement without any form of Energy Storage. In some of the options investigated the added flexibility is available where the electrical machine can be operated as both a motor (Power Take In – PTI) and a generator (Power Take Off – PTO).

Within a generic CODLOD hybrid architecture there are still a number of options for how to integrate an electric propulsion motor. The hybrid equipment options relevant to this VLF application are summarised as follows:

- Machine Speed: The electric machine could either be propeller-shaft mounted (low speed – direct drive) or connected through the gearbox (high speed):
  - Direct Drive: In this application the electrical machine would be low speed (<200rpm) and directly drive the propeller shaft. The machine would be large (high torque), heavy and expensive. The electric machine is used for low speed cruise and boost if provided by a larger conventional engine driving through the motor. This means at low speed the noisier mechanical drivetrain could be disconnected for ASW operation - this is similar to the T23/T26 frigate hybrid system. For VLF there is no ASW requirement and so the main benefit of a direct drive system would not be realised.
  - Gearbox Driven: In this case the electric motor would be a high speed (>600rpm) machine connected through the GB. The machine would be smaller, (lower torque), lighter and cheaper. The LF mechanical baseline would already have a gearbox and so only a relatively minor modification would be required to allow a secondary input.
- Machine Type: Induction, Synchronous or Permanent Magnet:
  - Induction: These machines are inherently reliable, and are a well-proven technology. When coupled to a bi-directional Active-Front-End (AFE) power electronic converter induction machines can seamlessly serve as both a motor and a generator. The use of an AFE converter results in a very high quality generated waveform suitable for direct connection to the main distribution network, without the need for isolation transformers.
  - Synchronous: These machines are often used for conventional shaft generators for fixed speed operation directly connected to the main power grid. They do not lend themselves well to a Hybrid PTO application where the propeller shaft speed will vary. For the PTI application this type of machine would require a synchroconverter which typically results in supply-side distortion and hence propulsion transformers are typically installed.
  - Permanent Magnet (PM): PM motors are a type of synchronous machine albeit where the excitation is provided by permanent magnets. PM machines are typically higher cost, but do offer increased efficiency and a smaller, more compact package.
- AND or OR Hybrid: Two control options exist for the operating philosophy for a hybrid propulsion system. Either the two sub-systems (mechanical and electrical) operate independently and never together – known as “OR” operation – or they operate in concert at high power each making a contribution – known as “AND” operation. At the levels of hybrid propulsion power being considered for the VLF, minimal benefits are going to be gained by adopting an “AND” hybrid: ~1MW at the top end is not going to make a useful difference to maximum ship speed due to the cubic nature of the power vs. speed curve.

6.1. Candidate Hybrid System for the VLF

In order to investigate an affordable hybrid equipment fit the following assumptions have been made:

- The HMs will be a standard, high speed induction machines, coupled to the GB's PTO/PTI shaft. This satisfies the affordability brief, as direct-drive, shaft mounted machines are specialist, large and expensive units and high-speed PM machines offer minimal sizes advantages at the ratings being discussed for increased cost;
- 1MWe, 1000rpm machines have been physically represented. These more than satisfy the 12kt target speed, whilst allowing ample capacity for PTO to support the ship's electrical load;
- Shock capability will be delivered using suitable shock mounts below the HMs and flexible couplings. Conceivably a PTI-only LSD solution could use a sacrificial motor, as low-speed capability can still be delivered using the main engines, whereas for 'full hybrid' (PTI and PTO) the HMs would be required to be shock-capable as the DGs would be;
- It shall be an "OR" hybrid system.

The hybrid drivetrain arrangement can be seen in Figure **6**. Key points to note:

- The propulsion GBs (labelled 2 on Figure 6) are slightly larger and heavier than the baseline CODAD units owing to the additional, non-standard, hybrid machine pinion outboard which meshes directly with the pinion of the outboard main engine;
- The HM (labelled 5) is accommodated in the next, aft compartment, coupled to the GB through a watertight bulkhead seal;
- Hybrid propulsion with PTO can enable a reduction in the number of DGs, in the variant shown below from four to two (one of two shown, labelled 4)- this is when hybrid becomes particularly attractive as fewer prime movers equates to reduced maintenance burden, and also a reduction of the number of ancillary support systems. Note however that as the DGs are used for both LSD and ship service they may have to be of a higher rating.

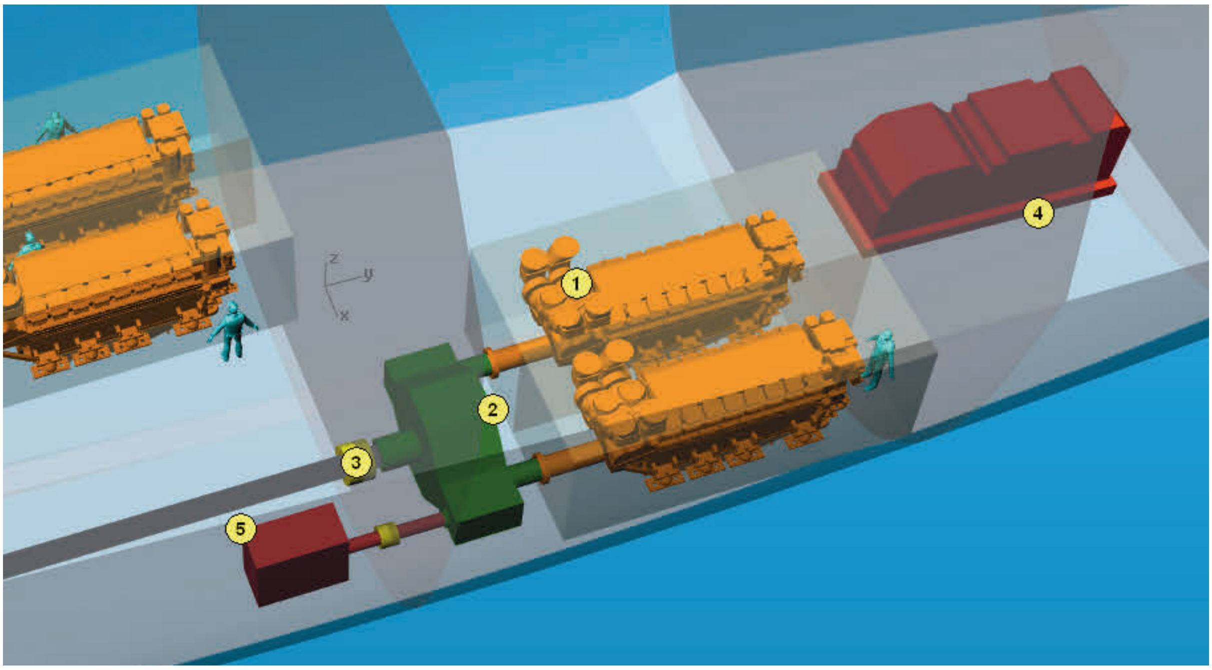

Figure 6- Hybrid VLF Stbd Propulsion Train and Fwd DG

6.2. The Hybrid GB

On consultation with gearbox suppliers, the preferred solution for the hybrid machine input to the GB is on the aft side of the GB, i.e. the propeller shafting coupling side, as shown in Figure 6. To provide an input on the fwd side with the sufficient offset required to clear the main engines additional idler gears would be needed which would introduce extra weight and cost into the GB. The fwd arrangement may be preferential from an integration perspective however as it avoids the need for a watertight shaft seal around hybrid machine shaft, particularly if the hybrid machine is shock-mounted (as the shaft seal would have to be more elaborate to accommodate the potential shaft deflections).

The David Brown Santasalo hybrid GB design used in this study features double helical gears, and a PTI/PTO capability of up to 2MW:

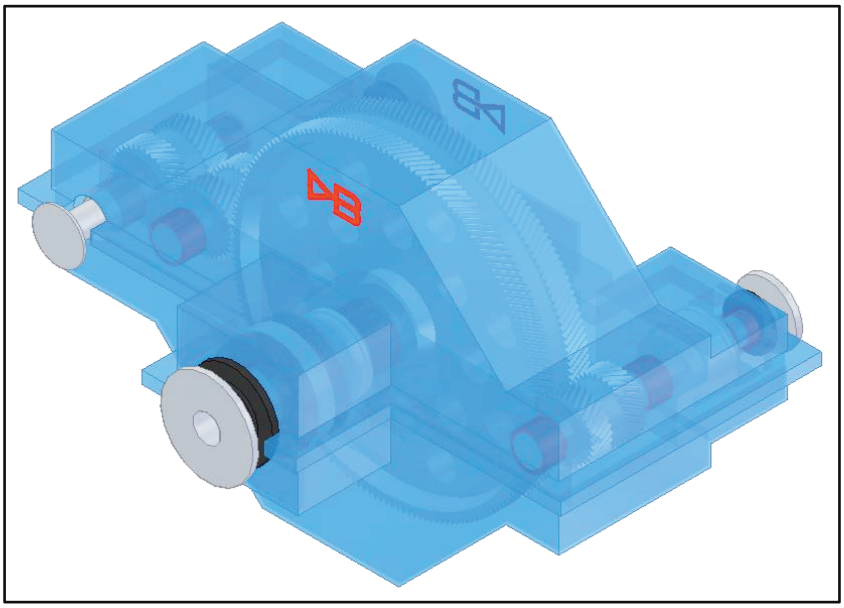

Figure 7- David Brown Santasalo Hybrid GB

7. Hybrid VLF Performance & Cost Analysis Method

P&P system performance comparisons were carried out using BMT's proprietary propulsion assessment tool. This tool allows candidate propulsion equipment characteristics to be input along with the ship's service predicted electrical load, power-speed curve, and operating profile. The propulsion system architecture (mechanical, hybrid etc.) was then selected, and for each speed point of the operating profile the equipment line-up (what's running/shutdown) chosen. The model then displays the equipment loadings and fuel consumption for that speed point. Machinery line-up is then adjusted to optimise the performance at that speed-point for whatever the most important criteria is, be it minimising fuel consumption (running equipment at optimum efficiency/minimum SFC), maximising resilience (for example both shaftlines being driven/all prime movers running), minimising number of prime movers running, etc. The tool is then configured to give results such as annual engine running hours per engine type, and annual fuel consumption based on the operating profile. Through-life cost comparisons can then be carried out by monetising these outputs.

This particular tool uses an input power-speed curve described in terms of P_d, (power to the propeller), which assumes constant propeller efficiency across the speed range. It does not therefore allow simulation to be made of the off-pitch propeller efficiency penalty when being driven at low loads with the CODAD system. At 10% load a diesel engine is still operating at around 40% speed, and so the CPP has to run at a sub-optimal, fine pitch. Modelling the propeller efficiency in such conditions is complex and an accurate prediction is not possible. This 'zero-pitch loss' aspect is neglected within this particular analysis, but is recognised and needs to be borne in mind when comparing fuel consumptions for different systems, particularly where the results are close.

At low ship speeds with the CODAD system one shaft will be trailing, with propulsion being provided by one diesel in order to avoid running two diesels at even lower loads. This appendage drag is accounted for by assuming a 10% increase in P_d. This value has been shown to be a reasonable assumption ascertained from prior BMT analysis.

8. Analysis Results & Discussion

Table **1** contains the results of the analysis, where 4 different configurations of VLF hybrid propulsion are compared.

Costing assumptions:

- Fuel Cost = £500/tonne;
- Engine Support Cost = £10 per MW per hour- a representative figure. These are the costs assigned to engine upkeep. (Buckingham, 2013);
- Vessel Life = 30yrs;
- "Total Lifetime Saving" constitutes fuel costs, engine support costs, and initial purchase cost deltas.
- No price escalations assumed.

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System No.	Propulsion System	Main Diesel Ship Fit	DG Ship Fit	% Fuel Saving	Fuel Saving p.a.	Lifetime Fuel Saving	Engine Support Saving p.a.	Lifetime Engine Support Saving	Initial Purchase Cost Delta	Total Lifetime Saving
1	Mechanical	4 x 16V8000	4 x 16V2000	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
2	PTO	4 x 16V8000	2 x 16V2000	2%	£ 53 K	£ 1,591 K	£ 87 K	£ 2,610 K	-£ 424 K	£ 4,625 K
3	PTI to 12kts then Mech	4 x 16V8000	4 x 16V2000	0.4%	£ 16 K	£ 466 K	£ 253 K	£ 7,596 K	£ 820 K	£ 7,242 K
4	PTI to 12kts then PTO	4 x 16V8000	4 x 16V2000	1%	£ 39 K	£ 1,159 K	£ 316 K	£ 9,468 K	£ 820 K	£ 9,807 K
5	PTI to 12kts then PTO	4 x 16V8000	2 x 12V4000	1%	£ 31 K	£ 915 K	£ 317 K	£ 9,522 K	£ 312 K	£ 10,125 K

Table 1- Hybrid Analysis Annual Fuel Consumption and Cost

- System 1 is the baseline (CODAD plus 4 DG) solution;
- System 2 uses PTO for all operating points- no LSD, and so the baseline solution with 4 DGs can be reduced to 2. Although this system meets the 25kt requirement there will be a slight top speed reduction when compared to systems 1 & 3 which use all of the main engines' power for propulsion;
- System 3 uses PTI for LSD to 12kts, then mechanical propulsion- no PTO, so baseline DG configuration remains. Note that if one of the DGs is out of service, LSD is only possible up to a maximum of 9kts;
- System 4 is full hybrid i.e. PTI & PTO. LSD to 12kts, then PTO. Uses the baseline DG configuration. Again there will be a top speed reduction when compared to systems 1 & 3 which use all of the main engines' power for propulsion;
- System 5 again is full hybrid, but with different DGs- 2 x MTU12V4000M53B @ 1.5MWe each. Again there will be a top speed reduction when compared to systems 1 & 3. Note that if one of the DGs is out of service LSD may not be possible at all- dependent on ship service load at the time.

All of the hybrid systems analysed have the potential to offer total lifetime saving benefits, with illustrative savings of between £5M-£10M over the vessel life.

8.1. Engine Support Cost Savings

The total lifetime savings offered by the hybrid systems are dominated by the systems' reduced engine support costs. These come from the reduced overall engine operating hours enabled by the ability to consolidate the number of prime movers being used at any one time, and also by the flexibility of being able to choose the most suitable (lowest usage cost) engine type (main diesel or DG) to perform the propulsion or generation task required. For example at low ship speeds the expensive-to-maintain main diesels can be shut down, using the DGs (which are running anyway) instead to provide propulsion through the HMs. At higher ship speeds the main diesels provide power generation through the HMs, as they are already being used for propulsion, so allowing DGs to be shut down.

8.2. Fuel Consumption Benefits

All hybrid configurations show slight fuel consumption benefits over the baseline, with system 2 (full-time PTO) showing the greatest benefits. The fuel saving results for the hybrid systems may at first seem less than expected, but it is worth understanding the overall total power conversion losses associated with the hybrid modes of propulsion and generation, see Figure **8**:

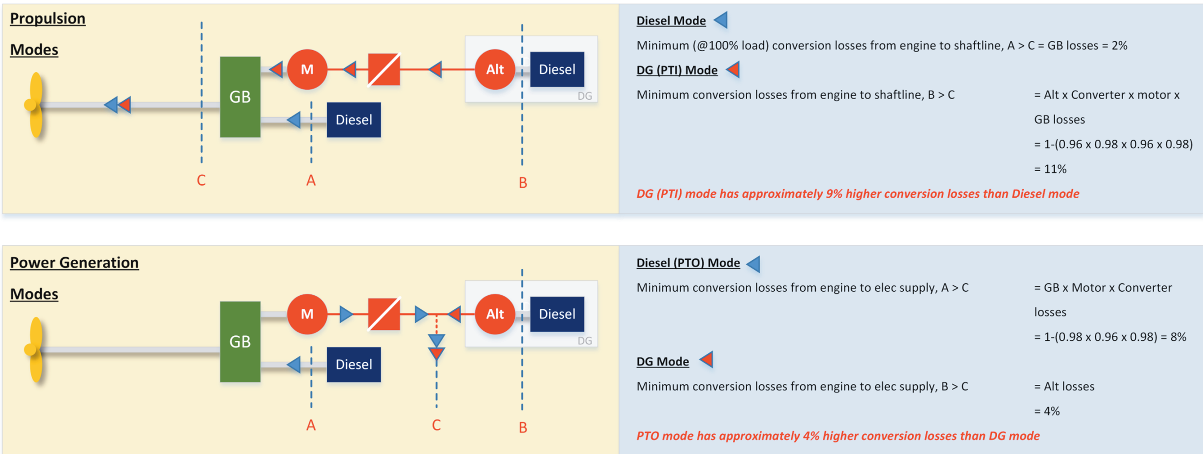

Figure 8- Hybrid Propulsion Modes- Power Conversion Loss Considerations

- Propulsion Modes- Main diesel propulsion has the least associated losses to the shaftline, just that of the GB at roughly 2%. PTI mode using the DGs however has accumulated losses of 11% once the electrical and mechanical power conversion losses have been considered. In systems 3,4 and 5 above (where PTI is used up to 12kts) despite the far higher conversion losses PTI just wins out to Diesel propulsion, as the SFC of the main diesels at extremely low loads is so much poorer than the DGs, which operate at a far more optimal loading. Indeed if the zero-pitch losses were to be modelled the difference would be greater.

- Power Generation Modes- PTO has accumulated conversion losses of 8% from main diesel to the electrical consumers, whereas from the DG set-diesel to consumers the accumulated loss is just 4%. Once SFC is factored in however it can be seen when comparing systems 1 & 2 that PTO offers net fuel efficiency benefits, due to the far favourable SFC of the main diesels once they achieve a moderate load.

8.3. Initial Purchase Cost Deltas

The initial purchase cost deltas of implementing hybrid capabilities can be seen in Table 1. If PTO is employed across the operating profile (system 2) an initial cost saving of approximately £400K is possible. The cost of implementing the hybrid components (HM, converter, GB changes, couplings etc.) roughly matches the cost saving of only procuring two DGs, with the saving coming from only needing to fit two sets of uptakes & downtake systems, including SCRs, rather than four. Systems 3 & 4 do not benefit from this prime-mover reduction as they are required for PTI and therefore cost more than the baseline. System 5 uses, larger DGs, and although only two are fitted there is a slight initial cost increase over the baseline.

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9. Conclusions

For the baseline VLF, the CODAD propulsion maximises speed whilst minimising complexity. A current example of this straightforward, power-dense CODAD system being adopted is for the French FTI Medium-Sized Frigate programme.

This paper has demonstrated the potential economic benefits that various degrees of hybridisation can offer to a LF, using VLF as an example, providing the customer has the appetite for a non-mechanical propulsion system. In addition to the economic benefits, hybrid propulsion offers more propulsion modes which in turn can provide increased resilience, flexibility and availability. Physical integration work has shown that the incorporation of a circa 1MW-per-shaftline hybrid system into VLF although spatially challenging, is feasible.

Hybrid propulsion really comes into its own when its architecture enables a reduction in the number of prime movers and their associated ancillary systems. The corresponding reduction in the number of uptake and downtake systems is particularly attractive for a LF, as these are voluminous and costly particularly if SCR systems are required.

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