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Technical Report

Integration Impacts of a Hybrid Contra-Rotating Shaft-Pod (HCRSP) Arrangement on Naval Auxiliaries

By:

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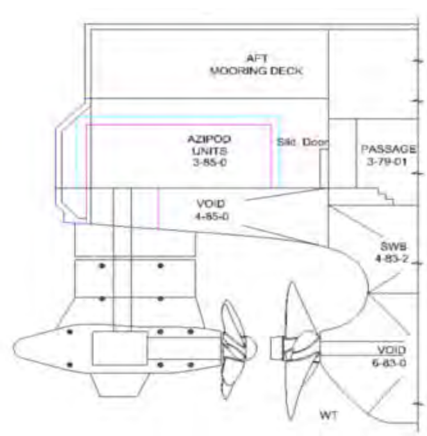

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This study supports the model scale evaluation by investigating the wider system implications of HCRSP on ship design and performance, specifically to identify if the hydrodynamic advantage can be translated into through-life cost and performance benefits.

The study considers the physical and electrical integration aspects of the HCRSP concept and the corresponding impact on fuel consumption, speed, weight, and redundancy. It focuses on the impacts of retrofitting a HCRSP system into both a currently operational T-AKE 1 and a new build, modified-repeat design. Additionally the impacts of a HCRSP concept on future 20 and 24-knot naval auxiliary ship designs are discussed.

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Abstract

Model scale testing and evaluation[1] of a Hybrid Contra-Rotating Shaft-Pod (HCRSP) concept on Military Sealift Command's (MSC's) T-AKE 1 design suggests a potential 7% reduction in the delivered power required, when compared to that of the current single shaft, single propeller system.

This study supports the model scale evaluation by investigating the wider system implications of HCRSP on ship design and performance, specifically to identify if the hydrodynamic advantage can be translated into through-life cost and performance benefits.

The study considers the physical and electrical integration aspects of the HCRSP concept and the corresponding impact on fuel consumption, speed, weight, and redundancy. It focuses on the impacts of retrofitting a HCRSP system into both a currently operational T-AKE 1 and a new build, modified-repeat design. Additionally the impacts of a HCRSP concept on future 20 and 24-knot naval auxiliary ship designs are discussed.

Executive summary

Model scale testing and evaluation of a Hybrid Contra-Rotating Shaft-Pod (HCRSP) concept on Military Sealift Command's (MSC's) T-AKE 1 design suggests a potential 7% reduction in the delivered power required, when compared to that of the current single shaft, single propeller system.

This study's primary aim is to support the model scale evaluation by investigating the wider system implications of HCRSP on ship design and performance, specifically to identify if the hydrodynamic advantage can be translated into through-life cost and performance benefits. The study considers the physical and electrical integration aspects of the HCRSP concept and the corresponding impact on fuel consumption, speed, weight, and redundancy.

The primary focus design for the study is MSC's T-AKE 1 class. It considers the impacts of retrofitting a HCRSP system into both a currently operational T-AKE 1 and a new build, modified-repeat design. Additionally the impacts of a HCRSP concept on future naval auxiliary ship designs are reviewed through consideration of both nominal 20 and 24-knot designs.

The proposed HCRSP concept replaces the rudder system on a single skeg ship design with an electric pod. The pod's pulling propeller is mounted directly behind a conventional shaft-line with the respective propellers operating in close proximity, but in opposite directions, providing a contra-rotating propeller arrangement. Potential benefits of the HCRSP arrangement include:

- Improved propulsive efficiency providing an opportunity to reduce fuel consumption and hence through-life costs, and/or higher ship speeds for the same installed power;
- Enhanced slow speed maneuverability with an azimuthing electric pod;
- Enhanced redundancy, availability, and operational flexibility from the replacement of a single propulsor with a system using two independently driven propulsors;
- The ability to integrate higher powers or speeds into single skeg designs, allowing larger vessels to retain the hydrodynamic benefits of a single skeg.

A range of analysis and design work was completed to support the study's conclusions. This included: modeling of fuel consumption, speed, and engine operation using standard NAVSEA's assumptions (DDS 200) and current T-AKE 1 design data as a basis; an estimation of the impacts on T-AKE 1 lightship weights, centers of gravity, and trim; an estimation of the changes to T-AKE 1's electrical service load; a 2D CAD assessment of the physical integration of the pod system into the current T-AKE 1 hull-form. In addition, electrical integration issues were discussed with subject matter experts from *ABB* and *Converteam*. Key general conclusions are summarized along with specific conclusions for each of the four ship concepts considered.

General conclusions

The physical integration of the pod system, including its electrical systems, is feasible on the four ship concepts considered, but most challenging when integrated into existing designs. New designs should be able to be arranged to provide improved operating clearances for the pod, maintaining protection of the pod and its propeller within the hull extents, and providing the required mounting structure.

The HCRSP concept offers a reduction in fuel consumption when compared to a single shaft-line system, but less of a reduction than suggested by the hydrodynamic efficiency benefit. The impact on fuel consumption depends on how the pod is connected to the ship's electrical system, and the number and load factor of the operational Diesel Generators (D-Gs). Electrical connection is complicated by the uneven propulsion load split between the pod and the shaft-line motors. This results in the connected D-Gs operating at lower, often less efficient, load factors. Although not considered in detail and less significant in scale, anticipated fuel consumption improvements will be reduced due to additional reductions in electrical system efficiency, the need to provide additional electrical power for the pod system, and the change in overall ship displacement.

The lower propulsion power requirement results in a small increase in speed for the same installed power. Adding additional installed power, subject to space availability, could provide additional speed. This option sacrifices efficiency at low speeds as larger D-Gs will be operating, at any given speed, at a lower load factor and hence at higher specific fuel consumption. Large D-Gs also limit the system's ability to meet continuous operation at low-loads potentially promoting the need for a dedicated 'harbor' generator.

Electrical integration should be considered the most significant HCRSP risk and will require more detailed investigation. The potential need to integrate different motor and Variable Speed Drive (VSD) technologies at different shaft speeds (frequencies) and power levels into an integrated electrical system may generate unacceptable harmonics. This issue may be amplified by the transient loads of Underway Replenishment (UNREP) systems. Improved harmonic filtering, better matched motors and VSD design, or operating the system in a 'split-bus' arrangement (pod and shaft motors connected to separate electrically isolated switchboards) may overcome these issues but may also reduce the efficiency benefits of the HCRSP concept.

The reduction in required power may translate into fewer D-Gs operating at certain speeds and hence a potential reduction in through-life maintenance. This impact is dependent on the vessel's operating profile and the time spent at those specific speeds.

Pod systems are significantly heavier than the rudder systems they replace. Although the overall ship weight impact is relatively small, there will be a need to modify the vessel and/or its loading profile to overcome the stern trim moment created.

If physical separation of the main D-Gs can be achieved, the resulting ship should be able to be classed as having two independent propulsion systems. This can provide through-life cost benefit in terms of reduced port charges where restrictions for single shaft vessels are being enforced and would also allow the vessel to benefit from the improved maneuverability due to the pod. The HCRSP concept is likely to offer improvements in system redundancy and failure recoverability.

Retrofit of HCRSP into an in service T-AKE 1

This option was considered to assess the viability of retrofitting HCRSP into an in-service T-AKE 1 to act as a potential demonstrator for the concept. A key aim, therefore, was to minimize the overall impact to the existing ship design, its performance and, hence the extent and cost of conversion. Specific conclusions to this option include:

- The *ABB VO1800* pod in a HCRSP arrangement would provide a sustained speed of 21 knots. Physical integration of the pod system requires a small transom extension to provide protection for the strut element of the pod. This option still leaves the after part of the pod's main body protruding aft of the transom potentially resulting in some operational restrictions.
- It is recommended that a new hull section be designed to incorporate the transom hull extension, the pod's supporting structure and steering gear, and the hull-to-pod strut transition shaping. This should offer the opportunity to reduce conversion dry dock time and costs. It also appears feasible, with some modifications, to install the new pod VSD and transformers within the spaces around the steering gear room.
- It is recommended that the current T-AKE 1 D-G system and connections be retained. Additional power could be realized by replacing the in-line 8 cylinder (8-L) D-Gs for 12 cylinder V-type (12-V) units; however the size of the current D-Gs would make this a high cost option for limited additional speed and potentially reduce efficiency at lower speeds. No locations were identified for additional D-Gs of sufficient power and efficiency to make their addition attractive. Re-connecting the D-Gs to better match the uneven load demand of the two motor systems allows higher speeds to be achieved in a split-bus mode but negatively impacts fuel consumption and the scale and cost of electrical system changes.
- Subject to a detailed harmonic analysis, it is proposed that the pod can be electrically connected to either of the main switchboards. This minimizes changes to the current electrical system, allows split-bus operation up to around 19 knots (i.e. including UNREP), and common bus connection for speeds up to 21 knots.

The impacts of an HCRSP system on an existing T-AKE 1 design are summarized below:

Pod assumption	ABB VO1800	Change in max. electrical load	+450 kW_e
D-G arrangement	Current T-AKE	Change in lightship	+437 mt (+1.7%)

Sustained speed (knots)	21 knots [Common-bus connection]	19 knots [Split-bus connection]

Operational speed & mode [Current D-Gs - even switchboard power split]		10 knot transit	13 knot transit	13 knot UNREP	20 knot transit
Electrical load reduction - HCRSP		-177 kW_e	-442 kW_e		-1,136 kW_e
Fuel consumption reduction - HCRSP		-2.2%	-3.6%	-3.3%	-5.1%
Reduction in fuel load - HCRSP [14,000 nm; 20 kts]	Common-bus	-49 mt	-85 mt	-87 mt	-168 mt
	Split-bus	-44 mt	-79 mt	-78 mt	-167 mt

In summary, retrofitting a HCRSP system into a T-AKE 1 is feasible and would offer maneuvering, redundancy, and fuel consumption benefits. The need to minimize changes to the ship will result, however, in a dilution of the HCRSP benefits due to the non-ideally matched D-G and electrical system and the inability to optimize the after-body design. If unacceptable system harmonics require the ship to operate in a split-bus mode, it will not achieve 20 knots sustained.

Integrating HCRSP in a new build modified-repeat T-AKE 1

This option was considered to assess the potential viability of integrating HCRSP into a modified-repeat T-AKE 1 based ship design. Key aims were, again, to minimize the overall impact of the HCRSP to the existing ship design and to assess what benefits integrating the concept at the design stage could offer. Conclusions for this option include:

- Retaining the design of the proposed hull module for the retrofit option may still offer the lowest cost integration option. The cost vs. benefit of a range of design modifications should, however, be assessed in a modified-repeat design. These include options for a new custom design for a longer pod strut moving the current main shaft-line/skeg further forward to better accommodate the pod, adding a full width transom extension, the redesign of internal spaces to incorporate the pod's supporting electrical system, and options for segregating the main D-Gs into independent spaces.
- Additional power and speed could be achieved through the selection of the new up-rated (higher specific power) version of the currently specified diesel engine offering an 11% gain in power. The integration of 2 × 12-V D-Gs (replacing the 8-L units) is also a lower cost option in a new-build providing 22 knots sustained. This option has negative impacts on low speed efficiency and is poorly matched to low load operation.
- It is recommended that the electrical system be re-designed with matched pod and shaft VSDs to reduce potential harmonics issues, to allow improved integration of the pod system into the switchboards, to allow the use of a better optimized and smaller shaft-line motor system, and to be able to operate in a split-bus mode across the entire speed range.

In summary, designing a HCRSP system into a modified-repeat T-AKE 1 design would allow a better optimization of power generation and electrical systems. Higher powers and speeds can be achieved more cost effectively and harmonic issues can be overcome through the ability to operate across the speed range in a split-bus mode. Improvements to the physical integration of the pod will depend on the level of acceptable investment, ranging from adopting the proposed solution for the retrofit T-AKE 1 through to a new after body shape designed to optimize flow, pod protection, and clearances, but potentially requiring entirely new model tests.

HCRSP in future naval auxiliary designs

Integration of HCRSP into new designs offers the best opportunity to fully realize the system's advantages. The aft hull shape of the ship can be optimized for the pod and the D-G and electrical systems can be matched to the operational, power split, and low load requirements.

For a new 20-knot naval auxiliary design with similar power density to that of T-AKE 1, no significant additional integration risks were identified.

The HCRSP offers a range of build and design benefits when compared to a twin shaft-line arrangement typically required for a higher powered 24-knot ship design. The pod system can be fitted towards the end of a ship build resulting in greater flexibility with suppliers, a better cost profile, and the removal of a critical-path (shaft alignment) in the ship build plan. The mounting of the motors on the centerline is less constrained than in a twin shaft system where long shafts are required to minimize shaft inclination and to allow motor diameters to fit within the hull envelope. There will be an overall reduction in appendages and their associated drag and better overall hull design and resistance.

The potentially significantly higher installed power required for a 24-knot large naval auxiliary will require larger or additional D-G sets and machinery spaces. This is true irrespective of the selection of HCRSP or traditional shaft-lines. This could be mitigated by exchanging the 500 rpm D-Gs for 900 rpm D-G sets; however, this will increase fuel consumption and potentially require a larger number of individual D-Gs. It is also likely that at least one lower powered D-G unit will be needed to efficiently manage low load operation.

Recommendations

The following specific recommendations are made:

- It is recommended that trailing edge flaps on the pod be investigated as they may provide further efficiency gains by providing minor course correction without actuating the pod's primary steering gear and, hence, maintain good flow across the propellers.
- It is recommended that a detailed electrical assessment and design exercise be performed for any design considering HCRSP arrangement including an assessment of the potential harmonic issues.

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Abbreviations

ABS	American Bureau of Shipping
AC	Alternating Current
ARM	Availability, Reliability & Maintainability
CISD	Center for Innovation in Ship Design
CLF	Combat Logistics Force
DDS	Design Data Sheet
D-G	Diesel-Generator (set)
EAR	Expanded Area Ratio
ELA	Electrical Load Analysis
HCRSP	Hybrid Contra-Rotating Shaft-Pod
HV	High Voltage (>1,000 V AC)
LCG	Longitudinal Center of Gravity
LV	Low Voltage (<1,000 V AC)
MGO	Marine Gas Oil
MSC	Military Sealift Command
n	Rotational Speed
NAVSEA	Naval Sea Systems Command
NSWCCD	Naval Surface Warfare Center Carderock Division
OEM	Original Equipment Manufacture
P_d	Delivered Power
SAD	Still Air Drag
SFC	Specific Fuel Consumption
SWBD	Switchboard
THD	Total Harmonic Distortion
UNREP	Underway Replenishment
VCG	Vertical Center of Gravity
VSD	Variable Speed Drive
η_X	Efficiency (of x)

Tasking

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- *Mr. Peter S. Anderson* – VP business development *IMECO*, for support, data, and advice on the ABB pods
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1 Introduction & background

1.1 Introduction

Model scale testing and evaluation[1] of a Hybrid Contra-Rotating Shaft-Pod (HCRSP) concept on Military Sealift Command's (MSC's) T-AKE 1 design suggests a potential 7% reduction in the delivered power required, when compared to that of the current single shaft, single propeller system.

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The primary focus design for the study is MSC's T-AKE 1 class. It considers the impacts of retrofitting a HCRSP system into both a currently operational T-AKE 1 and a new build, modified-repeat design. Additionally the impacts of a HCRSP concept on future naval auxiliary ship designs are reviewed through consideration of both nominal 20 knot and 24-knot designs.

The proposed HCRSP concept replaces the rudder system on a single skeg ship design with an electric propulsion pod. The pod's pulling propeller is mounted directly behind a conventional shaft driven propeller, with each propeller rotating in opposite directions as illustrated in Figure 3. Potential benefits of the HCRSP arrangement include:

- Improved propulsive efficiency providing an opportunity to reduce fuel consumption and, hence, through-life costs and/ or provide higher ship speeds for the same installed power.
- Enhanced slow speed maneuverability with an azimuthing electric pod.
- Enhance redundancy, availability, and operational flexibility from the replacement of a single propulsor with two independently driven propulsors.
- The ability to integrate higher powers or speeds into a single skeg design, allowing larger vessels to retain the hydrodynamic benefits of a single skeg.

1.2 Ship concepts and aims

Four ship concepts are considered in this study:

1. **T-AKE 1 Retrofit –** a HCRSP retrofitted into a currently operational T-AKE 1. Aims are to minimize the overall impact to ship design, performance, and hence extent and cost of any conversion, and to assess options that can maximize overall

[1] 2011; NSWCCD-50-TR--2011/TBC; "Resistance and Powering Experiments with T-AKE Model 5665-1 and Hybrid Contra-Rotating Shaft-Pod Propulsors Phase 1 and Phase 2"; K. M. Forgach, M. J. Brown.

endurance and fuel consumption at 10-20 knots. The potential for a higher maximum sustained speed is also explored.

2. **T-AKE 1 modified-repeat –** a HCRSP system installed on a modified-repeat T-AKE 1 new build allowing greater optimization at the design stage. The aim is to still minimize changes to T-AKE 1 concept to minimize material and design costs but also to better optimize the HCRSP installation. Again, options for enhancements to endurance, fuel consumption, and speed are considered.
3. **New 20 knot naval auxiliary design –** The aim is to assess the impacts of integrating HCRSP into a completely new naval auxiliary design. It is assumed the 20 knot design illustrates the comparison of HCRSP systems with a single skeg design.
4. **New 24 knot naval auxiliary design –** This option is considered to allow the comparison of a single skeg, single pod HCRSP option with a traditional twin shaft-line system likely to be required to provided the required thrust and power for 24 knots.

1.3 Review of T-AKE 1 class

USNS *Lewis and Clark* (T-AKE 1), the class lead ship, is a Combat Logistics Force (CLF) Underway Replenishment (UNREP) vessel which replaces the *Kilauea* class (T-AE 26) ammunition ships and *Mars* class (T-AFS 1) combat stores ships. The class characteristics are summarized in Table 1.

Table 1: T-AKE 1 class key characteristics

Parameter	Value
Length ; Beam	689 feet (210 m) ; 106 feet (32.3 m)
Displacement	40,539 LT (41,188 mt) full load
Draft	29.9 feet (9.12 m)
Design speed	20 knots
Range	14,000 nm @ 20 knots
Max dry cargo volume	886,963 ft^3 (25,116 m^3)
Max cargo fuel volume	24,959 US barrels (3,968 m^3)

In its primary mission, the T-AKE 1 provides logistic lift to deliver cargo (ammunition, food, limited quantities of fuel, repair parts, ship store items, and expendable supplies and material) to U.S. and allied Navy ships at sea. In its secondary mission, the T-AKE 1 may operate in concert with a *Henry J. Kaiser* Class (T-AO 187) oiler as a substitute station ship to provide direct logistics support to the ships within a Carrier Battle Group [(2)].

The ship is designed and constructed to commercial specification, classed by the *American Bureau of Shipping (ABS)*, and built by *General Dynamics National Steel and Shipbuilding Company*. All fourteen T-AKE 1 ships will be operated by the U.S. Navy's Military Sealift Command (MSC) with T-AKE 14 due to be delivered late 2012.

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[2] 2010; http://www.msc.navy.mil/factsheet/t-ake.asp

Figure 1: USNS Lewis & Clark (T-AKE 1) (3)

The class has a single 6.5 m propeller powered by tandem (2 × 11.3 MW) synchronous electric propulsion motors driven by synchro-converter Variable Speed Drives (VSD). Electrical power is provided by 2 × *Fairbanks Morse* (*MAN*) 8.16 MW_e 8-L 48:60 and 2 × *Fairbanks Morse* (*MAN*) 9.18 MW_e 9-L 48:60 medium speed (500 rpm) Diesel Generator (D-G) sets into an High Voltage (HV – 6.6kV) integrated electrical system providing both ship-service and propulsion power. Figure 2 shows a graphical representation of the T-AKE 1 class's single line diagram, with the main generators and the matching electrical system[4].

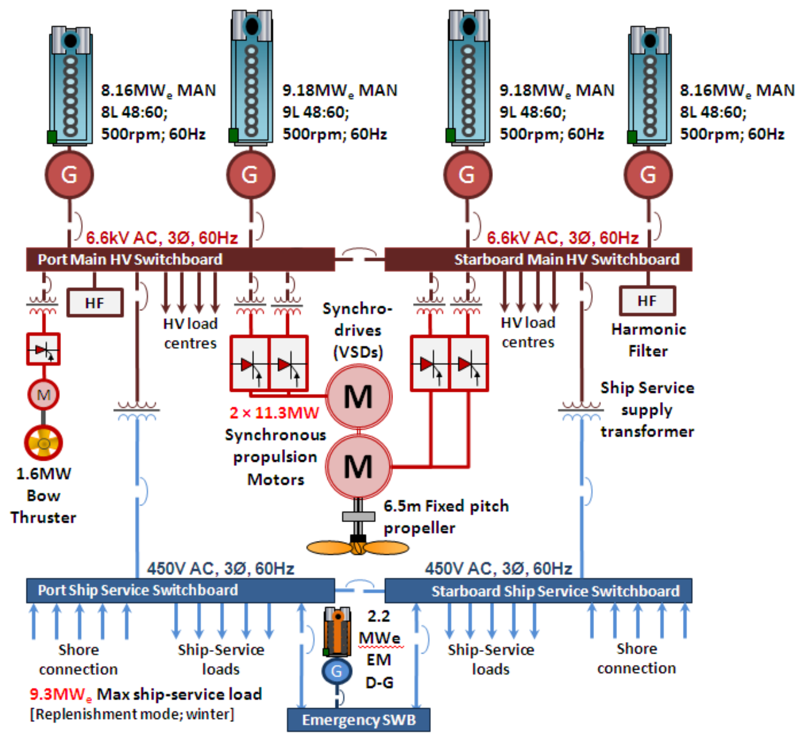

Figure 2: Graphical representation of T-AKE 1 class electrical system

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[3] 2010; http://www.msc.navy.mil/inventory/pics/lewisandclark.jpg

[4] Based on NAVSEA Drawing 320-7488777

1.4 Overview of HCRSP concept

The proposed HCRSP arrangement consists of an independent hull-mounted electric driven pod system with a pulling propeller. It is mounted directly behind a conventional shaft-line, with their respective propellers operating in close proximity but in opposite directions – i.e. providing a contra-rotating propeller arrangement. The pod provides approximately one third of the total power and the shaft the residual two thirds. The purposely designed propellers are designed to work together to improve overall propulsive efficiency. Key characteristics of the two propulsors are summarized below in Table 2 and illustrated in Figure 3.

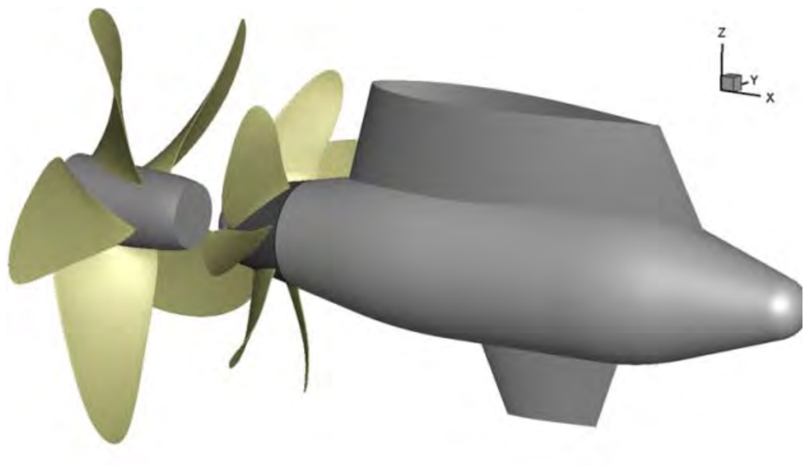

Figure 3: HCRSP arrangement – 3D view looking from aft port quarter

Table 2: HCRSP arrangement for T-AKE 1 – key features

Parameter	**Shaft-line (Forward propeller)**	**Pod (Aft propeller)**
Power split	69%	31%
Propeller diameter	6.92 m (22.7 feet) [6.5% larger than propeller on current T-AKE 1 class]	4.85 m (15.9 feet) [70% forward diameter]
Expanded Area Ratio (EAR)	0.494	0.422
Propeller speed ratio	-	95% of shaft's
Nominal propeller speed	87 rpm @ 20 knots	83 rpm @ 20 knots
Propeller type	Aft-facing; 5 blades	Forward-facing; 7 blades

1.5 System assumptions

The following assumptions have been used in this study.

1.5.1 T-AKE 1 propulsion powering

The hydrodynamic study this study supports has considered a range of different power, speed, and design relationships between the pod and main shaft. This study has based its conclusions on the following powering assumptions:

- A 'Mid' displacement of 33,912 mt (33,376 LT) is used as a baseline loading condition – this displacement is believed to represent a realistic normal maximum displacement of the T-AKE 1.
- All powers include still air drag, a 4% power margin, and are fully appended.
- For the baseline single shaft arrangement:
  - Propeller speed = 109 rpm @ 20 knots
- For the HCRSP arrangement:
  - Propeller speeds: Shaft = 87.3 rpm & pod = 83.2 rpm @ 20 knots (1.05 ratio)
  - Estimates of delivered power for the two arrangements are shown in Figure 4 based on the hydrodynamic study.

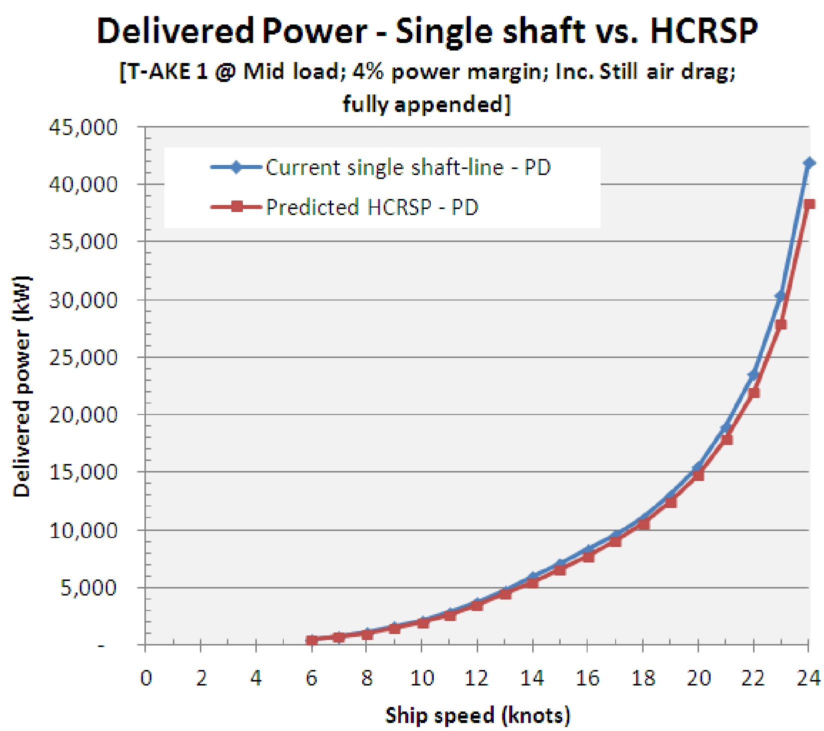

Figure 4: Delivered powers – T-AKE 1 with original shaft-line and HCRSP

1.5.2 T-AKE 1 ship-service powering and operating profile

The T-AKE 1 has a relatively high ship-service load compared to its propulsion power and, hence, this load can be a dominant load at low to moderate speeds with a corresponding influence on fuel and range calculations.

Ship-service loads and key operating point assumptions were derived from the T-AKE 1 Electrical Plant Load Analysis (EPLA)[5]. No detailed alternative operating profile was identified. These are summarized in Table 3.

[5] NAVSEA Drawing no. 310-748876 – 2001

Table 3: Key operating modes and associated ship-service loads

Mode	Low transit	Mid transit	UNREP	Max transit
Speed	**10**	**13**	**13**	**20**
Maximum ship-service load (kW_e)	7,700	7,700	**9,300**	7,800
	Assuming maximum electrical loads, winter conditions; no growth margin included			

1.5.3 Efficiency and margin assumptions

Fuel and performance calculations are based on the following efficiency and margin assumptions:

- Shaft mechanical efficiency on both the shaft-line and pod is assumed to 99%.
- Electrical system efficiencies are based on the T-AKE 1 EPLA[5]:
    - Efficiency assumed broadly constant across the speed range of interest – 13-20 knots. It will, in reality, drop slightly within this range and then significantly for powers below 20%.
    - Motor efficiency η_{Motor} = 96%
    - Motor drive efficiency η_{Drive} = 97%
    - Electrical transmission efficiency η_{Trans} = 99%
    - Switchboard efficiency η_{SWBD} = 99%
    - Net efficiency from generator to shaft = $\eta_{Motor} \times \eta_{Drive} \times \eta_{Trans} \times \eta_{SWBD}$ = 91.2%
- The new pod motors and drives are likely to have different efficiency characteristics to that of the older T-AKE 1 shaft-line system. This impact is not considered in the study.
- The losses within the generator are assumed to be included in the manufacturer's electric power output data.
- Powering predictions are based on standard NAVSEA margin policies:
    - For power system sizing purposes, a 20% growth margin is added to electrical loads;
    - For fuel calculations – DDS 200 margins are assumed;
    - For power system sizing, the maximum winter transit mode ship's service load is used (7,700 kW_e)[5]; for fuel consumption and range calculations, 75% of this load is assumed for the 24 hour average load;
    - For fuel calculations at the specific speeds of interest (10, 13, 20 knots), the ship-service loads shown in Table 3 are used.
- Ship-service loads were not altered to reflect additional pod electrical loads as the impact was considered unlikely to affect the load profile significantly. Section 4.5 discusses the implications of the change in electrical load due to HCRSP system.

1.5.4 System assumptions

Pod power, torque, rpm and dimensions are based on the use of the *ABB VO Azipod* family of electrically driven pulling podded propulsors.

Main diesel generator's Specific Fuel Consumption (SFC) variation with power, masses, and footprints are based on manufacturer's data (*Fairbanks-Morse*/ *MAN*) for the 48:60 ranges of diesel generators.

1.5.5 Operational assumptions

To assess the installation issues fully, it was necessary to make some operational assumptions. Based on discussions with ABB representatives and the expected operation of the HCRSP system, the operating modes shown in Table 4 are assumed.

Table 4: Assumed HCRSP operating modes

Operating mode	Shaft-line operation	Pod operation	Steering operation
Slow speed maneuvering	Off-line	Operating in conjunction with bow-thruster	Pod @ ± 90º
Slow speed reversing	Off-line	Electrical reverse with bi-directional propeller	Pod @ ± 90º
Confined waters; UNREP; & cruising	Operating		Pod @ ± 30-40º (i.e. like a rudder)
Emergency stop	Reverse with bi-directional propellers – i.e. electrically		Pod @ ± 30-40º
'Get you home' operation	Either shaft or pod motor operating alone		Pod @ ± 30-40º (Assuming steering available)

Key points to note include:

- Pod design is capable of 360º operations, but adequate maneuvering capability is considered available with a limited 180º operation if the pod is able to electrically reverse its propeller – this is also preferable for emergency stopping.
- The addition of a vertical flap on the after part of the pod's strut may offer adequate cruise speed maneuvering for course correction while allowing the propellers to remaining aligned – this could then offer additional fuel saving benefits & potentially additional steering redundancy.
- For electrical reversing, four quadrant motor drives are required to manage reverse torque during the transition from forward to reverse operation.
- It is assumed that adequate redundancy can be provided to the pod's steering system that allows the system to meet class rules and to operate when HV supply is lost to the pods motor. Class will require two redundant powered steering systems and potentially a manual actuating system. This is also highly desirable to reduce risk in its UNREP operating mode when ammunition transfers are untaken while underway.

2 System sizing

2.1 Pod sizing

For the T-AKE 1 based options, it was necessary to confirm the pod sizing.

Table 5 shows the original powering requirements for the current single propeller driven T-AKE 1. It also shows the delivered power predictions for the HCRSP arrangement and the corresponding required propulsion motor power.

Table 5: Predicted power for current T-AKE 1 system and HCRSP

	Original shaft-line		HCRSP				
	Shaft motors		Shaft motors		Pod motor		Total
Speed (knots)	Delivered power (kW)	Motor power (kW)	Delivered power (kW)	Motor power (kW)	Delivered power (kW)	Motor power (kW)	Motor power (kW)
20	**15,583**	**15,740**	**10,013**	**10,114**	**4,450**	**4,675**	**14,789**
21	18,974	19,165	12,123	12,245	5,344	5,614	17,859
22	23,581	23,819	14,940	15,091	6,523	6,852	21,943
23	30,400	30,707	19,127	19,320	8,239	8,655	27,976
24	41,945	42,369	26,348	26,614	11,164	11,728	38,342
Assuming: Mid-loading condition; 4% power margin; 1% shaft-line losses							

Electric motors are generally sized by torque, so the relationship between power and operating rpm is critical to sizing. The current maximum shaft power (2 × 11,262 kW) and torque of the tandem shaft motor allows it to contribute to speeds up to and including 23 knots without torque limitations.

To identify the matching pod size, the predicted powers in Table 5 were plotted against the maximum power-speed relationships shown on *ABB's* initial VO series pod sizing chart, shown in Figure 5. This allowed the assessment of suitable pod sizes for different maximum speed options.

Figure 6 shows the original *ABB* reference sizing chart from which the pod performance data was taken.

The following conclusions can be made:

- The shaft motors have sufficient power and torques to support speeds up to and including 23 knots.
- The *VO1800* size supports the current maximum sustained speed of 20 knots.
- 21-22 knots is probably achievable with *VO1800* following consultation with the OEM and/or minor changes to the pod's propeller speed (i.e. an increase in rpm).
- If higher ship speeds were required, a significant change in propeller speed, a change in the power split between the shaft and the pod, or the adoption of the *VO2100* size pod would be required.

For the consideration of integration issues on T-AKE, it is assumed that the *VO1800* pod is used, but comments are also provided on the potential impacts of a larger pod.

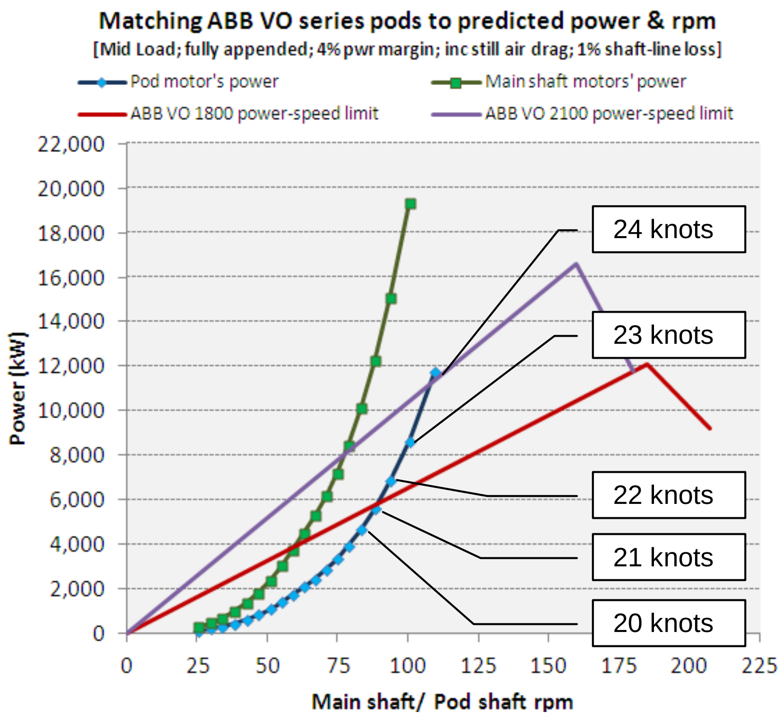

Figure 5: Matching pod power-rpm limits to predicted power

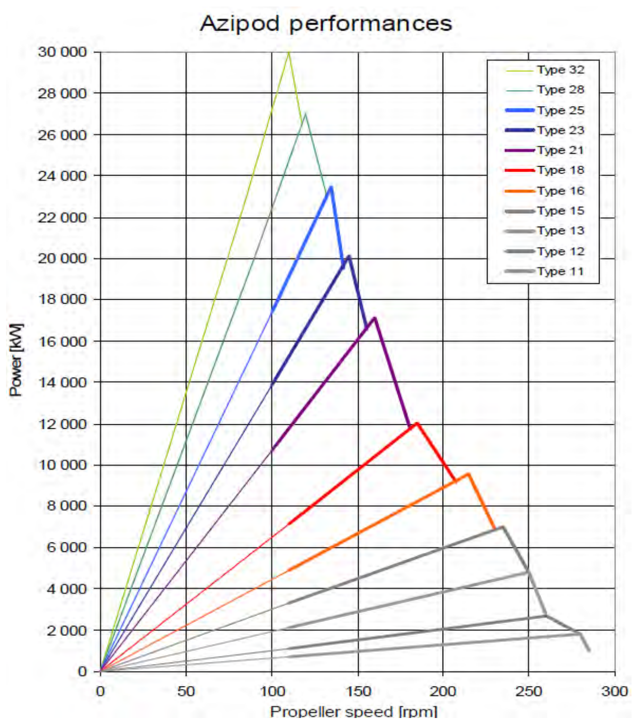

Figure 6: ABB VO series pod selection chart [(6)]

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[6] **2004 – ABB Oy, Finland**

2.2 Power generation sizing

Figure 7 shows the resultant electrical load demand from the D-Gs for speeds from 20-24 knots. This data is based upon standard NAVSEA power generation sizing sustained speed assumptions, the anticipated electrical system efficiencies, and a maximum winter ship-service load (UNREP @ 13 knots),.

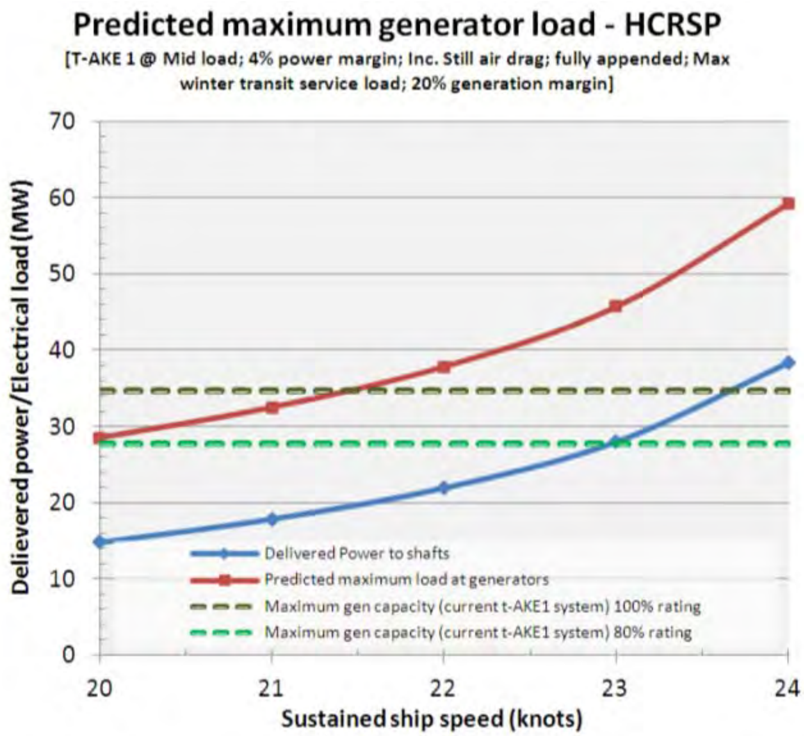


Figure 7: Electrical load and delivered power versus sustained speed

Figure 7 shows that the currently installed D-Gs should allow the HCRSP to achieve a sustained speed of 21 knots with the engines running at 94% of their maximum rated power. In realistic operational scenarios, 23^+ knots should be achievable if all of the generator load can be shared between the pod and shaft.

Higher speeds would require additional installed power. Two approaches are possible to increase overall installed power:

1. Add additional new D-G sets

Potential locations for additional D-Gs were considered, including within the currently defined machinery spaces, and within the superstructure or spaces created in transom extensions. In reviewing the general arrangements, no suitable locations were identified for additional D-Gs. It may be possible to mount additional compact high-speed D-G sets in new spaces created in the superstructure or in the transom extension potentially required for the pod installation, but these options would pose significant sub-system integration issues and only provide limited additional power. These more power dense D-Gs would also have a significantly higher SFC than the current medium speed D-G sets and, hence, negatively impact, or even negate, the efficiency benefit of the HCRSP system.

2. Replacing some or all of the current diesel generators.

The currently specified 500 rpm D-G sets have the advantage of providing very high efficiency and hence, low fuel consumption. These units are large, so that despite the ship being in excess of 41,000 tonnes, the main D-G sets are a tight fit within the main generator space. The D-Gs are also a size that would require removal of side-shell and significant dry-dock time to allow their removal or replacement in a retrofit.

If the option of replacing the current D-Gs is considered in a new-build, then two factors come into play. Firstly, the modern version of the 48:60 D-G set[7] has gained a 15% increase in power, moving to 1,200 kW per cylinder. Replacing the currently specified units with modern higher rated options should achieve a sustained speed of 22 knots. Secondly, the current general arrangements suggest it would be possible to replace the two eight cylinder (8-L) D-Gs with two twelve cylinder (12-V) D-G units. This assumes retention of other two nine cylinder (9-L) D-Gs. This has negative, but acceptable impacts on maintenance space and access, and would produce 45% more power within the same space allocation, equivalent to an additional eight cylinder D-G set. Combining these two options would allow a sustained speed of 23+ knots to be achieved.

Conclusions

- Based on the design implications of replacing main D-G sets and the lack of availability of space for an addition D-G unit it is recommended that any retrofit retains the current D-G system/ arrangement.
    - 21 knots sustained, 22-23 knots sprint is achievable at full load.
    - It may be possible to up-date the engines to benefit from the newer 1,200 kW cylinder rating through minor changes to the current engines and their control system (requires consultation with manufacturer).
- For new build options:
    - The 11% higher rating of the more modern version of the D-G designs can be integrated for minimal cost.
    - Replacing 2 × 8-L with 2 × 12-V D-Gs would allow speeds up to 22 knots sustained at full load conditions, but at a high cost, with negative impacts on access, and low speed, harbor, and at anchor operation.
- Required power nearly doubles between 21 and 24 knots – this clearly has significant implications on fuel consumption and range at these speeds.
- The above conclusions assume that the pod and shaft motor loads are shared between all connected D-Gs on a 'common-bus'. If a spilt-bus/ island mode[8] is required then these speeds will not necessarily be achieved – See Section 3.2

[7] http://www.fairbanksmorse.com; FM-MAN 48/60 D-G data

[8] Split-bus or island mode – a mode where the total load is split between two, or more, switchboards; i.e. only D-Gs connected to that switchboard will power the connected loads and any failure or fault on a single switchboard will not affect the other switchboards, their generators, or loads.

3 Electrical system integration

The hydrodynamic advantages of the HCRSP arrangement need to be considered against the impacts on the matching electrical system, and hence any corresponding impacts on system efficiency and operation.

Electrical issues that require consideration include:

a) Compatibility issues between the pod and shaft-line motors and their matching VSDs;

b) Potential impact of these compatibility issues of operating in UNREP mode, and the potential impact of the UNREP systems on the HCRSP system;

c) Pod electrical connection – how is the pod physically connected to the electrical system and what impact will it have on the existing shaft-motor connections;

d) The impact of designing for or, operating in, split-bus/ island mode – i.e. does the electrical system need to power the pod and shaft from independent power supplies, and if so ,what is the impact on engine fuel burn and running hours;

e) The changes needed to the electrical system scope of supply – what sub-systems, or components can be retained or need to be replaced.

These issues were discussed with representatives from both *ABB* and *Converteam* and the outputs are noted here[9].

3.1 Motors & variable speed drives – compatibility risks

The HCRSP concept demands that two independent propulsion systems (i.e. the pod and the shaft-line) are powered from a single common power generation system. Each of the propulsion systems has the potential to use different types of motor and matching VSDs. VSDs are required to convert the fixed frequency AC supplied via the main switchboards into the variable frequency AC required to power the motors across their speed range. Compatibility between these potentially different systems needs consideration.

Both pod and main shaft motors are synchronous designs and hence should have similar control, power, and torque characteristics. This allows them to be driven and to be controlled by similar VSD designs. The *ABB* pod is typically supplied with an *ABB ACS6000* series VSD which could be matched to T-AKE 1's current 6.6kV AC supply. This system is likely to be more modern in design than the older *Alstom* VSD design and when combined with the different loads (and hence electrical frequencies) seen at each motor, has the potential to generate undesirable harmonics when connected to a common-bus. The extents of this issue are hard to judge without detailed electrical system modeling, but this issue should be considered as significant risk that would need early analysis before a retrofit is considered.

[9] Original T-AKE electrical system was supplied by *Alstom* in France. *Converteam (CVT)* was formed from the *Alstom* marine systems group in the UK after the T-AKE contract.

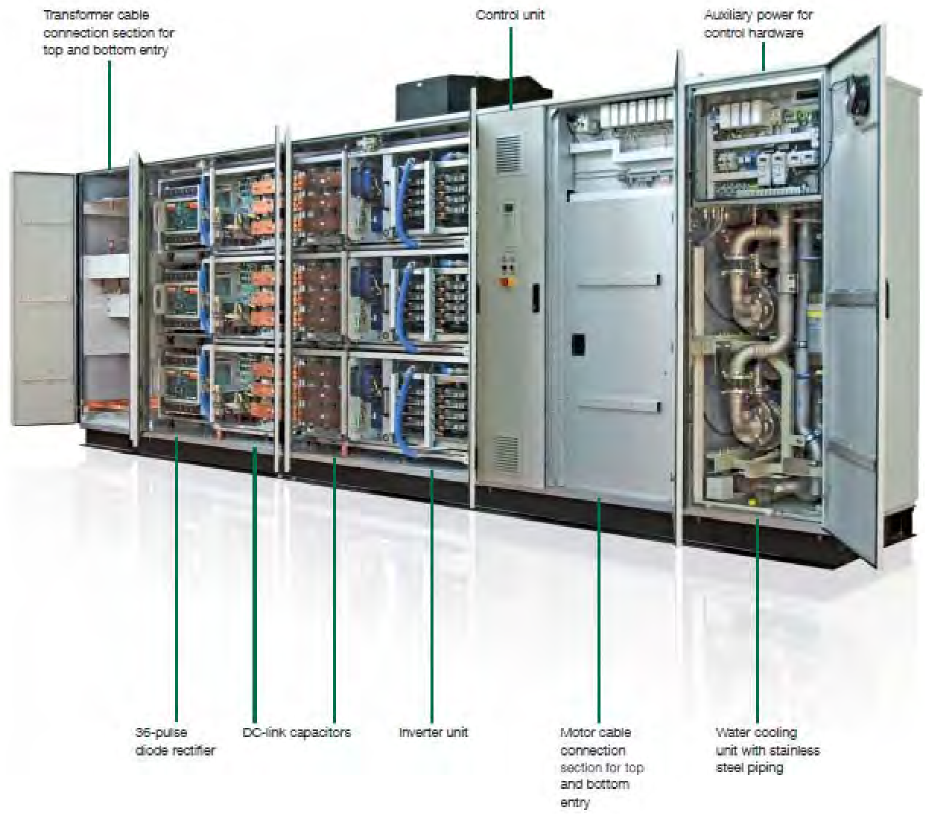


Figure 8: An example of an *ABB ACS series* VSD for Synchronous motors[10]

The harmonic issues may be amplified when operating in UNREP mode. UNREP systems generate large electrical loads (20% increase in ship-service load) and often significant transients. Future all-electric UNREP systems are likely to create significant electrical noise and harmonics on the system, which may further increase the risk of unfavorable harmonics. Mitigation could be provided by:

i. Changing the VSDs on the main shaft motors to match the new pod VSDs;

ii. Redesigning the electrical filter system to compensate;

iii. Operating the pod and shaft from different switchboards and hence separate D-G sets in a split bus/ island mode.

While the last option is also desirable from a redundancy perspective, the current power generation system cannot be easily split to meet the uneven loads generated by the HCRSP system. The implications of this operation on performance are considered in greater depth in Section 3.2.

Conclusions

- It is recommended that a more detailed electrical assessment be conducted if the retrofit is considered. This should look at the potential harmonics and protection

[10] 2009; Product brochure – Medium Voltage AC drive – ACS 5000, 1.5Mw-21MW, 6-6.9KV; *ABB*, Oy, Finland

issues associated with the selected HCRSP motors and VSDs. The impact of transient loads during UNREP operations should also be considered.

- Alternative VSD and protection systems should be considered, as well as operating modes for the electrical system. Impact on filter systems should also be addressed as Total Harmonic Distortion (THD) is likely to increase.
- In a new ship or modified design it is recommended that more optimally sized motors and VSD of a common architecture and type be used in both the pod and main shaft systems. It is also, again, recommended to conduct an early electrical analysis to consider the impacts of common-bus and split-bus/island operation.

3.2 Electrical connection options

The performance of the generation options discussed in Section 2.2 is predicated on the system being able to fully share the propulsion loads from the shaft and the pod motors across the whole of the power generation system; this is often described as common 'bus' operation. In a common-bus mode the two main HV switchboards (SWBD) are electrically connected, so that all connected D-Gs share the total electrical load. It is also common, however, to isolate the main switchboards from each other into what is often described as a split-bus or island mode. This provides higher levels of propulsion availability, redundancy, and allows quicker, more reliable recovery from faults. Equally a single fault is less likely to cause a totally 'black ship' where all power is lost.

The current T-AKE 1 system can operate in either a common-bus or split-bus mode and is configured with each of the shaft motors fed from a different main HV switchboard. The impact, therefore, of a single switchboard wide failure or fault is the loss of only 50% of the total propulsion power. This is shown diagrammatically in Figure 9 where the starboard switchboard and system is shown as unavailable (greyed out) and isolated from the starboard system. This system shows that designing an electrical system for both common-bus and split-island operation is relatively easy where two shafts share common motor and VSD technology and design, and where the power split between them is broadly equally, allowing easy splitting of generation power into each switchboard.

In a retrofit the pod with its single motor requires a new connection in the SWBDs. For maximum flexibility it is likely that the pod system would require the ability to be electrically connected to either of the main SWBDs. This connection method would allow spilt-bus operation of one of the two motors on the shaft-line from one SWBD and the pod motor from the other up to speeds of around 16 knots. Between 16 and 19 knots in split-bus operation, however, the second motor on the shaft-line will be required, resulting in the potential for a single SWBD level failure to result in the loss of both the pod and one shaft-line motor. This arrangement also results in different loads being supplied from each of the two main SWBDs. If the system is operated in a common-bus mode where both SWBDs are electrically connected and all connected generators share all the connected loads, the system runs the risk of a single failure leading to a total loss of propulsion power.

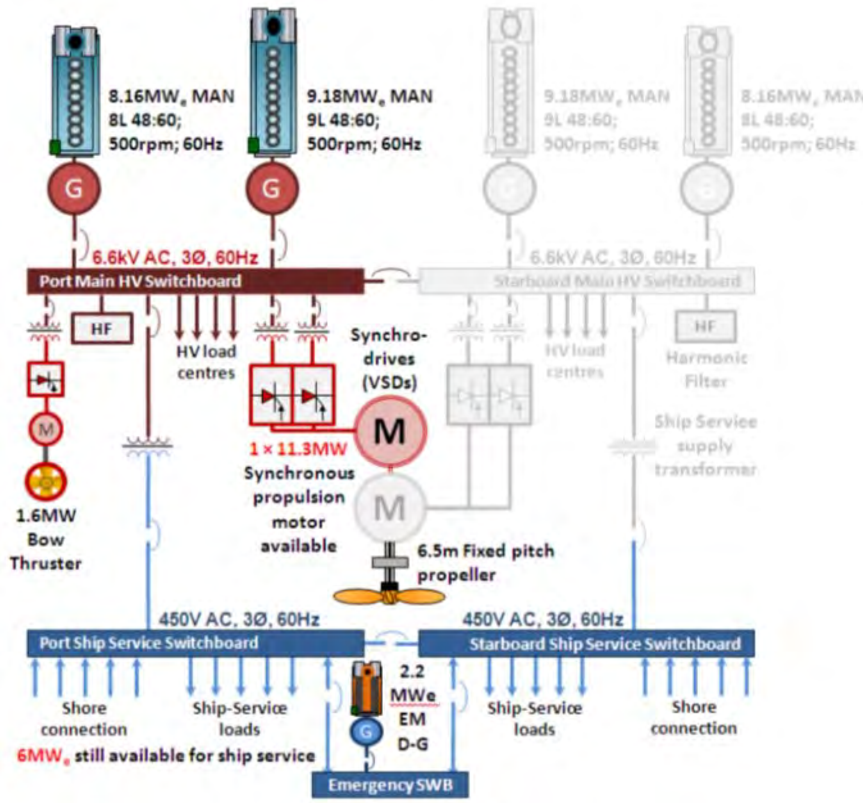


Figure 9: Current T-AKE 1 – impact of single switchboard level fault

Several connection methods are therefore possible:

1. Connect the pod via switching to both switchboards. This allows spit-bus operation up to about 19 knots, but requires common-bus operation for higher speeds. (Figure 10 – left)
2. Move shaft motor's connections to a single HV switchboard and connect the pod to the other. This will result in uneven power levels on each switchboard and hence one switchboard restricting maximum ship performance. Generators will also operate at different percentage loadings, with some running at high loads and some not seeing full load, and hence different maintenance profiles. This would require complete re-design of switchboards. (Figure 10 – right)
3. As in option 2, but in a new build allowing the use of a single new motor and VSD system. (Figure 11 – left)
4. Dual wound pod motors – some motor designs have two independent electrical windings to allow connection to two independent sources and hence provide similar redundancy to the current T-AKE 1 shaft-line motor system. In this way both the pod and shaft-line could be powered from both switchboards and any failure would result in only a 50% decrease in available power. This study has not considered the feasibility of this, but it may be prohibitive within the power density limits of a pod design.

While the uneven loading of the two switchboards due to propulsion loads could in theory be partially mitigated by redistributing ship-service loads, this is impractical as ship-service loads are generally also split evenly between the two ship-service switchboards to ensure system availability and redundancy. (Figure 11 – right)

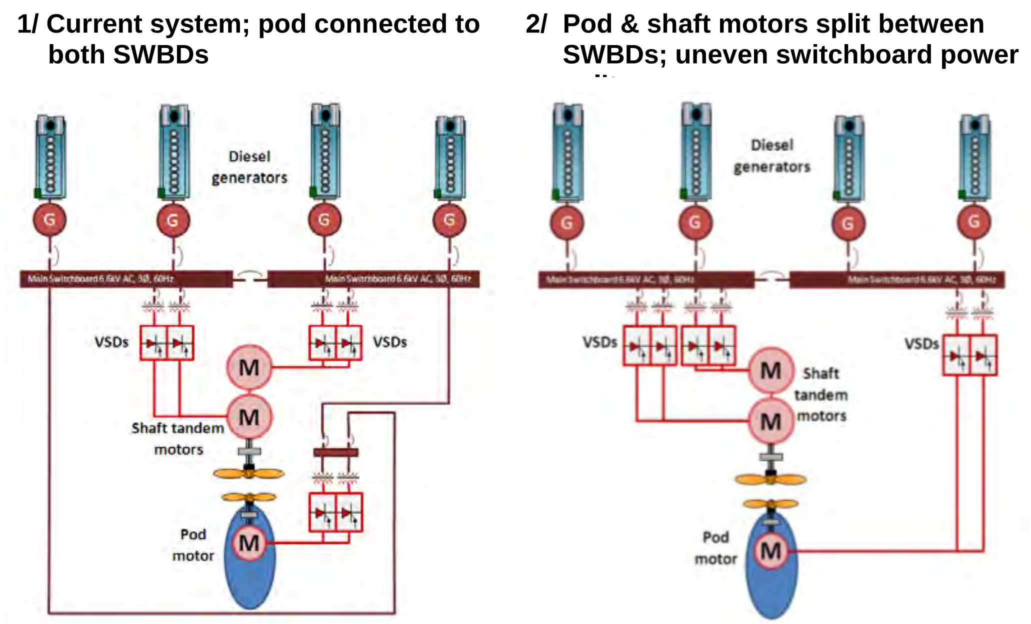


Figure 10: Electrical connection options – 1 (left) and 2 (right)

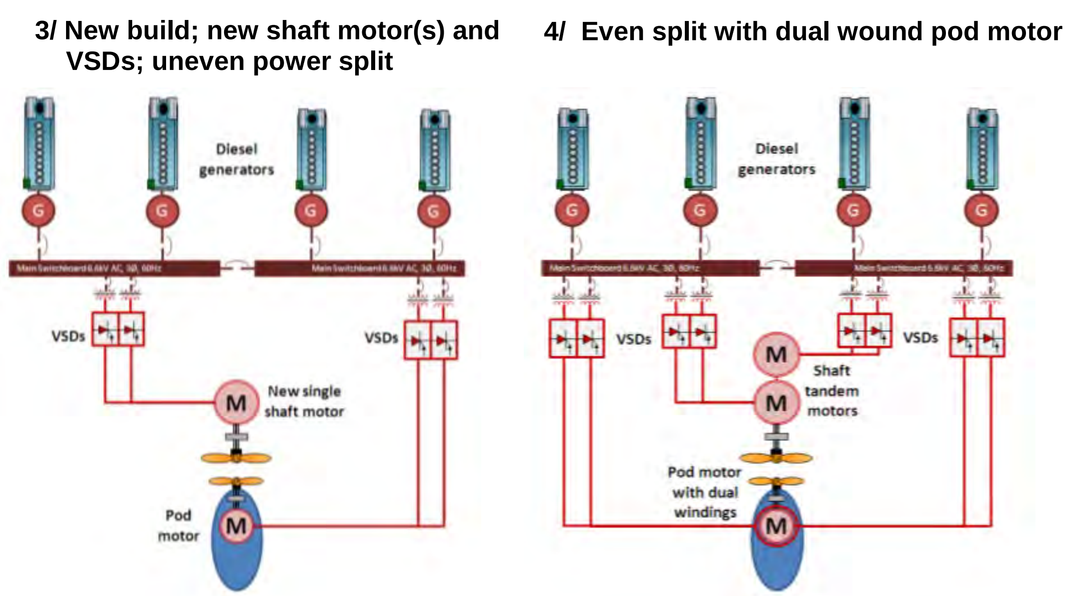


Figure 11: Electrical connection options – 3 (left) and 4 (right)

Conclusions

- For the retrofit connection option 1 is likely to be the most desirable if the compatibility options of common-bus operation can be addressed.

- For new build ships system option 2 is more desirable as this extends the speed range at which split-bus operation is possible and hence provides better high speed redundancy. Option 3 improves on this where it is possible to replace the current shaft-line tandem motor system with a single motor allowing better integration into a single switchboard, effectively mimicking (albeit with uneven load split) the current T-AKE 1 system.
- Option 4 is attractive from an electrical connection and power balance standpoint, but no dual wound pods are known to be available.
- The electrical connection for the pod's steering system should also be considered. The steering system is likely to require two low voltage (LV) electrical connections, one from each ship-service switchboards. This would provide adequate redundancy for class and safety regulations, and would allow direct connection to emergency generation system during a failure on the HV system.

3.3 Impact of split-bus operation on power generation

The HCRSP arrangement relies on an uneven power split between the shaft-line and the pod, and in a retrofit scenario, potentially dissimilar motor and VSD technologies. If suggested compatibility risks push the requirement for the pod and shaft motors to be fed from independent power systems (i.e. a split-bus arrangement), then several matching power systems can be considered. These options and their impact on maximum sustained speed are summarized in Table 6. The data assumes the pod is connected in as suggested by option 2 in the previous section (Figure 10 – right)

Table 6: Impact of operating with a split-bus

	HCRSP power system option			
Switchboard mode & load split	Common-bus n-a	Split-bus Even	Split-bus Un-even	Split-bus Un-even
D-G system	Current T-AKE 1 generating system	Current T-AKE 1 generating system	Current T-AKE 1 generating system	**NEW higher power D-G system**
D-Gs – Pod connected switchboard **[connected generator power]**	1 × 8-L 48:60 1 × 9-L 48:60 **[17.34MW$_e$]**	1 × 8-L 48:60 1 × 9-L 48:60 **[17.34MW$_e$]**	2 × 8-L 48:60 **[16.32MW$_e$]**	2 × 9-L 48:60 [New rating] **[21.60MW$_e$]**
D-Gs – Shaft connected switchboard **[connected generator power]**	1 × 8-L 48:60 1 × 9-L 48:60 **[17.34MW$_e$]**	1 × 8-L 48:60 1 × 9-L 48:60 **[17.34MW$_e$]**	2 × 9-L 48:60 **[18.36MW$_e$]**	2 × 12-V 48:60 [New rating] **[28.8MW$_e$]**
Service load split	Max winter UNREP mode load (9.3MW$_e$) split 50:50 between each SWBD			
Max sustained speed [D-Gs below 80% MCR]	19 knots	17 knots (limited by shaft switchboard)	18 knots (limited by shaft switchboard)	21 knots (limited by shaft switchboard)
Max sustained speed [D-Gs below 100% MCR]	21 knots	19 knots (limited by shaft switchboard)	20 knots (limited by shaft switchboard)	22 knots (limited by shaft switchboard)

Note: MCR – Maximum Continuous Rating

Note: Data in Table 6 is based on the NAVSEA power generation sizing margins for sustained speed, the anticipated electrical system efficiencies, and a maximum winter ship-service load, as noted in Section 1.5.2.

Split–bus operation will also result in the use of more generators at certain speeds and hence have a potentially negative impact on fuel consumption and engine running hours and hence their maintenance. These impacts are reviewed in Section 5.2.2.

Conclusions

- If Split-bus operation is required in a minimally changed electrical system, then the sustained speed will be reduced. In reality at normal operating powers and loads, it is still likely to achieve 20 knots.
- Achieving 20 knots (sustained) in split-bus mode will require changes to the shaft motor's connections to allow connection to a single SWBD, and re-design of the SWBDs to reflect the changes to connections, and their corresponding connected loads;
- In all split-bus options considered for a retrofit and a modified-repeat T-AKE 1, there would be excess generation power on the pod's switchboard;
- These issues further support the need for a more detailed assessment of the electrical system.

3.4 Electrical system scope – required changes

Section 2.2 suggested two potential viable D-G options in a retrofit or new build T-AKE 1; retention of the current D-G system, or the exchange of D-Gs for up-rated design or with a larger number of cylinders. These D-G set options would impact the overall extent of the electrical system as described in Table 7.

Table 7: Projected impacts of HCRSP concept on T-AKE 1 electrical system

Parameter	Added Pod Using current D-G sets	Added Pod Replaced some/all current D-Gs
Installed power	No change	Max 31% increase (replacing 2 × 8-L D-Gs with 12-V models (new ratings))
Shaft motors	No change – de-rated	Some de-rated (retrofit) New single motor (new build)
Shaft motor VSDs	Potentially retained – may be desirable to replace for a similar design/ technology to those used for the Pod in new builds (See Section 3.1)	
Pod VSDs	New added to system	
Main switchboards	Modified for new connections; New units if uneven load distribution in split-bus mode	New – but potentially in similar footprint/ volume
Transformers	Existing units retained Additional new units for pod drives	Mostly new – depending on power changes and VSD design

It is assumed that the shaft motors would be de-rated with software changes in a retrofit. Replacing the motors would incur high acquisition cost, and require significant dry-dock time. Synchronous motors have a fairly flat efficiency curve down to around 20% maximum power, however there may be a small reduction in efficiency at a given speed because of the need to de-rate the motors; this is likely to be in the 0.5 to 2% range. The current shaft motor VSDs will also experience a slight efficiency loss if retained. If the VSDs are replaced for compatibility reasons, it is logical to replace them with better matched (in terms of power) drives to regain maximum efficiency across the power range.

If a common-bus operation can be utilized at high speeds, then the switchboards need only be adapted for the additional outputs for the pod drives. If split-bus operation is required, or additional generation power is added to the system, this is likely to require entirely new switchboards to match the new powers, connections, and the unbalanced power split. These changes and those to the VSDs would also have corresponding impacts on the matching transformers.

Conclusions

- Adding additional generating power or the need to operate in split-bus mode at high speeds has the potential to require significant changes to the electrical distribution system. Retaining the current D-G arrangement, and hence power levels, limits the required changes, but this can only achieved if the previous discussed compatibility issues are addressed;
- Operating within the current maximum rating of key systems will also ensure limited impacts on the existing cabling system and hence reduced engineering and effort costs.

4 Physical integration

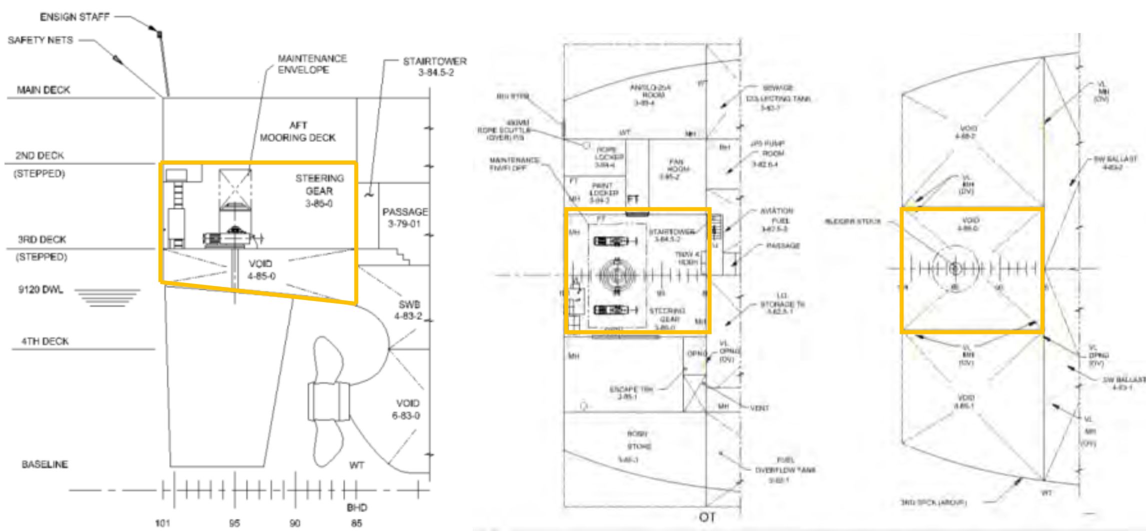
This section considers the physical integration issues associated with HCRSP on the four ship designs being considered. Impacts on the design and build process are also discussed.

4.1 Pod system installation – T-AKE 1 retrofit

The physical integration of the pod system as a retrofit on T-AKE 1 is the most challenging integration issue and is thus considered first. For a retrofit option it is desirable to minimize the physical changes to the ship design to reduce the design, build, and installation costs, and hence to maximize the potential through-life cost benefit of the potential fuel reduction.

The HCRSP concept shown here replaces the current steering gear and rudder system with an *ABB VO1800* pod. In addition the existing shaft-line has a larger replacement propeller (a 6% increase in diameter) – this increase in diameter is easily managed within the current hull design constraints.

The rudder and its associated machinery occupies a section of the ship spanning 8.5 m across the centerline beam-wise and extends from the transom to the next forward bulkhead on the 3rd deck. The space below the 3rd deck is void and consists of the rudder stock and its mounting structure. Figure 12 shows the current propulsion arrangement in profile and plan views with the impacted areas highlighted.



Profile View | 3rd deck plan view | Waterline plan view

Figure 12: Current propeller, shaft and rudder arrangement – T-AKE 1

Figure 13 shows the proposed new HCRSP arrangement based on the preferred separation between the two propellers and the *ABB VO1800* design, incorporating the longest standard strut design available from *ABB*. This highlights several key installation areas for focus; these are:

i. **Rudder effectiveness –** there is only a minor variation in effective area between the original rudder and the pod, and is considered unlikely to be an issue when combined with the vectored thrust from the pod.

ii. **Pod depth –** the maximum standard height of the pod strut is 4.35m; this is insufficient to reach the hull without an additional transition piece. Discussions with *ABB's* representatives suggest that a longer strut could be designed with updated steering system bearings to handle the additional lateral forces that this would incur; however for a retrofit the design this may be less desirable from a cost perspective than creating a simple new integrated hull transition piece.

iii. **Mounting structure –** The pod's steering axis position is 2.4m behind the original rudders. This will require totally new mounting positions and supporting structure. The higher weight of the pod is also mounted nearer the transom. This drives the need for additional structure aft of the current transom.

iv. **Propeller and pod protection –** Typically it is preferable to have the pod and propeller operating within the projected plan view of the ship's hull. This is done to allow operation of ship in close proximity to docks, other ships, and tugs. Several options were considered:

   a. Pushing the whole transom aft to the maximum extents of the pod length – this would be a costly in terms of added structure; would create additional un-required volume, and is likely to require a reassessment with class of issues such as intact stability and global bending moments.

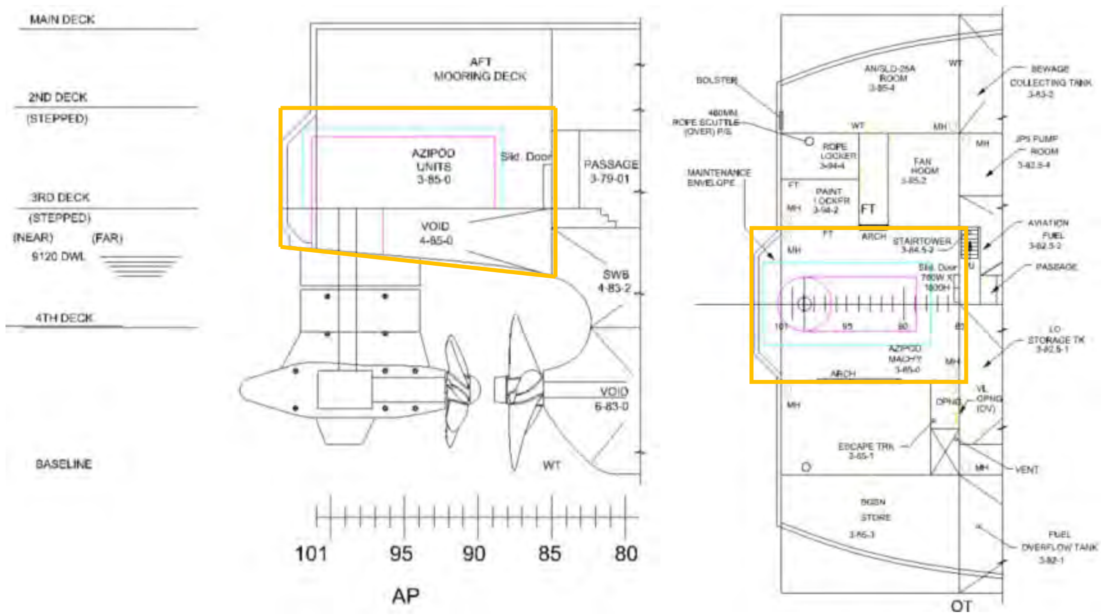
   b. A more localized transom 'bump' that encloses the maximum extent of the whole pod and the propeller when operating to ±90°.

   c. A more localized transom 'bump' that only encloses the extents of the pod's strut and the propeller when operating at ±90°. This leaves the aft section of the pod's main body protruding from the hull when the pod is facing forward. This could be mitigated with additional tubular style 'propeller guard' structures behind the ship.

Conclusions

- Based on these design issues, it is proposed that the installation of the HCRSP concept as a retrofit would take the form of a new modular section to occupy the space highlighted in Figure 13;
- This single structural module could include the volume and structure required to house the new pod supporting structure, the 1.46m transom extension, the new hull to pod transition piece, and the pod steering gear;
- By designing the new section as a single module, better transition of structural loads into the existing structure could be achieved.
- Some external shaping is also suggested to reduce potential impact of additional transom slamming, ease structural maintenance, and to aid issues such as rope handling.

- The module could be constructed and tested separately from the ship, minimizing the time in dry dock, and hence installation costs.
- Installation of a larger pod size (i.e. *VO 2100*) is also possible, with the pod's stock still forward of the current transom perpendicular, but will be longer requiring more substantial structural changes and a larger transom extension.



Profile View 3rd Deck Plan View

Figure 13: Proposed retrofit installation – T-AKE 1

4.2 Pod system installation – modified & new designs

For a modified-repeat T-AKE 1 with a HCRSP system, it may be desirable from a cost perspective to purely implement the design changes suggested for the retrofit. For a new ship design or re-designed modified-repeat T-AKE 1 a range of additional options should also be considered. These include:

- Supply of the pods with a longer strut, better matched to the hull design & depth – This could provide greater steering moment, but probably has a limited cost to benefit ratio unless included in a longer ship production run.
- Move the main shaft-line forward in the design – this would allow the pod to fit within the current T-AKE 1 hull definition, but would incur significant re-deign, potentially re-classification, and may have negative impacts on overall hydrodynamic performance. This option is however essential in any totally new design and probably essential if a larger pod is required on a T-AKE 1 hull-form.
- On a modified-repeat T-AKE 1, add a transom extension across the full width and height of the transom – but this will incur fabrication and re-design costs but to a lesser degree than on a retrofit. It would produce a cleaner design and reduce

some of the operational restrictions at the transom – e.g. tugs could push the transom directly.

The above features are easier to incorporate in a new naval auxiliary ship design, especially within a given length constraint. For the 20-knot new design option, no significant additional physical pod installation issues would be expected.

The physical integration of HCRSP pod system on a future high power (24-knot) naval auxiliary is unlikely to be challenging if incorporated early in the design. This option would also offer a number of build benefits to the ship when compared to a twin shaft-line arrangement, including:

- The removal of the shaft-line installation and alignment process which should save significant engineering effort and cost during the build process.
- The removal for the need for fabrication of shaft-line appendages.
- The potential to fit the pod system towards the end of the build, and even when the ship is in the water. This would allow later delivery of the pod, resulting in greater flexibility with suppliers, a better cost profile, and the removal of a critical-path in the ship building plan.
- The installation benefits of a short skeg mounted shaft-line with zero-rake and zero-inclination. The mounting of the motors on the centre-line is also less constrained than in a twin shaft system where long shafts are often required to minimize shaft inclination and to allow motor diameters to fit within the hull envelope.

4.3 Power generation & electrical system – T-AKE 1 options

D-G set options and potential changes to the electrical system are discussed in Sections 2.2 & 3.4 respectively. These options need to be considered in a retrofit and a modified-repeat T-AKE 1 against the physical constraints set by the current design.

Two main issues need to be addressed: the maximum installable D-G power, and the location of the additional VSDs and matching transformers for the pod's motor.

As discussed in Section 2.2 the current D-Gs are a size that would require significant effort and cost to replace in retrofit design. No suitable locations were identified for additional generator sets. If the option of replacing the current generator sets is considered in a new-build, then the current general arrangements suggest it would be possible to replace the two 8-L D-Gs with two 12-V D-G units, if the other two 9-L units are retained. This arrangement is shown in Figure 14 with the geometrical extents of the 12-V D-Gs shown as a red box over the location of the current outer 8-L D-Gs.

The pods require dedicated new VSDs and transformers. The currently defined main HV electrical space that contains the shaft VSDs, the main HV transformers, and main switchboards, has no additional free space. In a retrofit it would be necessary to re-allocate a space for the additional systems. Initial sizing of matching *ABB ACS* series VSDs and transformers suggests that the space to the starboard of the proposed pod steering room could be suitable. This space would need to be designated a HV space and hence require physical separation from some surrounding systems, new fire-fighting systems, and the electrical protection the designation entails. This space, although perhaps not ideal in size and location (near lube oil and aviation fuel tanks) has the advantage of being close to the pod minimizing the need for long runs of multi-phase HV cabling. Notionally the route for the HV supply cables to the VSDs from the main switchboards would either be along the 3rd deck passageway or above the 3rd deck through some of the cargo areas.

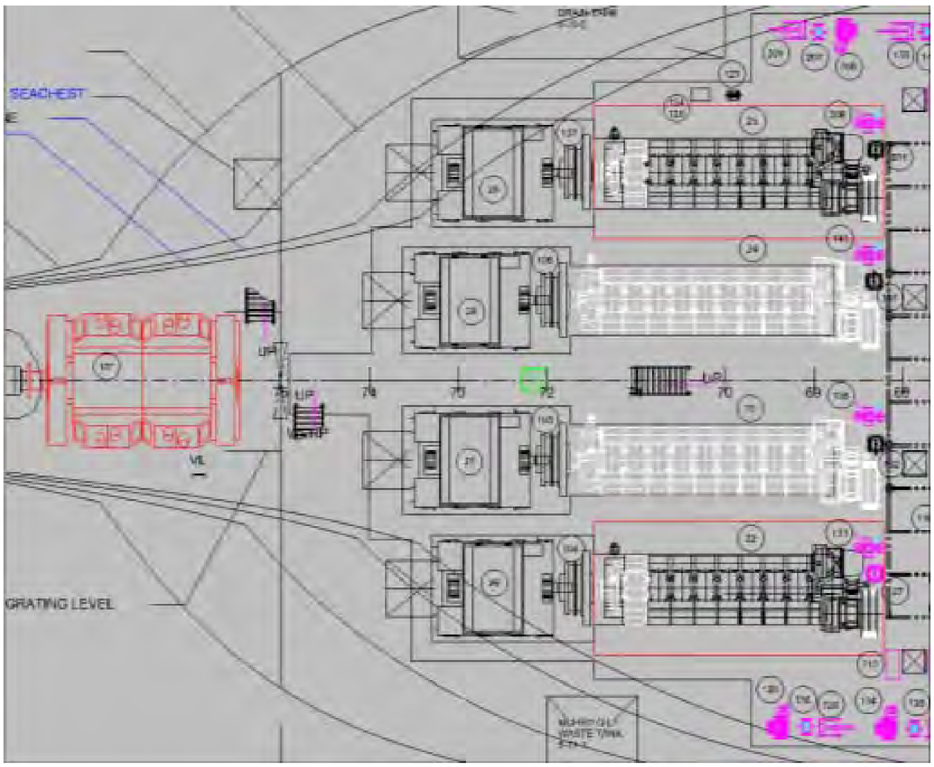


Figure 14: Impact of exchanging 8-L D-Gs for 12-V D-Gs in new build T-AKE 1

In a modified-repeat T-AKE 1, spaces could be re-designed to allow a more logical mounting of the pod's VSDs and hence potentially improving issues such as survivability, and cable run complexity. Possible usable locations on a modified-repeat T-AKE 1 include:

- Current spaces around shaft motors – housing shaft motor VSDs and releasing space in main HV electrical spaces for the pod VSDs.
- Redesigned 3rd deck spaces and tanks around the transom modified to house a new dedicated HV space.

4.4 Power generation & electrical systems – New designs

For a 20-knot new ship design, no significant physical installation challenges are expected for either the D-G sets or electrical system; however, the overall machinery system volume and footprint are likely to be higher for the HCRSP system than for a single shaft system because of the additional electrical system components required.

The significantly higher installed power potentially required for a future 24-knot large naval auxiliary will require larger/ additional, machinery spaces to mount the larger/ additional, matching D-G sets. This is true irrespective of the selection of HCRSP or traditional shaft-lines. This could be mitigated by exchanging the 500 rpm units for 900 rpm class D-G sets; however this will negatively impact fuel consumption and potentially require a larger number of installed D-Gs. It is also likely that at least one additional lower powered D-G unit will be needed to efficiently manage low-load operating modes.

4.5 Impact on auxiliary electrical loads

The new pod system requires a range of addition auxiliary electrical loads. These loads will reduce the overall efficiency benefits of the HCRSP system at any given speed.

Table 8: Electrical load impact of HCRSP system

System/ parameter	Current T-AKE 1	Net changes in a Retrofit HCRSP T-AKE
Rudder system	50 kW_e	– 50kW_e
Pod systems	-	+ 104 kW_e [Cooling system] +215 kW_e [Hydraulics]
VSD loads [fans, exciters etc]	270 kW_e	+ 81 kW_e [scaled on power change]
Motor exciters	~ 500 kW_e [tandem motors]	+ 100 kW_e [Similar power, but 3rd motor (exciter) - 20% uplift assumed]
Total additional load [maximum – compared to current T-AKE 1]		**+ 450kW_e**
Percentage of maximum ship's electrical load at 20 knots [winter; max cruise electric load]		~ + 2.5%
Impact on fuel burn of additional load [HCRSP system with common-bus connection; winter UNREP mode; & T-AKE 1 D-Gs]		~ + 62 kg/h (+1.5% of total)

These loads are maximum loads, so are in reality likely to be smaller during the majority of operation. VSD load changes attempt to reflect the likely drop in load on the existing shaft motor VSDs, but may still be an overestimate. Overall there is likely to be less than 1% impact on fuel consumption at nominal loads. Electrical power savings can probably be achieved in a new build if a dedicated new shaft motor and VSD are installed; this should bring the overall electrical load change down to a minimal level.

4.6 Impact on weights

An initial estimate was made for the impact of retrofitting an *ABB VO1800* based system onto the T-AKE 1[11]. A summary of this weight analysis is presented in Table 9.

[11] 2011; NAVSEA Drawing no. 833-8194532; T-AKE 11 weight report

The most significant impacts are within the propulsion plant (the pod, its system, and new propellers), and electrical system (new VSDs, transformers and cabling for the pods). Structure weight also rises by about 0.8% reflecting the need for the transom extension, the pod transition piece, and additional strengthening (foundations) for the heavier pod system. The overall weight impact is unlikely to be a significant risk.

It was not possible to accurately assess the impact of the weight changes on the locations of the center of gravity; however, using the change in moments from mid-ships and assuming each changed weights are point masses, a rough estimate for the impact on overall sinkage and trim was made. This yielded an insignificant change in overall sinkage and an approximate -1.5% trim change to the bow. Under current full load conditions the T-AKE 1 already has a bow-up trim, meaning implementation of the HCRSP concept will cause further trim instability which will is likely to increase further in lighter load conditions. The risk associated with trim would need further investigation.

Table 9: Estimated weight impact on T-AKE 1 of a retrofit HCRSP system

		Current T-AKE 7	Retrofit T-AKE (same D-GS; minimal change)			
		Weights [tonnes]	New weight [tonnes] / Variation [tonnes ; %]			Justification [affected SWBS groups]
SWBS	Total lightship	25,559.54	25,996.53	436.99	1.7%	
100	Structures	15,709.38	15,832.46	123.08	0.8%	Changes to structure due to transom extension & heavier (than the existing rudder) pod foundations [SWBS 110, 120, 130, 182]
200	Propulsion plant	1,398.42	1,643.30	244.88	17.5%	Changes to include pod & its systems, & new propellers [SWBS 236, 245, 298]
300	Electrical plant	1,019.56	1,112.04	92.48	9.1%	Changes to include new drives, transformers, and cabling [SWBS 314, 321, 324]
400	Command & surveillance	247.95	247.95	-	0.0%	No Changes due to HCRSP
500	Auxiliary systems	3,686.47	3,661.68	(24.79)	-0.7%	Trivial changes to upgrade auxiliaries for pod systems, and trivial internal volume [SWBs 510, 522, 536, 561, 562, 598]
600	Outfit & furnishings	2,217.01	2,218.35	1.34	0.1%	Trivial changes due to new transom section - coatings & fittings [SWBs 611, 621, 624, 631]
700	Armament	1,280.75	1,280.75	-	0.0%	No Changes due to HCRSP

If additional or larger D-G sets are considered in a modified-repeat T-AKE 1 this has the potential to add significant further weight in both the main machinery space, but also in the auxiliary main electrical spaces. Again these impacts would need consideration with respect to trim and foundation structure.

A new-build design could be better optimized at the design stage to better manage the structural and trim implications of a heavier pod system, and hence these issues are unlikely to be a significant risk.

5 Performance impacts

This section considers the impact of HCRSP on ship's speed, fuel consumption, and range, and compares the results to the predicted performance of the current T-AKE 1 system. Impact to D-G maintenance is also considered, as is the performance impact of split-bus operation compared to that resulting from common-bus operation.

Figure 15 shows the predicted propulsive efficiencies for both the current single shaft-line T-AKE 1 and the proposed HCRSP arrangement. This shows a clear efficiency advantage for the HCRSP system across the T-AKE 1's speed range.

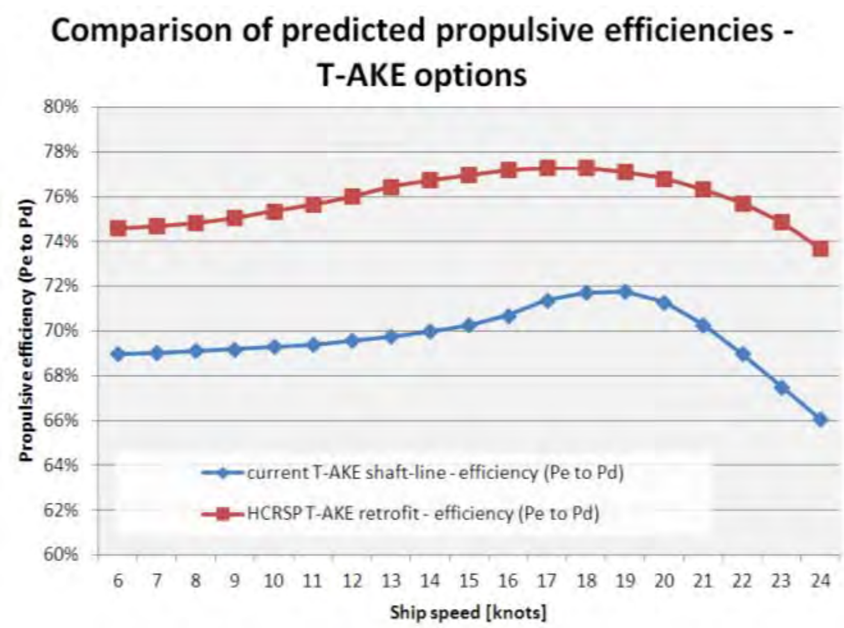


Figure 15: Predicted propulsive efficiencies – shaft and HCRSP options

For this efficiency advantage to be translated into higher speeds or fuel savings, the impact of this reduction in propulsion load on the matching electrical and D-G system needs to be considered. This change in overall system loading will result in a change in:

- The efficiency of each of the electrical system components, principally in the propulsion motors and the VSDs;
- The Specific Fuel Consumption (SFC) of the main D-Gs;
- The number or type of D-Gs operating in a specific mode – e.g. the same speed may be achievable operating a smaller 8-L D-G rather than a 9-L D-G.
    - This impacts SFC, but also D-G running hours and hence maintenance.

As discussed in previous sections, there is an impact on performance associated with the need, or desire, to operate a system in split-bus/ island modes.

These issues are important to assess early on, as any negative efficiency changes in the diesel or electrical systems have the potential to reduce or even negate the propulsive efficiency advantage of the HCRSP arrangement.

5.1 Maximum speed – T-AKE 1 options

Predicted speeds for the various D-G and electrical connection options are highlighted in previous sections - See Table 6 in Section 3.2

5.2 Fuel consumption and engine loading – T-AKE 1 options

The fuel consumption of any system depends on the efficiency characteristics of all of the power and propulsion system components. While a hydrodynamic efficiency benefit of HCRSP is clear, its implementation will also impact the efficiencies of the other components within the power system due to change in load seen at each component. Consideration of fuel consumption and endurance highlights these issues.

Fuel consumption calculations in this section are based on DDS 200-1 methodology, assumptions, and margins and the loading and ship-service load assumptions described in Section 1.5. Fuel consumption trends are considered across the speed range and in detail at the key operating modes identified in Section 1.5.2.

Constant electrical system efficiency across the speed range for both the current and the new system is assumed. This efficiency encompasses the propulsion motors, VSD, transmission, transformer, and switchboard losses. In reality, electrical system efficiency will slowly degrade at lower powers dropping a few percent between 100% and 20% maximum power and then rapidly below 20%. Although this effect is small in the power range of interest (10-20 knots), it will result in higher fuel consumption than shown with greatest percentage effect experienced at the lowest speeds.

Manufacture's data was used for the SFC trends of the *Fairbanks Morse* (*MAN*) 48:60 medium speed (500 rpm) diesel generators. This trend is shown in Figure 16 along with a smoothed approximation trend line used for fuel calculations.

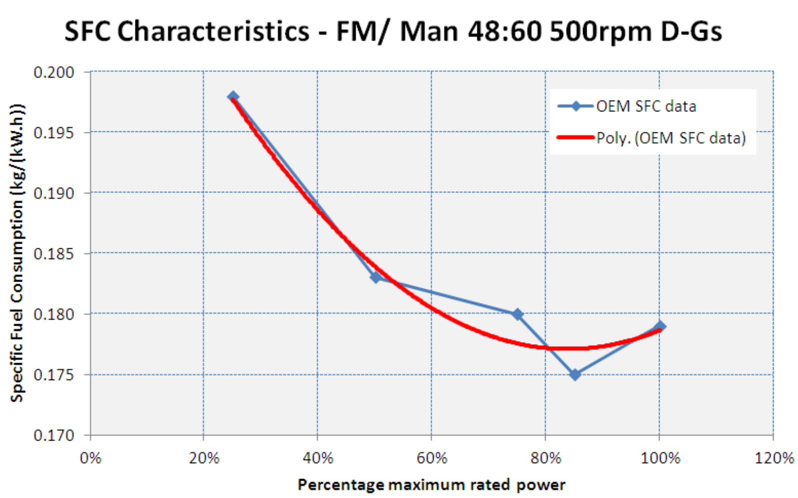


Figure 16: SFC characteristic of 48:60 D-G sets

Figure 16 shows that the SFC varies 3-4% between 40 and 100% maximum rated power and has an optimal point at around 80-85% power, reflecting the typical operating design point in many commercial ships. Fuel modeling has, therefore, attempted to select the engine combination at each speed that allows the engines to operate as near as possible to this optimum engine loading.

5.2.1 Common-bus connection

Initial fuel consumption calculations assumed that the HCRSP is operated on a common-bus generation arrangement. This allows all the generators to operate at equal loading and for the potential to achieve low powers with single-generator operation. The HCRSP system was compared to the current system in common-bus and the split-bus modes, with split-bus operation forcing two-generator operation up to 12 knots.

Figure 17 shows the range achievable at each speed per tonne of fuel assuming a typical 'cruise' mode ship-service load of 7,700 kW_e. Figure 18 shows the same data as a required fuel load for the current target range of 14,000 nm.

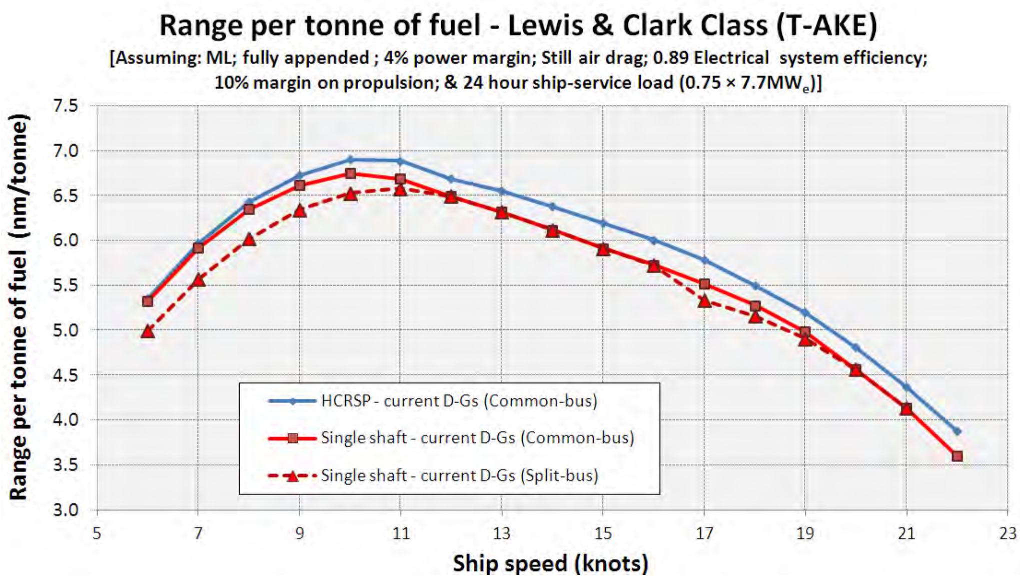


Figure 17: Range per tonne of fuel – T-AKE 1 shaft and HCRSP options

The plots show that there is the potential to reduce fuel consumption across the speed range resulting in lower fuel burn through life and potentially enhanced range for the same fuel load. The impact of running two, rather than one, generators in the speed range up to 12 knots and 4 rather than 3 between 17-19 knots is also notable.

Overall engine loading was lower at all speeds but it was only possible to reduce the total number of engines running at 19 and 20 knots which. This causes a slight reduction in fuel consumptions, but would allow a HCRSP fitted T-AKE 1 to reduce overall engine operating hours through life and, hence, extend time between D-G overhauls.

Based on the current USN fuel cost assumptions for F76 of $175 per barrel ($1,305 per mt), this equates to a cost saving at 20 knots of around $219,000 for a single transit equivalent to the current specified range of 14,000 nm.

Based on the current commercial price of Marine Gas Oil (MGO)[12] of $997 per mt, the cost saving at 20 knots for 14,000 nm would be around $173,000.

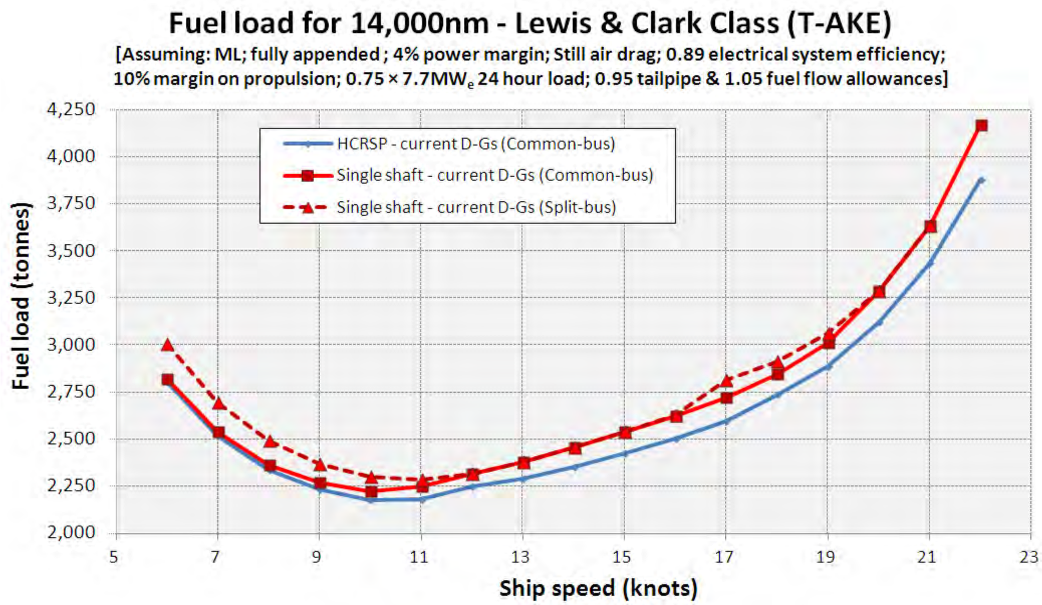


Figure 18: Fuel load for 14,000 nm – T-AKE 1 shaft and HCRSP options

Table 10 shows the power, fuel consumption, and engine operating data for the specific main operating modes.

Table 10: Fuel consumption and D-G loads (Common-bus)

Mode		Low transit	Mid transit	UNREP	Max transit
Speed [sustained] (knots)		**10**	**13**	**13**	**20**
Electrical connection		**Common-bus**			
Propulsion load (kW_e)	HCRSP	2,392	5,323		17,663
	Single shaft	2,569	5,765		18,799
Ship-service load (kW_e)		7,700	7,700	**9,300**	7,800
Load reduction , HCRSP (kW_e)		**-177**	**-442**		**-1,136**
Fuel reduction with HCRSP	Fuel rate (mt/hr)	-0.03	-0.07	-0.08	-0.22
		-2.2%	**3.6%**	**-3.3%**	**-5.1%**
	Fuel load for 14,000 nm (mt)	-49	-85	-87	-168
D-Gs on-line (% loading)	HCRSP	1 × 9-L (89%)	2 × 8-L (68%)	2 × 8-L (75%)	1 × 8-L & 2×9-L (88%)
	Single shaft	1 × 9-L (91%)	2 × 8-L (71%)	2 × 8-L (78%)	2 × 8-L & 2×9-L (71%)

[12] www.bunkerworld.com – MGO delivered at Houston (October 4th 2011)

5.2.2 Split-bus connection

As discussed in Section 3, electrical compatibility and redundancy issues may drive the need to operate a HCRSP system in a split bus arrangement. This may also be operationally necessary, for example, when operating in confined waters or in close proximity to other vessels during UNREP operations.

The most significant impact of split-bus operation on the HCRSP system will be in the need to operate more D-G sets at low speeds. As shown by Figure 17 and Figure 18 in the previous section, this impact also affects the current single shaft-line system. At some specific higher speeds, the uneven load split between the shaft and pod propulsion motors will also result in a need for additional operating D-Gs. The uneven load split will also result in the D-Gs on each switchboard operating at different load factors and, hence, not necessarily at the optimal SFCs.

Some re-balancing of the significant ship-service loads could help to reduce the differences seen at the switchboards, but system redundancy and availability requirements are likely to limit the amount of re-balancing possible. For the fuel modeling discussed in this section, it is, therefore, assumed that ship-service loads are equally split between the two switchboards representing a worst case scenario.

The impact of split-bus operation on the fuel consumption per hour, for the HCRSP D-G options outlined in Section 3.3 (Table 6) is shown in Figure 19. As the real variation is small and hard to decipher, the percentage change in fuel consumption of each option compared to the current baseline system (single shaft with a common-bus connection) is shown in Figure 20.

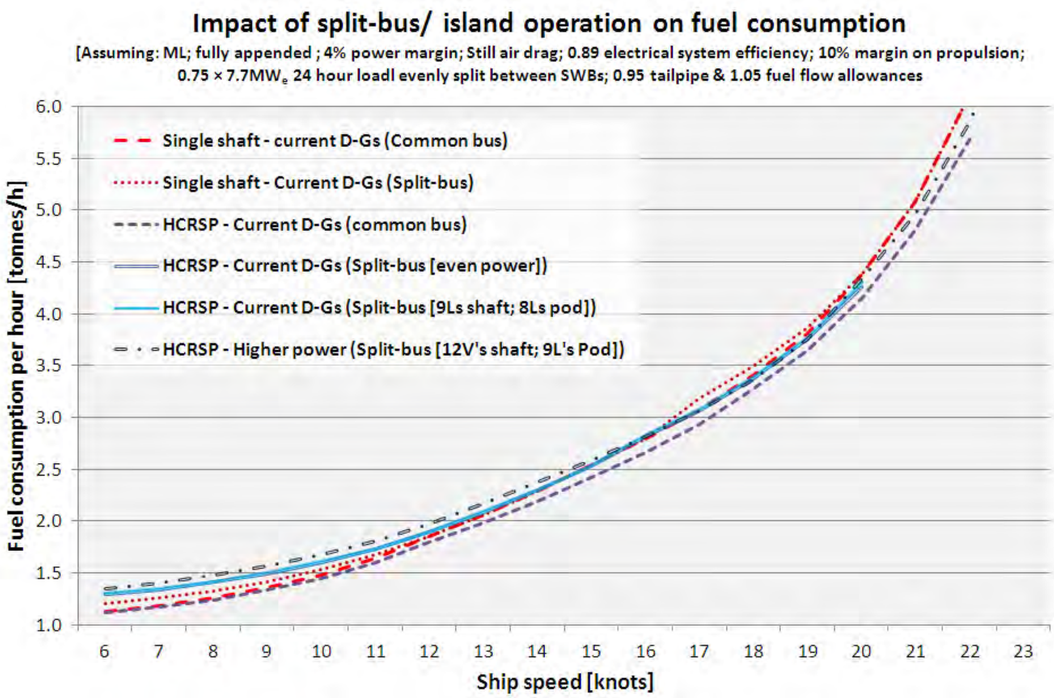


Figure 19: Impact of split-bus operation on fuel consumption rate

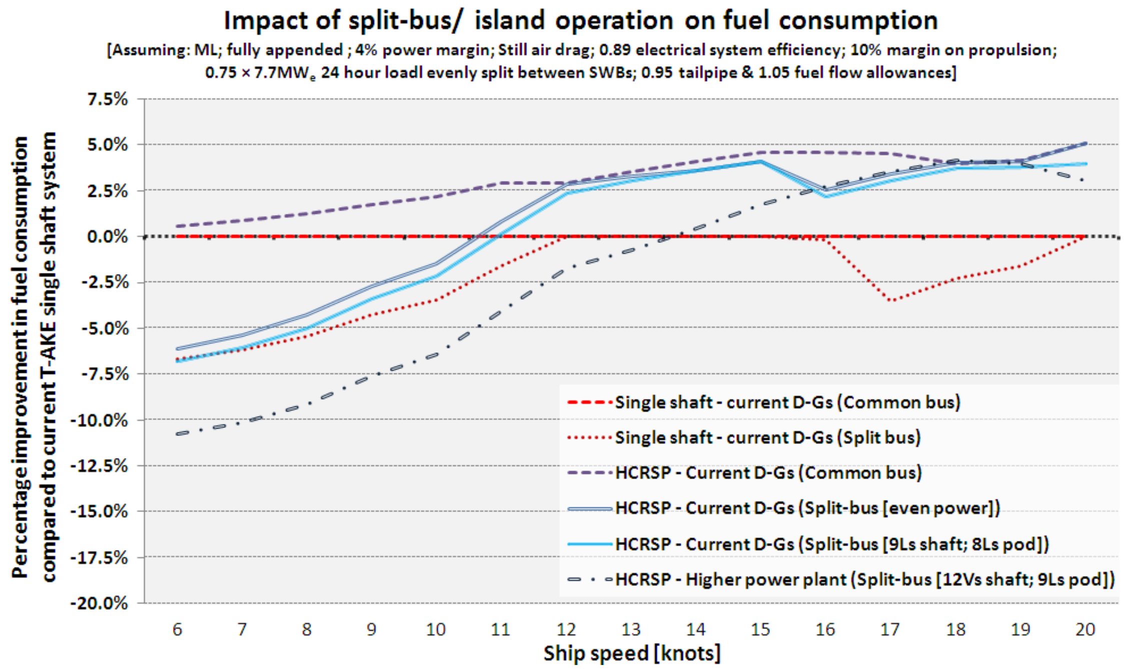


Figure 20: Impact of split-bus operation on fuel consumption

At low speeds, the impact of operating multiple D-Gs is significant when compared to the current system in common-bus mode. However, all the HCRSP system options utilizing the current D-G fit maintain an advantage over the current single shaft system when operating in a split-bus configuration.

The concept of splitting the current D-Gs unevenly with respect to power between the pod and shaft switchboards shows no real advantage and even a negative impact at low speeds. This is because of the need to operate a single 9-L D-G on the shaft switchboard at low speeds instead of a single 8-L in the evenly split system and the corresponding reduction in load factor and rise in SFC.

Above 10 knots, the split-bus HCRSP options burn less fuel than the current single shaft system in common-bus mode, but the fuel consumption advantage has been eroded slightly when compared to the HCRSP arrangement with a common-bus, with significant drops in benefit at speeds where more engines are operating in the split-bus systems (e.g. 16 knots). Overall system efficiency benefits are now between 2-5% at speeds over 10 knots.

The proposed higher power system has a notably worse performance up to 14 knots, but is comparable to the lower installed power options above 16 knots. Again, this is reflecting the lower power factors seen by the D-Gs at any given speed. This illustrates that sizing a system for higher speed risks reducing the fuel consumption advantages at lower speeds.

Table 11 shows the power, fuel consumption, and engine operating data for the specific main operating modes comparing the current shaft-line system in split-bus operation with the proposed HCRSP split-bus system using the current D-Gs. The key issue to note is the spread of engine loadings (power factors) in the HRSP system with D-Gs operating at up to 20% lower power factors than the D-Gs in the evenly powered current system.

Table 11: Fuel consumption and D-G loads (split-bus)

Mode		Low transit	Mid transit	UNREP	Max transit
Speed (sustained) (knots)		**10**	**13**	**13**	**20**
Electrical connection		**Split-bus**			
Propulsion load (kW_e)	HCRSP	2,392	5,323		17,663
	Single shaft	2,569	5,765		18,799
Ship-service load (kW_e)		7,700	7,700	**9,300**	7,800
Load reduction , HCRSP (kW_e)		**-177**	**-442**		**-1,136**
Fuel reduction with HCRSP [Current D-Gs - even power split]	Fuel rate (mt/hr)	-0.03	-0.07	-0.03	-0.22
		-2.2%	**3.6%**	**-3.3%**	**-5.1%**
	Fuel load for 14,000 nm (mt_e)	-44	-79	-78	-167
D-Gs on-line (% loading) [Current D-Gs - even power split]	HCRSP	2 × 8-L (45% & 55%)	2 × 8-L (56% & 80%)	2 × 8-L (63% & 87%)	1×8-L & 2×9-L (86% & 92%)
	Single shaft	2 × 8-L (51%)	2 × 8-L (71%)	2 × 8-L (78%)	2× 8-L & 2× 9-L (71%)

5.3 Performance impacts – new-builds

For a new-build 20-knot naval auxiliary, it should be possible to improve the optimization of the HCRSP system earlier in the development of the design. This would allow the hull lines to be better optimized for performance and better matching of D-Gs to across the speed range. This also allows the realization of more optimized electrical distribution system either allowing better optimized split-bus arrangements or removing the potential compatibility issues associated with common bus arrangements. Despite this potential to improve the design, it is likely that, if split-bus operation is required throughout the ship's speed range, the D-Gs will be sized and then operated non-ideally from an efficiency perspective and, hence, be likely to reduce the overall efficiency benefit of HCRSP.

For a higher power 24-knot new-build auxiliary, the HCRSP arrangement has the potential to allow higher powers to be installed into a skeg hull design. This should provide the potential to gain additional hull efficiency benefits over and above those of the propulsor arrangement when compared to a twin shaft arrangement as a result of better aft-body flow and fewer appendages. As already illustrated, however, installing larger or a greater number of D-G sets has an impact on low speed performance and efficiency. This can be mitigated if a larger number of prime movers are installed and, hence, a better spread of generator power is able to be matched to key operating speeds. This will have, however, a negative impact on arrangeable volume and area, cost, and weight.

6 Availability, Reliability and Maintainability (ARM)

The current shaft arrangement uses proven commercial synchronous motor systems and matching VSDs and, hence, probably represents the highest level of reliability of any current marine electrical system. It also provides the maximum availability achievable with a single shaft-line arrangement with the ability to power the single shaft-line with either of its two electrical motors and with each motor powered from an independent switchboard. This gives high availability in event of electrical faults or failures (most likely), but is still subject to redundancy issues based on location with the flooding of the main motor space, for example, potentially resulting in the total loss of propulsion.

The HCRSP arrangement gains additional system availability through the addition of a second independently driven propulsor, although the degree of improvement will also be influenced by the matching electrical system arrangement with split plant operation across the full speed range offering the highest level. Irrespective of system reliability, availability and redundancy levels should be higher with the HCRSP system as the pod's motors are not within the same space as the shaft motors; e.g. flooding or fire within the pod or shaft-motor spaces would not impact the other system. This arrangement should allow the ship to be classed based on having a second impendent shaft-line – a convention becoming more common on a range of commercial ships, and which is typically achieved through the installation of separate drop-down thrusters. For this advantage to be fully realized, the D-Gs will also require physical separation which is probably unachievable in the current T-AKE 1 arrangement due to the restricted volume available in the machinery space and the limited space available for additional D-G sets. These issues could be addressed in a modified repeat T-AKE 1 or a new design. If D-G separation can be achieved, then the system would allow the ship to enter some harbors without tug assistance and their associated costs.

With a second propulsor added, the potential single point of failure in the HCRSP system becomes the steering system. As already discussed, the steering actuators are likely to be electrically fed from two independent ship-service supplies neither of which is directly linked to the propulsion motor electrical supply. It is also likely that some form of manual actuation will be required. Despite this, the presence of the pod system, the added pod weight, and the proximity of HV electrics supporting the pod must be considered to increase the risk of steering loss due to fire, collision, or major electrical failure within, or near to, the pod.

Overall system reliability for the HCRSP is likely to be good with pods of the size proposed installed in a range of commercial ships and with their design incorporating commercial sub-systems and motors. However, access issues and the fact that they are designed for high power density is likely to result in lower levels of reliability compared to traditional shaft based electrical systems. Maintainability is also harder in the confined spaces within the pod, but this is mitigated by the limited level of maintenance required.

Overall the HCRSP arrangement should be able to improve overall ARM characteristics, providing good matching electrical design is achieved, and has the potential to move the ship towards having dual redundant propulsion system classification.

7 Conclusions and recommendations

The physical integration of the pod system, including its electrical systems, is feasible on the four ship concepts considered, but most challenging when integrated into existing designs. The overall weight and volume of the power system will be larger than for the single shaft option, but not prohibitively so, in a large naval auxiliary. New designs should be able to be arranged to provide operating clearances for the pod within the hull extents, and the required mounting structure.

The HCRSP concept offers a reduction in fuel consumption when compared to a single shaft-line system, but less of a reduction than suggested by the hydrodynamic efficiency benefit. The impact on fuel consumption depends on how the pod is connected to the ship's electrical system, and the number, and load factor of, the operational Diesel Generators (D-Gs). Electrical connection is complicated by the uneven propulsion load split between the pod and the shaft-line motors. This results in the connected D-Gs operating at lower, often less efficient, load factors. Although not considered in detail and less significant in scale, anticipated fuel consumption improvements will be reduced due to additional reductions in electrical system efficiency, the need to provide additional electrical power for the pod system, and the change in overall ship displacement.

The lower propulsion power requirement results in a small increase in speed for the same installed power. Adding additional installed power, subject to space availability, could provide additional speed. This option sacrifices efficiency at low speeds as larger D-Gs will be operating, at any given speed, at a lower load factor and hence at higher specific fuel consumption. Large D-Gs also limit the system's ability to meet continuous operation at low-loads potentially promoting the need for a dedicated 'harbor' generator.

Electrical integration should be considered the most significant HCRSP risk and will require more detailed investigation. The potential need to integrate different motor and Variable Speed Drive (VSD) technologies at different shaft speeds (frequencies) and power levels into an integrated electrical system may generate unacceptable harmonics. This issue may be amplified by the transient loads of Underway Replenishment (UNREP) systems. Improved harmonic filtering, better matched motors and VSD design, or operating the system in a 'split-bus' arrangement (pod and shaft motors connected to separate electrically isolated switchboards) may overcome these issues but may also reduce the efficiency benefits of the HCRSP concept.

The reduction in required power may translate into fewer D-Gs operating at certain speeds and hence a potential reduction in through-life maintenance. This impact is dependent on the vessel's operating profile and the time spent at those specific speeds.

Pod systems are significantly heavier than the rudder systems they replace. Although the overall ship weight impact is relatively small, there will be a need to modify the vessel and/or its loading profile to overcome the stern trim moment created.

If physical separation of the main D-Gs can be achieved, the resulting ship should be able to be classed as having two independent propulsion systems. This can provide through-life cost benefit in terms of reduced port charges where restrictions for single shaft vessels are being enforced and would also allow the vessel to benefit from the improved maneuverability due to the pod. The HCRSP concept is likely to offer improvements in system redundancy and failure recoverability.

7.1 Retrofit of HCRSP into an in-service T-AKE 1

- The *ABB VO1800* pod in a HCRSP arrangement would provide a sustained speed of 21 knots. Physical integration of the pod system requires a small transom extension to provide protection for the strut element of the pod. This option still leaves the after part of the pod's main body protruding aft of the transom potentially resulting in some operational restrictions.
- It is recommended that a new hull section be designed to incorporate the transom hull extension, the pod's supporting structure and steering gear, and the hull-to-pod strut transition shaping. This should offer the opportunity to reduce conversion dry dock time and costs. It also appears feasible, with some modifications, to install the new pod VSD and transformers within the spaces around the steering gear room.
- It is recommended that the current T-AKE 1 D-G system and connections be retained. Additional power could be realized by replacing the in-line 8 cylinder (8-L) D-Gs for 12 cylinder V-type (12-V) units; however the size of the current D-Gs would make this a high cost option for limited additional speed and potentially reduce efficiency at lower speeds. No locations were identified for additional D-Gs of sufficient power and efficiency to make their addition attractive. Re-connecting the D-Gs to better match the uneven load demand of the two motor systems allows higher speeds to be achieved in a split-bus mode but negatively impacts fuel consumption and the scale and cost of electrical system changes.
- Subject to a detailed harmonic analysis, it is proposed that the pod can be electrical connected to either of the main switchboards. This minimizes changes to the current electrical system, allows split-bus operation up to around 19 knots (i.e. including UNREP), and common bus connection for speeds up to 21 knots.

The impacts of retrofitting the HCRSP system are summarized in Table 12.

Table 12: Summary of impacts of retrofitting HCRSP on a T-AKE 1

Pod assumption	ABB VO1800	Change in max. electrical load	+450 kW_e
D-G arrangement	Current T-AKE	Change in lightship	+437 mt (+1.7%)

Sustained speed (knots)	21 knots [Common-bus connection]	19 knots [Split-bus connection]

Operational speed & mode [Current D-Gs - even switchboard power split]		10 knot transit	13 knot transit	13 knot UNREP	20 knot transit
Electrical load reduction - HCRSP		-177 kW_e	-442 kW_e		-1,136 kW_e
Fuel consumption reduction - HCRSP		-2.2%	-3.6%	-3.3%	-5.1%
Reduction in fuel load - HCRSP [14,000 nm; 20 kts]	Common-bus	-49 mt	-85 mt	-87 mt	-168 mt
	Split-bus	-44 mt	-79 mt	-78 mt	-167 mt

In summary, retrofitting a HCRSP system into a T-AKE 1 is feasible and would offer maneuvering, redundancy, and fuel consumption benefits. The need to minimize changes to the ship will result, however, in a dilution of the HCRSP benefits due to the non-ideally matched D-G and electrical system and the inability to optimize the after-body design. If unacceptable system harmonics require the ship to operate in a split-bus mode, it will not achieve 20 knots sustained.

7.2 Integrating HCRSP in a new-build modified-repeat T-AKE 1

This option was considered to assess the potential viability of integrating HCRSP into a modified-repeat T-AKE 1 based ship design. Key aims were, again, to minimize the overall impact of the HCRSP to the existing ship design and to assess what benefits integrating the concept at the design stage could offer. Conclusions for this option include:

- Retaining the design of the proposed hull module for the retrofit option may still offer the lowest cost integration option. The cost vs. benefit of a range of design modifications should, however, be assessed in a modified-repeat design. These include options for a new custom design for a longer pod strut moving the current main shaft-line/skeg further forward to better accommodate the pod, adding a full width transom extension, the redesign of internal spaces to incorporate the pod's supporting electrical system, and options for segregating the main D-Gs into independent spaces.
- Additional power and speed could be achieved through the selection of the new up-rated (higher specific power) version of the currently specified diesel engine offering an 11% gain in power. The integration of 2 × 12-V D-Gs (replacing the 8-L units) is also a lower cost option in a new-build providing 22 knots sustained. This option has negative impacts on low speed efficiency and is poorly matched to low load operation.
- It is recommended that the electrical system be re-designed with matched pod and shaft VSDs to reduce potential harmonics issues, to allow improved integration of the pod system into the switchboards, to allow the use of a better optimized and smaller shaft-line motor system, and to be able to operate in a split-bus mode across the entire speed range.

In summary, designing a HCRSP system into a modified-repeat T-AKE 1 design would allow a better optimization of power generation and electrical systems. Higher powers and speeds can be achieved more cost effectively and harmonic issues can be overcome through the ability to operate across the speed range in a split-bus mode. Improvements to the physical integration of the pod will depend on the level of acceptable investment, ranging from adopting the proposed solution for the retrofit T-AKE 1 through to a new after body shape designed to optimize flow, pod protection, and clearances, but potentially requiring entirely new model tests.

7.3 HCRSP in 20-24 knot future naval auxiliary designs

Integration of HCRSP into new designs offers the best opportunity to fully realize the system's advantages. The aft hull shape of the ship can be optimized for the pod and the D-G and electrical systems can be matched to the operational, power split, and low load requirements.

For a new 20-knot naval auxiliary design with similar power density to that of T-AKE 1, no significant additional integration risks were identified.

The HCRSP offers a range of build and design benefits when compared to a twin shaft-line arrangement typically required for a higher powered 24-knot ship design. The pod system can be fitted towards the end of a ship build resulting in greater flexibility with suppliers, a better cost profile, and the removal of a critical-path (shaft alignment) in the ship build plan. The mounting of the motors on the centerline is less constrained than in a twin shaft system where long shafts are required to minimize shaft inclination and to allow motor diameters to fit within the hull envelope. There will be an overall reduction in appendages and their associated drag and better overall hull design and resistance.

The potentially significantly higher installed power required for a 24-knot large naval auxiliary will require larger or additional D-G sets and machinery spaces. This is true irrespective of the selection of HCRSP or traditional shaft-lines. This could be mitigated by exchanging the 500 rpm D-Gs for 900 rpm D-G sets; however, this will increase fuel consumption and potentially require a larger number of individual D-Gs. It is also likely that at least one lower powered D-G unit will be needed to efficiently manage low load operation.

8 Recommendations

It is recommended that trailing edge flaps on the pod are investigated as they may provide further efficiency gains by providing minor course correction capability without actuating the pod’s primary steering gear and, hence, maintain good flow across the propellers.

It is recommended that a detailed electrical assessment and design exercise be performed for any design considering HCRSP arrangement including an assessment of the potential harmonic issues.

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