Next Generation Electric Propulsion for 5000 Ton Combatant Vessel

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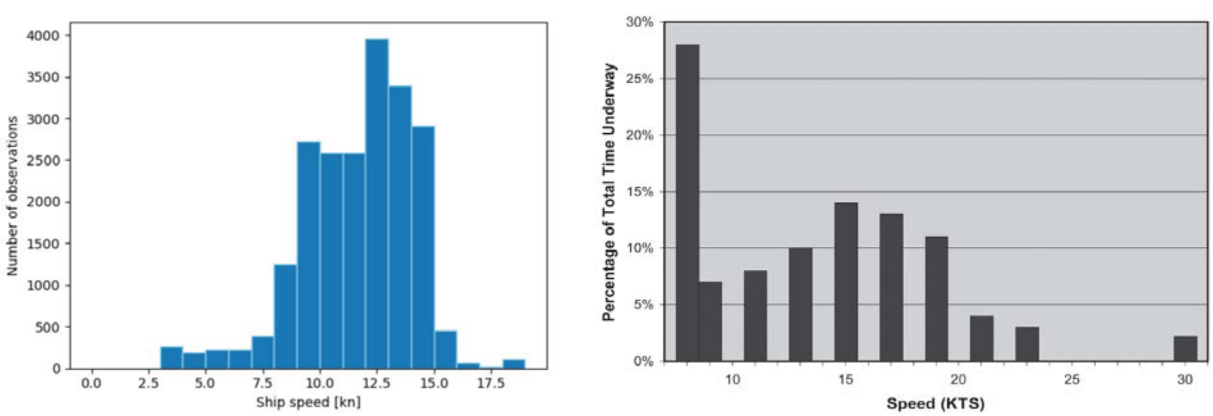
ABSTRACT

Integrated Electric Drive (IED) is widely recognized as an attractive solution for next generation electric propulsion applications as it decouples ship propulsion from conventional gas turbines, diesel engines and reduction gears. By decoupling the ship propulsion, ship designers are afforded increased plant layout flexibility as well as increased fuel economy relative to conventional mechanical propulsion systems.

Typically, combatant vessels operate along a cubic propulsion load profile vs. speed. However, the majority of these vessels spend a significant portion of time loitering and operating at relatively low speeds. Low speed operations are accompanied by resulting propulsion system inefficiencies from operating conventional mechanical propulsion equipment off rated design points. To mitigate these system losses, as well as to increase vessel range and survivability, next generation naval combatant vessels should incorporate integrated electric propulsion systems. This paper presents two IED propulsion systems for a next generation 5,000-ton frigate class vessel highlighting IED benefits and potential drawbacks, when compared to conventional mechanical propulsion plants. The focus of this paper is 5,000-ton class combatant vessels, however the presented approach can also be adopted for various classes of naval ships, such as mine sweeper hunter (MSH), aircraft carrier (CVX) and others.

INTRODUCTION

When establishing a vessel propulsion plant design, ship designers must consider factors which include system cost, arrangement complexity, fuel economy, maintenance and emissions compliance amongst many other competitive factors. Whether the vessel is a commercial cargo ship or a military combatant, the propulsion plant must be sized to accommodate peak loads and vessel speeds [1]. Commercial vessels are often designed to operate at moderate transit speeds, slightly off-peak rating and with a relatively narrow operating band. A typical commercial vessel annual operating profile is presented in Figure 1*(a)*, [2]. In contrast, naval combatant vessels typically operate along a profile that includes a significant portion of time



(a) *(b)*

Figure 1: Commercial vessel annual distribution of ship speed [2] *(a)* and naval combatant annual distribution of ship speed [3] *(b)*

loitering and operating during low-speed activities [1], more closely represented by the operating profile of Figure 1*(b)*, [3].

In recent years, some commercial vessels have taken advantage of excess available propulsion power during transiting operations, employing a shaft generator system to optimize operation of the main low speed diesel engine, increasing efficiency, saving energy and reducing emissions [4]. These systems achieve performance benefits through leveraging additional low speed propulsion diesels capacity to generate power from a separate shaft line generator, enabling the ship to de-energize one or multiple lower performance auxiliary medium speed diesel generator sets [8], and operating the propulsion diesel at or near its design rating. A comparison of specific fuel consumption (SFC) for each prime mover type is shown in Figure 2; further clarifying the advantages afforded by low-speed diesel and part load advantages afforded by low and medium diesels, when compared to a similarly rated Gas Turbine (GT).

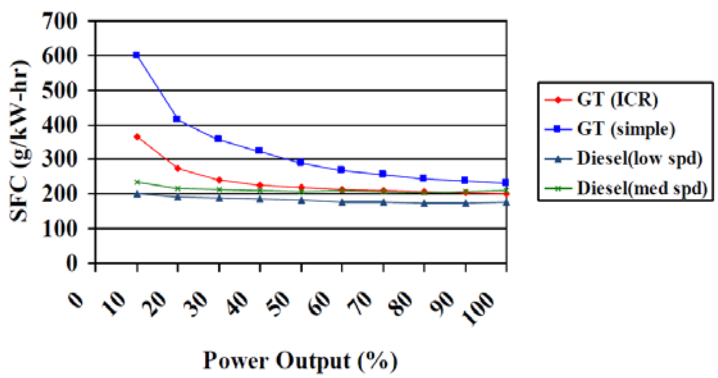


Figure 2: Typical fuel consumption for mechanical prime movers [8]

Typical naval combatant vessels have moved away from low-speed diesel propulsion, instead leveraging more compact and power dense [8] GT propulsion systems. References [5], [6] provide comprehensive reviews of GT propulsion systems, summarizing that GT efficiency is a function of load and that inherent cubic load profiles required for ship propulsion dictates that during typical loitering and other low-speed activities the propulsion systems will be operated at less than 25% of capacity and suffer from poor propulsion plant efficiency. Given these facts, Integrated Electric Drive propulsion systems are an attractive solution for mitigation of low-speed propulsion system losses on next generation combatant vessels. Moreover, these propulsion arrangements offer additional benefits, such as fuel savings, reduced noise signature, increased propulsion flexibility and survivability [5] - [7].

This paper presents two IED systems for a next generation 5,000-ton combatant vessel, highlighting IED benefits when compared to conventional mechanical propulsion plants. The benefits of integrated electric propulsion systems are the same for most combatant ships, thus the principles described in this paper can be adapted for other platforms. Throughout this process, notional propulsion and power plant characteristics and arrangements will be developed and analyzed for the purpose of describing strengths and weaknesses of each approach.

CHARACTERISTICS OF INTEGRATED ELECTRIC DRIVE

Reference [6] provides a comprehensive review of integrated electric propulsion systems, outlining prevalent propulsion arrangements and identifying gear mounted and low speed direct drive IED as widely adopted propulsion systems. Typical gear mounted and direct drive IED propulsion systems are presented below in Figure 3. Each of these two IED configuration provide a 5,000-ton frigate class vessel benefits in the form of simplified mechanical systems through elimination of controllable pitch propellers and associated hardware, higher overall system efficiency relative to mechanical propulsion, enhanced performance from near full torque at zero speed (e.g. acceleration) and improved vessel producibility, ergonomics and survivability due to decoupling of line shafts from GTs and Diesel engines [6].

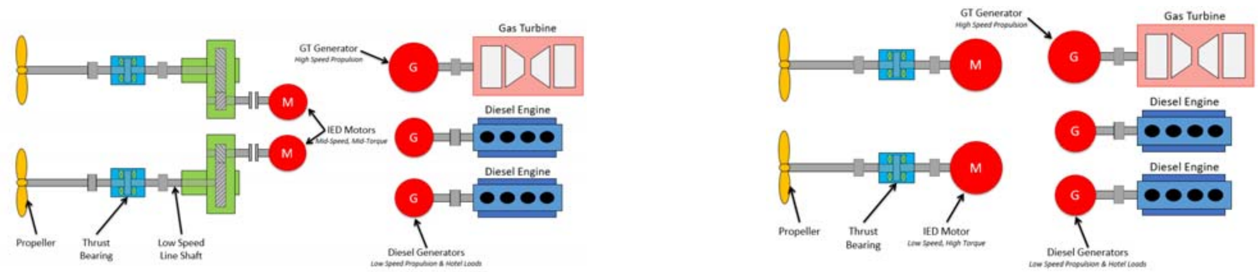


Figure 3: Typical gear mounted IED system *(left)*, Typical direct drive IED system *(right)*

To counter benefits, a few drawbacks are associated with IED. Relative to mechanical and hybrid electric propulsion systems, IED may increase the propulsion plant footprint and system weight. Additionally, propulsion motors with poorly applied Variable Frequency Drives (VFD) can result in increased power system harmonic distortion that lead to ship service load interface and Electro Magnetic Interference (EMI) challenges; typically mitigated with active rectification and propulsion transformers. Acquisition costs are often higher than conventional mechanical propulsion systems, although these costs are usually offset through fuel savings and lower maintenance costs over the operating life of the vessel.

DESIGN CONSIDERATIONS FOR POWER AND PROPULSON SYSTEM

In contrast to conventional mechanical propulsion systems, IED requires the 5,000-ton class combatant ships power system to be sized for both hotel (ship service) and main propulsion loads; increasing demand from a few megawatts of power generation to tens of megawatts. A consequence of this step change in power system demand is that conventional low voltage power systems become impractical due component availability as well as continuous and fault current limitations (e.g. switch gear, circuit breakers, etc.); thus conventional 450V and 690V systems are replaced with 4160V+ Medium Voltage (MV) distribution systems. Below Figure 4 provides limits of standard switchgear and circuit breakers, assuming non-forced air cooling and typical combatant vessel generator impedances.

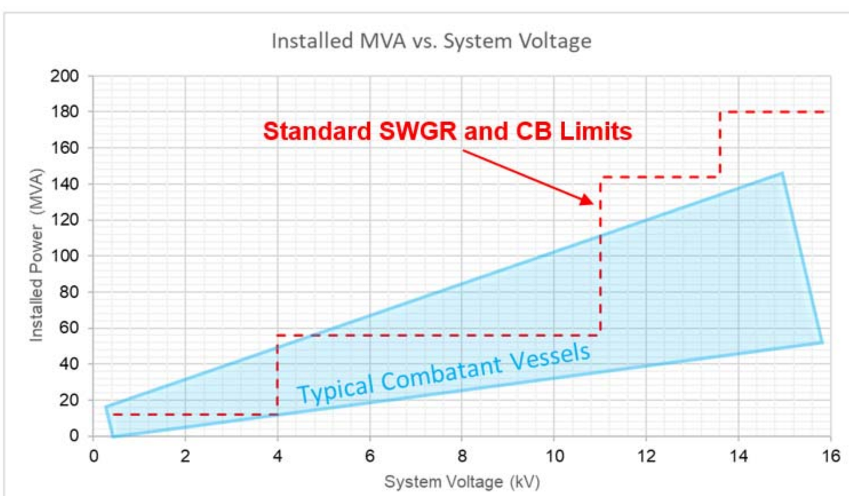


Figure 4: Typical combatant installed MVA vs. system voltage

For non-combatant vessels, where cost is often the highest priority, increased power system demand can be accommodated by relatively inexpensive diesel generators operated in parallel. Current trends indicate that modern combatant vessels favor the compactness and weight advantages afforded by Gas Turbine Generator (GTG) sets [9]-[14], [16], [19], over more economical DGs. Despite recent trends towards Naval Vessel electrification (FFX-II, FFX-III, KDDX, DDG-1000, etc.), currently there is limited availability of ruggedized and marinized GTG packages available for combatant vessels. This limited availability manifests as quasi-discrete GTG power levels being generally available from only two manufactures, General Electric (GE) and Rolls Royce (RR).

For combatant ships, these gas turbines from Rolls-Royce and General Electric are widely used. Rolls Royce has several ruggedized GTG packages with military pedigree, which could be suitable for the proposed 5,000-ton class combatant vessel. Below, Figure 5 presents RR's 35 MWe, MT-30 GTG package as well as the 4 MWe, AG59160RF GTG package. RR's MT-30 is an aeroderivative gas turbine package which entered service in 2008 on the Littoral Combat Ships as a mechanical propulsion turbine and is currently used in the U.S. Navy Zumwalt class destroyer as well as the UK Royal Navy's Queen Elizabeth class aircraft carrier for power generation [16]. The AG9160RF GTG is a derivative of RR's (Formerly Allison Division of General Motors) 501-K17 2.0 MWe GTG package first installed in 1972 on the U.S. Navy Spruance Class destroyers and most recently on the Flight III DDG-51 vessels [16]. Below Table I provides a summary of available RR GTG offerings.

Figure 5: Rolls Royce MT30 GTG *(left)*, Rolls Royce 4.0MW AG9160RF GTG *(right)* [11]

Table I. Rolls Royce Marine Gas Turbine Generator Packages

Rolls Royce Gas Turbine Generator Offerings [9]-[11], [16], [21]		
Package or Turbine Designation	**Nominal Generator Power**	**Recent Combatant Vessel Experience**
MT30 Gas Turbine Generator	35 - 39 MWe	USN Zumwalt, UK Navy Queen Elizabeth
WR-21 Gas Turbine Generator	21.5 MWe	UK Navy Type 45
RR4500	3.8 - 4.5 MWe	US Navy DDG-1000
AG9160RF	4.0 MWe	US Navy DDG-51 (Flight III)
AG9140	3.0 MWe	US Navy DDG-51, Korean and Japanese AEGIS Class
Allison 501-K17	2.0 - 2.5 MWe	US Navy Spruance Class, US Navy CG-47 Class

In addition to Rolls Royce's GTG offerings, General Electric has a long history of providing ruggedized and marinized GT packages for combatant vessels.

GE's LM2500 package was first qualified for propulsion of the US Navy Spruance Class destroyers [17], and in following years was implemented worldwide, recently announcing that the LM2500 package had been adopted for use by 35 navies [18]. Below Figure 6 depicts GE's LM2500+ GTG package, as well as the LM500 GTG package. The LM2500+ is an up-rated LM2500, where one additional stage of compressor has been added to increase compressor airflow, increasing output power and GT efficiency; The LM500 is aeroderivative GT which powers Korea's PKX-A and PKX-B patrol boats, Japan's 24DDH and 22DDH destroyers and several other patrol boat vessels [13], [14]. In 2005 the LM500 was recently adapted for naval power generation under the U.S. Navy funded DD(X) program [18].

Figure 6: GE LM2500+ GTG [13] *(left)*, GE LM500 Auxiliary GTG *(right)*

In addition to GE's LM500 and LM2500 product lines, GE also offers the LM6000 as a marinized and shock qualified GTG package, capable of producing 45 MWe of electric power [12]. Table II provides a summary of GE marine's GTG offerings.

Table II. General Electric Marine Gas Turbine Generator

General Electric Gas Turbine Generator Offerings [12]-[14], [19]		
Package or Turbine Designation	**Nominal Generator Power**	**Recent Power Generation Experience**
LM6000 Gas Turbine Generator	45 MWe	Industrial Applications, Marinized / Shock Qualified in 2015
LM2500+ Gas Turbine Generator	29 MWe	Commercial Marine, KDDX
LM500 Gas Turbine Generator	3.8 - 4.2 MWe	Industrial Applications, DD(X) Land Based Test

There are other turbine western OEMs, in addition to General Electric and Rolls Royce, who produce gas turbines (Siemens, Pratt & Whitney, Kawasaki, Solar Gas Turbines, etc.). However, these products are generally industrial in nature and not prevalent in current naval vessels, likely because they have not been suitably ruggedized or marinized or there are limited business prospects.

NOTIONAL PROPULSION & POWER SYSTEM

The Leonardo DRS and Doosan Enerbility team have established two notional IED propulsion systems for the 5,000-ton frigate class vessel. This approach can be similarly applied to all combatant ships, such as the next generation of minesweeper hunter and aircraft carriers for the ROK Navy. Each configuration takes advantage of the power density and peak efficiency afforded by GTGs, while leveraging DGs to achieve off peak efficiency and n+1 redundancy during typical loitering and transiting operations. Due to the notional vessel size and anticipated mission profile a direct drive IED system was selected, offering maximum plant flexibility, and reduced propulsion plant signature [6].

Ship propulsion power requirements are inherently cubic, dictating that during loitering and other low-speed operation, the propulsion system will only be operated at 25% of capacity or less [1],[3], [6], [8]. To combat poor off-design efficiency of gas turbine generators, the proposed propulsion and power distribution systems leverage DGs to accommodate typical frigate hotel, radar, and propulsion loads. The first proposed propulsion and distribution system considered for the 5,000-ton class frigate vessel is depicted schematically in the single line diagram of Figure 7. This system line up leverages a single 38 MWe RR MT30 gas turbine generator and three smaller 4 MWe diesel generators to source all distribution and propulsion loads, including two 19 MW Permanent Magnet (PM) propulsion motors and associated Variable Frequency Drives (VFDs).

This distribution system features a 6.6 kV split bus design, offering n+1 redundancy for most of the ship operational profile (less sprint) and enhanced operating flexibility to optimize vessel fuel consumption during low and moderate speed operations. To achieve n+1 redundancy during non-sprint activities, the GTG would be used to source power in the event a DG trip offline. While 4,160 V distribution was initially considered as stated above, anticipated continuous and fault currents make 6.6 kV or higher distribution voltages attractive, as they maintain breaker continuous and fault current values within available standard commercial and navy switchgear ratings while offering the vessel additional capacity for future electric plant loads. As the vessel design matures, the designer may consider increasing distribution voltage further to minimize continuous current ratings of the switchgear and to minimize shipboard cabling weight.

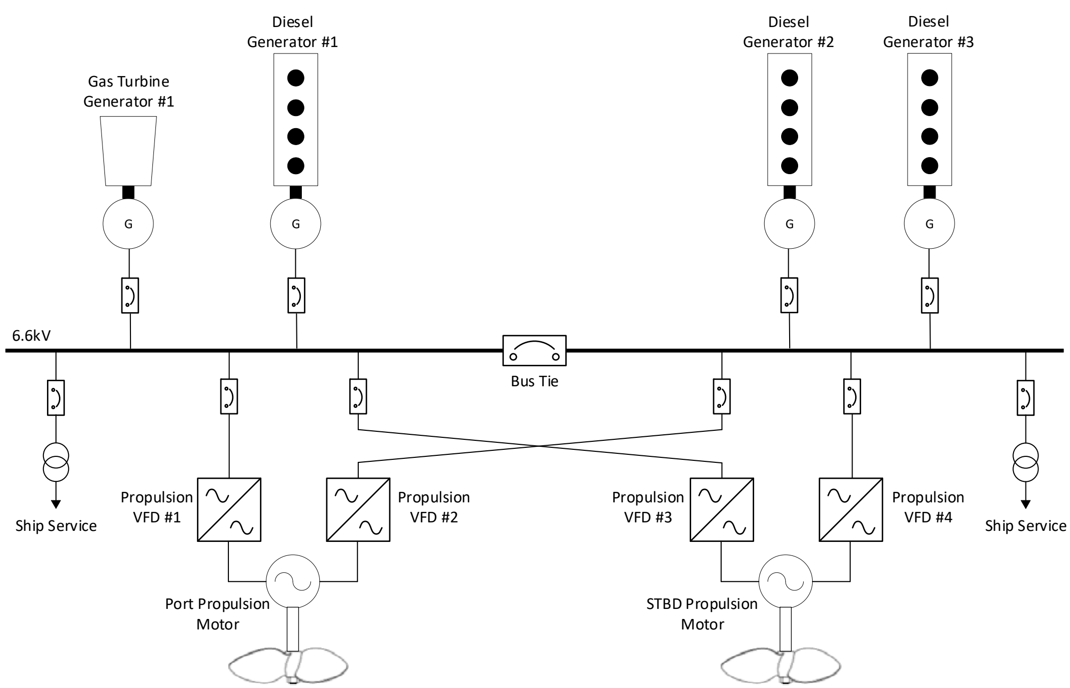


Figure 7: Propulsion & power distribution system single line diagram, option #1 (38 MWe RR GTG)

The frigate class distribution system is required to provide power for typical ship service loads (pumps, HVAC, etc.), ship radar systems as well as propulsion loads. Typical radar loads for a frigate sized vessels are a constant power draw of 1.5 - 2.5 MWe [15] for each radar; and for purposes of this paper, it assumed that average hotel loads consume the same amount of average power, 2.0 MWe. Combing the anticipated hotel and radar loads, the power system will need to continuously provide 6.0 MWe of electrical energy in addition to propulsion loads.

Leveraging the 12.0 MWe of DG power available, 3.0 MWe can then be allocated to each propulsion shaft, enabling the frigate to operate in economical transit / loitering mode without the GTG online. Assuming the frigate hull form results in a typical cubic load profile, the 3.0 MWe of available power enables to vessel to achieve approximately 15 knots; enabling it to operate approximately along 65% of the Reference [3] ship speed profile without the GTG online. This is particularly attractive as it reduces part load operation of the GTG package, minimizing maintenance as well as vessel fuel costs. Additionally, this notational arrangement can accommodate the load of two propulsion motors by using a one GTG set.

The second configuration considered replaces the 38 MWe RR GTG package with GE's 29 MWe LM2500+ GTG. This configuration also leverages a ruggedized and marinized GTG package suitable for a combatant vessel and is depicted schematically via the Figure 8 single line diagram. Unlike the RR GTG configuration, this switchgear line-up no longer features a symmetric feeder arrangement. Feeder symmetry does not impact system performance; however, it could be advantageous for ship designers and is achievable by moving one of the DG feeders or GTG into a separate switchgear cabinet with the bus tie circuit breakers.

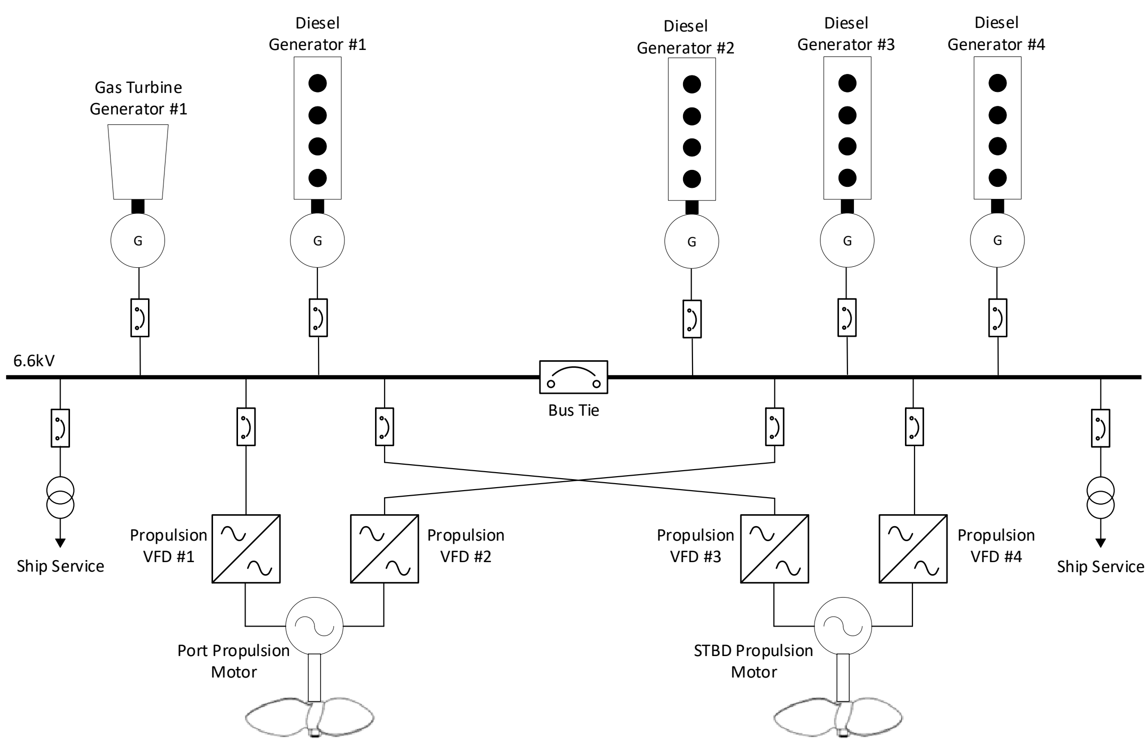


Figure 8: Propulsion & power distribution system single line diagram, option #2 (29 MWe GE GTG)

Like the 38 MWe RR GTG power system, this configuration also leverages a 6.6 kV split bus design, but this time incorporates four, 4.5 MWe DG sets to achieve the propulsion and power system demand. The increased rating and quantity of DG sets offers n+1 redundancy for a larger majority of ship operational scenarios and introduces additional operational possibilities. For example, the 5,000-ton frigate class is now capable of achieving greater than 20 knots with only 3 DGs online, affording the vessel n+2 redundancy or the opportunity to take one DG offline during transiting operations and maintain and offline GTG. Additionally, the frigate is now capable of achieving nearly 25 knots on DGs only, accomplishing > 89% of vessel operating scenarios without utilizing the GTG set.

PROPULSION MOTOR DESIGN

The most important consideration in an IED system is the selection of a propulsion motor. Currently, permanent magnet motors and induction motors are widely applied to ships. Permanent magnet machines are distinguished from competing machine types by their ability to achieve superior combinations of high torque/power density and high efficiency [20]. These fundamental characteristics align with the 5,000-ton frigate class vessel's need to minimize size and weight of shipboard equipment to maximize range and payload. Consequently, PM propulsion motors are a superior choice for the 5,000-ton frigate class vessel and thus, both proposed propulsion systems leverage a pair of 19 MW permanent magnet propulsion motors.

Permanent magnet motor size and weight are about 50-70% of comparable induction motors; likely why PM technology is prevalent in existing submarines [22], [23] and expected to be selected for future surface ships. The proposed Mil-Spec pedigree PM motor for the 5,000-ton class frigate delivers a power dense, high efficiency, extremely reliable, and rugged propulsion solution. The continued function of the propulsion motor throughout the life of the ship is critical to crew safety and mission success. Leonardo DRS propulsion motors are designed to achieve stringent MIL-spec requirements for shock, vibration, and noise. To that end, it is designed to Grade A shock requirements per MIL-S-901D, as they are essential to the safety and combat capability of the ship and MIL-STD-167-1A vibration. A typical PM propulsion motor with a tightly coupled propulsion drive is shown below in Figure 9; the proposed 5,000-ton frigate class propulsion motor will be configured similarly to minimize engine room space and equipment weight

Figure 9: Typical 36.5 MW Permanent Magnet Propulsion Motor.

Another advantage of a DRS PM propulsion system is that low noise is standard. DRS' PM propulsion motors can meet the stringent structure and airborne noise requirements of MIL-STD-740-1 & MIL-STD-740-2 without the need to resilient mounting the machine; enabling the 5,000-ton frigate class vessel to conduct Anti-Submarine Warfare (ASW) operations. In additional to ASW capability, the hard-mounted configuration also eliminates the cost and maintenance required by resilient mounts and associated shaft couplings, typically required for installation and alignment.

CONCLUSIONS

The benefits of a properly designed IED system are truly wide ranging, offering the modern combatant vessel with significant advantages over conventional mechanical drive. The correct implementation of IED will offer the end user with operational flexibility and redundancy (n+1), as well as reduced signature, increased fuel economy and an electric plant lineup which well suited for anticipated future loads, such as pulse power and energy weapon systems.

This paper introduces two innovative configurations for propulsion and power distribution systems for a notional 5,000-ton class frigate vessel but also it can be applied for other naval ships such as mine sweeper hunter (MSH), aircraft carrier (CVX) ships and etcetera Both configurations involve the combination of GTG and DG power systems with two 19 MW PM propulsion motors. Of course, the rated power of the propulsion motor depends on the ship's displacement and required speed. These configurations provide the vessel with the benefits of high-power density offered by GTGs while maximizing fuel efficiency during low-speed loitering and transiting activities with the help of DGs and PM propulsion motors. Furthermore, Mil-Spec pedigree was taken into consideration in the design, with the propulsion motors being Mil-Spec compliant, and the GTG options limited to those with ruggedized marine and/or Mil-Spec pedigree.

REFERENCES

[1] C. Corey, F. Fleming, *"Combined Radial-Axial Flux Motor for Improved Electric Propulsion Efficiency and Volume Density,"* 2020 ASNE Advanced Machinery Technology Symposium (AMTS), 2020.

[2] F. Baldi, F. Ahlgren, T.V. Nguyen, M. Thern, K. Andersson, *"Energy and Exergy Analysis of a Cruise Ship.*" Energies. 11. 2508. 10.3390/en11102508, 2018.

[3] S. Surko, M. Osburne, *"Operating Speed Profiles and the Ship Design Cycle,"* Naval Engineers Journal, Summer 2005, pp. 79-85.

[4] Z. Duan, Y. Chen, H. Gao, L. Liao, *"Analysis of Key Technologies for New Green Marine Propulsion Systems,"* E3S Web of Conferences. 194. 02008. 10.1051/e3sconf/202019402008.

[5] G. Castles, G. Reed, A. Bendre and R. Pitsch, *"Economic benefits of hybrid drive propulsion for naval ships,"* 2009 IEEE Electric Ship Technologies Symposium, 2009, pp. 515-520, doi: 10.1109/ESTS.2009.4906560.

[6] C. Corey, G. Castles, C. Wilgress-Pipe, HJ. Moon, *"Electric Propulsion for Modern Naval Vessels,"* 2021 International Maritime Defense Industry Exhibition (MADEX), Busan, Korea

[7] J. L. Kirtley, A. Banerjee and S. Englebretson, *"Motors for Ship Propulsion,"* in Proceedings of the IEEE, vol. 103, no. 12, pp. 2320-2332, Dec. 2015.

[8] N. Doerry, *"Sizing Power Generation and Fuel Capacity of the All-Electric Warship,"* presented at IEEE ESTS 2007, May 22-23, 2007, Arlington, VA.

[9] R. Partridge, *"Electrifying the fleet,"* Presented at Naval Ships Technology Symposium, 2021

[10] Rolls Royce Marketing, https://www.rolls-royce.com/products-and-services/defence/naval/gas-turbines/ag9140-generator-set.aspx, Accessed April 2023

[11] Rolls Royce Marketing, https://www.rolls-royce.com/products-and-services/defence/naval/gas-turbines/ag9160-generator-set.aspx, Accessed April. 2023

[12] General Electric Aviation Marketing Brochure, "*LM6000 Marine Gas Turbine*", 2018. https://www.geaerospace.com/sites/default/files/datasheet-lm6000.pdf

[13] General Electric Aviation Marketing Brochure, "*LM2500+ Marine Gas Turbine*", 2017. https://www.geaerospace.com/sites/default/files/datasheet-lm2500plus.pdf

[14] General Electric Aviation Marketing Brochure, *"LM500 Marine Gas Turbine"*, 2017. https://www.geaerospace.com/sites/default/files/2022-03/LM500-Datasheet.pdf

[15] U.S. Radar, *"Operational Characteristics of Radar Classified by Tactical Application,"* FTP 217, 1 August, 1943

[16] Rolls Royce Marketing, https://www.rolls-royce.com/media/our-stories/discover/2022/celebrating-50-years-of-delivering-marine-gas-turbine-generators.aspx, Accessed April. 2023

[17] W.R. Bobo, "*High Impact Shock Test of a General Electric LM2500 Propulsion Gas Turbine Module*." Proceedings of the ASME 1973 International Gas Turbine Conference and Products Show. ASME 1973 International Gas Turbine Conference and Products Show. Washington, DC, USA. April 8–12, 1973. V001T01A087. ASME. https://doi.org/10.1115/73-GT-88

[18] Defense & Aerospace Report, *"GE Marine's Awizus on LM2500 Engine Outlook, Future Shipboard Power,"* https://defaeroreport.com/2019/01/17/ge-marines-awiszus-on-lm2500-engine-outlook-future-shipboard-power/, accessed April 2023.

[19] GE Marketing, https://www.ge.com/news/press-releases/ge-delivers-lm500-auxiliary-gas-turbine-generator-set-us-navys-ddx-land-based-test, Accessed April. 2023

[20] T.M. Jahns, *"The expanding role of PM machines in direct-drive applications,"* Proc. of 2011 Intl. Conference on Electric Machines and Systems (ICEMS), Aug. 2011.

[21] https://www.rolls-royce.com/media/press-releases/2015/pr-28-07-2015-rr-completes-delivery-of-power-propulsion-systems-package.aspx

[22] Siemens AG, "SINAVY DC-Prop and SINAVY PERMASYN Integrated Propulsion Solutions for Submarines", 2016

[23] Navy Outlook, " The Dreadnought class submarine in focus", https://www.navylookout.com/the-dreadnought-class-submarine-in-focus/, Dec. 2017, accessed April 2023