Electric Propulsion for Modern Naval Vessels

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***Abstract*— Naval vessels typically operate along a profile that includes a significant portion of time loitering and operating during low-speed activities. In conventional mechanically driven vessels, this low speed operation is accompanied by propulsion system inefficiencies, as the propulsion turbines are operating off-design. To mitigate these system losses, as well as to increase vessel range and survivability, modern naval vessels incorporate electric propulsion systems.**

Integrated Electric Drive (IED) and Hybrid Electric Drive (HED) propulsion systems can be an attractive solution for mitigation of low-speed propulsion system losses. Moreover, these propulsion arrangements offer additional benefits, such as fuel savings, reduced noise signature, increased propulsion flexibility and survivability. This paper compares and contrasts IED and HED propulsion systems for naval vessels and proposes an adaptation of each system for the CVX-Class aircraft carrier.

I. INTRODUCTION

Typically, propulsion plants are sized to accommodate peak loads and vessel speeds [6]. While mechanical propulsion of naval vessels is commonplace, and well understood, this paper focuses on electrical propulsion systems. More specifically, this paper evaluates the adaptation of integrated electric and hybrid electric propulsion plants into modern naval vessels. A key component of Integrated Electric Drive (IED) and Hybrid Electric Drive (HED) propulsion systems is their use of electric motors to propel the vessel, rather than directly driving the propellers with a more conventional Gas Turbine (GT), reduction gear arrangement [1], [2], [4].

Introducing electric propulsion motors to the vessel, either in the form of an IED or HED propulsion system, allows replacement of the relatively low efficiency GTs operating off-design [4], [15], with the relatively high efficiency of an electric motor and synchronous generator. Typical electric motors and generators for propulsion applications attain efficiency ratings greater than 95% [3], [4]. Low-speed efficiency and power density of the electric propulsion system can be further enhanced through use of Permanent Magnet (PM) motors, or more advanced radial-axial motor topologies [4], [6].

The inherently cubic load profiles required for ship propulsion [7], dictates that during typical loitering and other low-speed activities the propulsion systems will be operated at less than 25% of capacity [6]-[8]. Reference [4] comprehensively investigates the efficiency of GT propulsion systems, summarizing that GT efficiency is a function of load. This reference further clarifies that operating at off-design load significantly lowers the GT efficiency. Fig. 1 presents the specific fuel consumption for a conventional propulsion GT. Based on this curve, it is obvious that a vessel operating at low shaft power (low to moderate ship speeds due to typical cubic relationship of power versus ship speed) results in, drastic increases in GT fuel consumption and corresponding low GT efficiency.

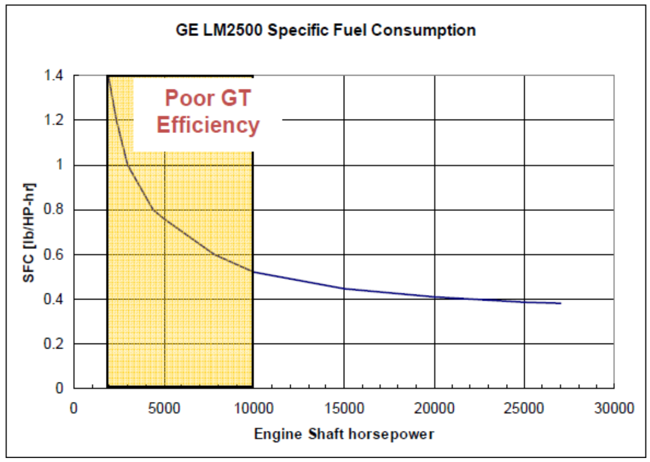

Fig. 1. Representative specific fuel consumption of gas turbine operating as vessel prime mover [4]

Alone, the increase in propulsion plant efficiency and corresponding reduction in vessel operating costs make IED and HED attractive for many naval applications. The inherent reduction in noise signature, increased vessel flexibility and survivability afforded through implementation of IED and HED propulsion make them ideal candidates for modern naval vessels, such as aircraft carrier and destroyer type vessels.

Following portions of this paper first present a brief history of electric propulsion in naval vessels, spending time to identify the advantages, disadvantages, maturity and risk of IED and HED propulsion systems. After reviewing the history of electric propulsion, this paper describes notional integrated electric and hybrid electric propulsion systems for an aircraft carrier vessel, such as CVX. Lastly, this paper concludes by summarizing strengths and weaknesses of each electric propulsion design for modern naval vessels.

II. HISTORY OF ELECTRIC PROPULSION

At present time, the electrification of marine vessels is widespread and broadly recognized as an effective way to increase vessel efficiency [3], [4]. While commonly adopted in recent decades, electric propulsion of naval vessels was first adopted more than a century ago, and first implemented in 1912 on the USS Juniper (AC3) [9], [10]. While there was some limited use of electric propulsion on various platforms throughout the 20th century, it was not until recent decades and the advent of advanced power electronics that has given rise to a renewed interest in this technology for ship propulsion [5].

Leveraging advancement in power electronics, the first modern implementations of electric propulsion was the Type 23 Duke Class frigate for the Royal Navy. The first Type 23 Duke Class frigate, the HMS Norfolk (F230), was launched in 1990 with a Combined Diesel Electric and Gas Turbine (CODLAG) propulsion system, which included two 1.5 MW DC motors on the line shaft of the ship [11].

In more recent years, there have been several notable IED and HED propulsion systems adapted to naval vessels. The US Navy's Zumwalt-Class destroyer was the first US Naval surface combatant to feature all-electric propulsion [12]. The Zumwalt-Class first started with a 36.5 MW permanent magnet propulsion motor, built by DRS Technologies. DRS' 36.5 MW propulsion motor featured a tightly integrated Variable Frequency Drive (VFD) and is shown below in Fig. 2.

Fig. 2. DRS' 36MW permanent magnet propulsion motor and variable frequency drive.

The 36.5 MW permanent magnet propulsion motor was successfully tested, achieving a peak efficiency of 98% [3], however the Zumwalt-Class ultimately down-selected a lower power, 34.6 MW propulsion solution. Another notable electric propulsion program is the 1.7 MW HED propulsion system currently deployed on the Daegu-Class Frigate (FFX-II) for the Republic of Korea Navy (ROKN).

Fig. 3. Full power integration testing of the FFX-II HED system at Leonardo DRS-Naval Power Systems, Inc. (Milwaukee, WI).

The FFX-II propulsion system, featured a "bearingless" PM motor, shown in Fig. 3, providing a compact, space saving configuration with low acoustic signature [5]. The FFX-II also incorporates a modular, compact VFD platform which employs a Three-Level Neutral-Point-Clamped (3LNPC) Power Electronics Module (PEM) as the foundational building block.

Fig. 4. FFX-II 1.7 MW variable frequency drive

The FFX-II VFD incorporated Active Front End (AFE) rectification to meet the input power quality requirements without the need for bulky phase-shifting input transformers. Reference [5] provides a comprehensive review of the FFX-II HED propulsion system.

Several other navies are in various stages of integrating HED or IED propulsion systems. For example, the Italian and French FREMM frigates are implementing PM solutions to achieve Anti-Submarine Warfare (ASW) operational performance [5], [12], [13]. Moreover the US Navy's next generation Columbia-Class SSBN submarine has adopted full electric propulsion to achieve new levels of stealth beyond what a conventional mechanical drive system can provide [5], [14].

Widespread adoption of hybrid electric and integrated electric propulsion systems, across many commercial and naval vessels has largely de-risked implementation of both technologies for modern naval vessels. As neither arrangement presents a notable technology risk, challenges will come in the form of vessel-specific integration and requirement verification, typical of all naval vessels (shock, vibration, electromagnetic interference, etc.). In light of this, the specific vessel size and mission requirements are primary factors when considering implementation of IED versus HED propulsion. The following sub-sections provide application considerations for electric propulsion configurations.

III. Hybrid Electric Propulsion

Hybrid electric propulsion for marine vessels is a topic which has been thoroughly analyzed and characterized in literature [3]-[5], [7], [15]. As a result of this comprehensive collection of work, the advantages and disadvantages of HED propulsion is well understood. This portion of the paper will describe the two most prevalent forms of naval vessel HED propulsion systems: 1) Gear Mounted, and 2) Shaft Mounted, as well as characteristics of application.

Gear mounted HED systems are typically integrated into naval vessels by integrating an electric propulsion motor onto on the main reduction gear. This arrangement often couples the electric motor through a clutch and via a power take-in section. One such example of gear mounted HED propulsion system is DRS' PA44 permanent magnet motor, used on the US Coast Guard Offshore Patrol Cutter (OPC), and shown below in Fig. 5. DRS' OPC solution included a PEM based VFD, similar to FFX-II.

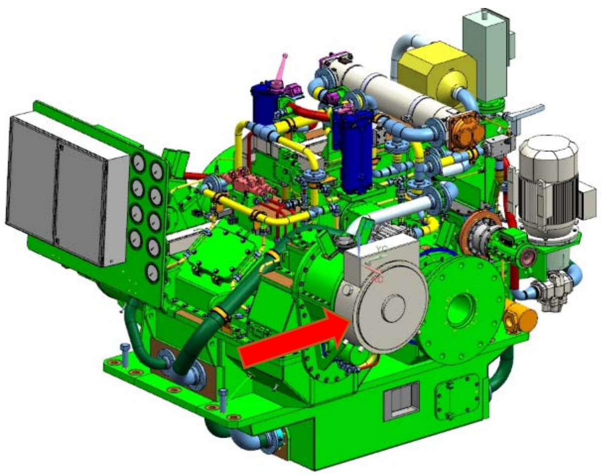

Fig. 5. DRS 625 HP PA44 permanent magnet motor integrated onto OPC main reduction gear

Gear mounted HED systems are used widely in commercial vessels, and some naval vessels, primarily for reasons of cost-effectiveness. In cases where naval vessels require the lowest noise signature, typical to ASW mission profiles, shaft mounted HED systems are preferable. A typical gear mounted HED system is shown schematically in Fig. 6.

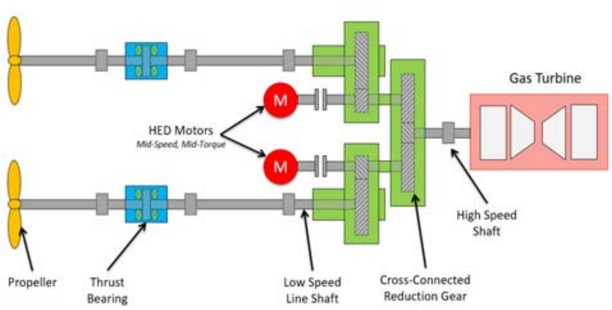

Fig. 6. Typical gear mounted HED system for naval vessel

Relative to gear mounted HED systems, shaft mounted HED systems, as shown in Fig. 7, offer reduced noised signature and overall improved system efficiency [5]. The reductions are primarily a result of mounting the HED motor directly onto the propulsion line shaft and optionally removing the propulsion motors bearings. In this configuration, the main reduction gear can be clutched out, eliminating parasitic losses as well as gear train noise sources during quiet operation using the HED system. This approach was taken on the FFX-II vessel, yielding a compact HED propulsion system the enable an enhanced ASW capability. Reference [5] provides a more comprehensive review of the FFX-II propulsion, and highlights the inherent benefits afforded through utilization of a shaft mounted HED system.

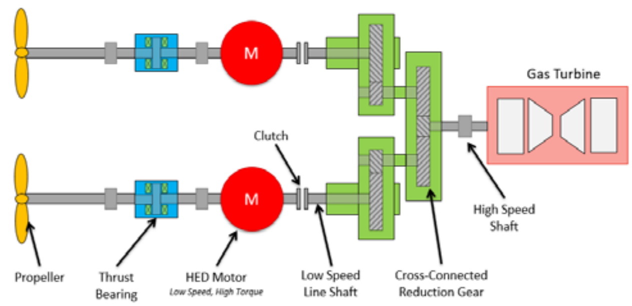

Fig. 7. Typical shaft mounted HED system for naval vessel

A. *Characteristics of Hybrid Electric Propulsion*

The inherently cubic load profile required for ship propulsion dictates that during loitering and other low-speed operation, the propulsion system will be operated at less than 25% of capacity [6] - [8]. While conventional GT and diesel propulsion are power dense sources, they demonstrate poor off-design efficiency, warranting inclusion of HED propulsion to improve fuel economy. Reference [4], [5], [15], and [16] provide a comprehensive evaluation of HED systems, which can be deduced into the following operational characteristics for HED propulsion

- Simplified mechanical systems. Often, prime movers are not reversible and require auxiliary reversing equipment. HED motors and VFDs can provide reverse propulsion, including crash stop and emergency reversing
- Excess ship service power can be used to provide low-speed propulsion power, attaining higher overall propulsion plant efficiency
- Propulsion redundancy offers improved survivability, relative to conventional mechanically driven vessels
- Electric motors can be coupled with a four-quadrant VFD to provide propulsion derived ship service (PDSS) power
- Shaft mounted HED systems can reduce the propulsion plant noise signature of the vessel
- HED motor can be used to boost total propulsion power, so that higher flank speed can be achieved or lower power prime mover can be used
- HED allows the vessel to operate in low power propulsion modes for extended time, without building up deposits of unburnt fuel (coking) in diesel prime movers

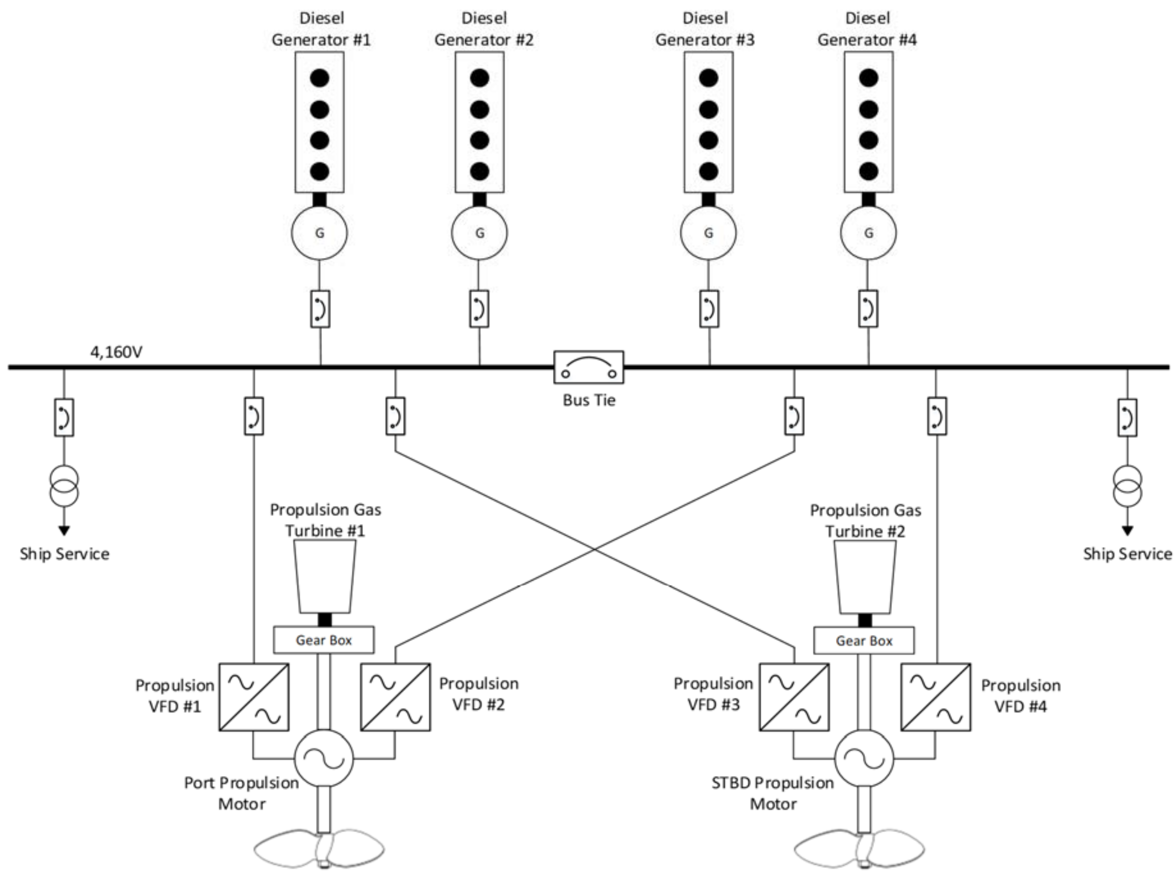

Fig. 8. Notional HED system for CVX-Class aircraft carrier

While there are several benefits to be considered when implementing a HED propulsion system, there can be some drawbacks.

- Propulsion plant complexity is marginally increased due to additional equipment, relative to both conventional mechanical drive and IED
- Additional equipment can increase acquisition cost. Acquisition costs are offset by fuel savings, and can be paid back sooner by optimizing full HED system capability (e.g. reversing and PDSS)

B. Notional HED System for CVX-Class Aircraft Carrier

Leveraging the above analysis, DRS has established a notional HED propulsion system for the CVX-Class aircraft carrier. Due to the notional vessel size and anticipated mission profile DRS recommends a shaft mounted HED solution, featuring four 11 MW Diesel Generator (DG) sets suppling power to the HED propulsion system, as well as hotel loads. This configuration will provide n-1 redundancy, while powering two 12 MW HED motors and hotel loads. The distribution system features a 4,160V split bus design with bus tie, as shown in Fig. 8. In this configuration, the HED motors are sourced from both portions of the split bus to enhance survivability and operation flexibility.

Each of the vessels two propellers are provided propulsion by a 36 MW GT, speed reducing gearbox and one permanent magnet propulsion motor. The propulsion maintains a rating of 12 MW for powering up to transit speed and is configured to boost GT propulsion during sprint operation. DRS anticipates that CVX will require approximately 40 MW of propulsion power, of which, 36 MW will be supplied by the propulsion GT and the remaining 4 MW will be sourced from the HED system. DRS recommends a permanent magnet motor for this application, because of the inherently high and broad efficiency performance permanent magnet technology provides [3], [6], as well as their ability to utilize a larger mechanical air gap between the rotor and stator. This solution ensures superior fuel economy during boost mode as well as enhanced shock survivability.

IV. INTEGRATED ELECTRIC PROPULSION

Similar to HED, IED propulsion systems are typically configured with and without speed reducing gearboxes. Since these arrangement are similar to HED, each arrangement offers similar benefits. A typical gear mounted propulsion system is presented in Fig. 9, while Fig. 11 describes a typical IED propulsion system that is directly coupled to the propulsion line shaft.

Reviewing referenced literature [4], [10], [17] - [19], and DRS' experience, gear mounted IED propulsion systems are adopted more widely in small naval and commercial vessels, where-as IED systems directly coupled to the propulsion line shaft are more prevalent amongst large naval vessels, and select commercial applications. This dichotomy exists due to the inherent characteristics of each IED arrangement.

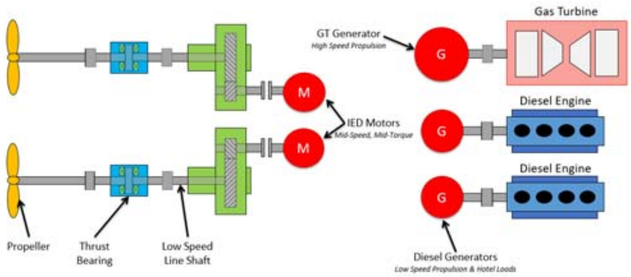

Fig. 9. Typical gear mounted IED system for naval vessel (electrical interconnections removed for clarity)

Both IED configurations offer significant advantages over conventional mechanical drive, allowing decoupling of ship propulsion from gas turbines and engines, increasing propulsion plant layout flexibility and fuel economy. The lower acquisition cost of gear mounted IED propulsion systems, coupled with their inherently reduced fuel consumption and emissions, relative to mechanical drive, is likely why they are adopted more broadly amongst commercial vessels. Moreover, electric machinery size and power is proportion to speed, thus increasing propulsion motor speed through a gearbox allows for a reduction in motor size. Since smaller vessels inherently have smaller engine rooms, the reduced propulsion package size is attractive to naval architects of these smaller vessels.

In contrast with gear mounted IED propulsion system, direct drive propulsion motors eliminate the need for a gear box, replacing it with a larger, lower speed propulsion motor. This configuration is often the most efficient, as it takes advantage of the high efficiency available in MW-class low speed propulsion motors, and eliminates parasitic losses from gearboxes and additional line shaft length and corresponding bearings.

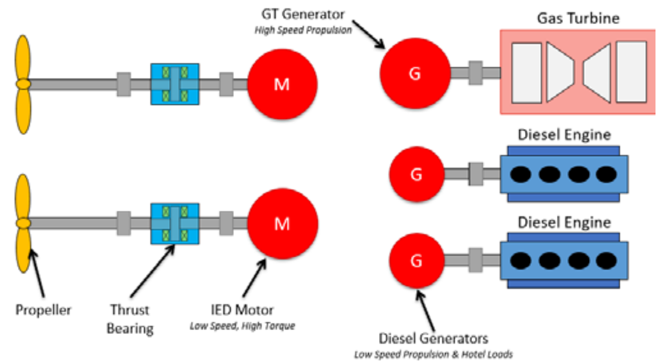

Fig. 11. Typical IED system for naval vessel (electrical interconnections removed for clarity)

A. *Characteristics of Integrated Electric Propulsion*

As was noted during evaluation of HED propulsion systems, 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 [6] - [8]. Poor off-design efficiency of conventional mechanical driven propulsion systems warrant replacement with

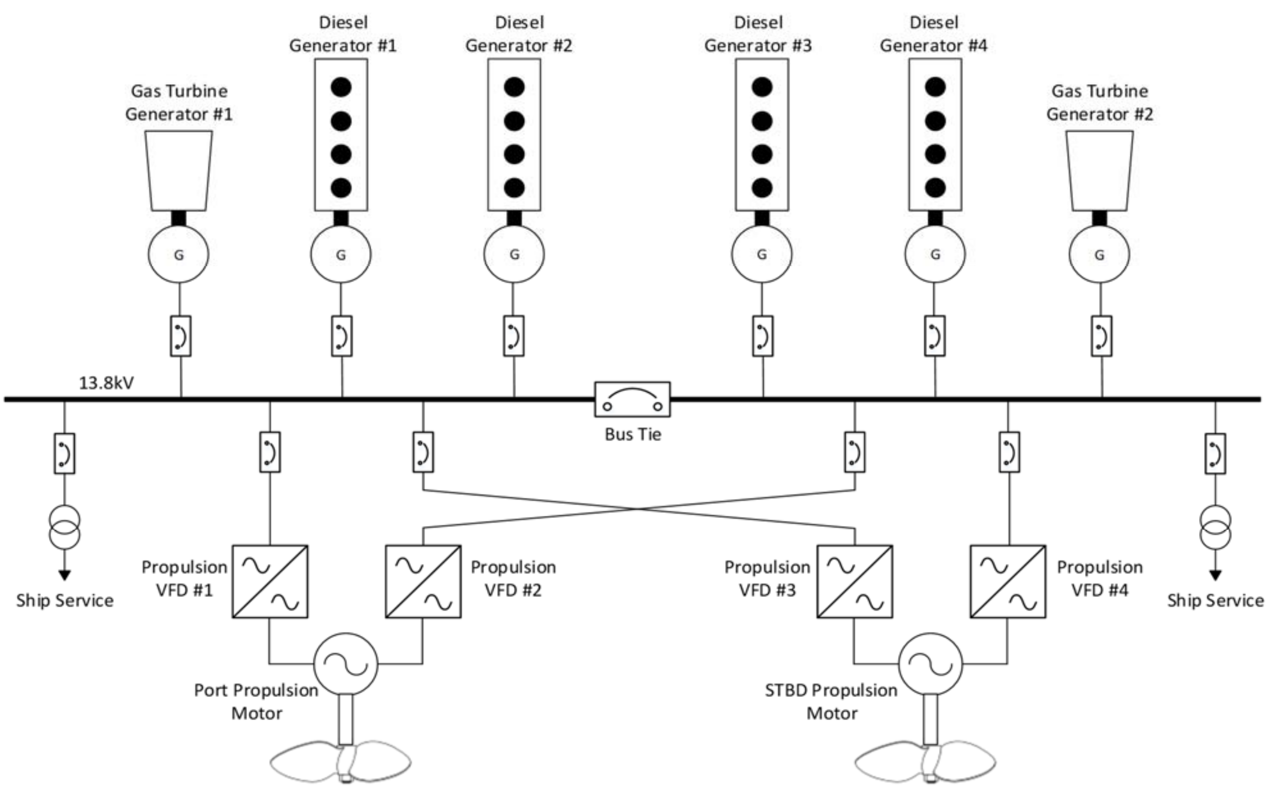

Fig 10. Notional IED system for CVX-Class aircraft carrier

an IED propulsion system to increase fuel economy. References [3], [10], [17] - [19] provide a comprehensive evaluation of IED systems, which can be deduced into the following operation characteristics of IED propulsion.

- Improved system efficiency, relative to mechanical propulsion
- Reduced number quantity and complexity of prime movers. DDG-1000 replaced two turbines and one gearbox per propeller with a single propulsion motor
- Improved vessel producibility, ergonomics and survivability due to the decoupling of line shafts from GTs and Diesel engines
- Electric propulsion can reduce the propulsion plant's noise signature
- Eliminates need for controllable pitch propeller and related support equipment
- Enhance performance from near full torque at zero speed (e.g. acceleration)
- Allows excess electrical power to be diverted to other future electrical loads like advanced radar and directed energy loads

While there are several benefits to be considered when implemented an IED propulsion system, there can be some drawbacks.

- Relative to HED and mechanical propulsion, the propulsion plant footprint may increase slightly, better suiting IED for larger vessels
- Propulsion motors and VFDs can have a large impact on electric distribution system. Typically mitigated with active rectification or propulsion transformer

Electric propulsion equipment can increase acquisition cost relative to mechanical drive, however these costs will likely be offset by fuel savings over the life of the vessel, and can be reduced further by taking advantage of full IED system capability.

B. Notional IED System for CVX-Class Aircraft Carrier

Similar to what was done when evaluating HED propulsion system, DRS has established a notional IED propulsion system for the CVX-Class aircraft carrier. Due to the notional vessel size and anticipated mission profile a directly coupled IED system, featuring four 11 MW DG sets and two 36 MW GTGs suppling power to the propulsion system and hotel loads is recommended. This configuration will provide n-1 redundancy and enhanced flexibility to optimize vessel fuel consumption during low and moderate speed operations.

Relative to DRS' proposed HED system, the IED distribution voltage has been increased to feature a 13.8kV split bus design. This voltage was selected due to the vessel's large propulsion power requirements as well as anticipated ship service loads. Based on DRS' assumed minimum system load, a system voltage of 13.8kV is the only voltage that keeps circuit breaker continuous and fault current values within available standard commercial and navy switchgear ratings.

Each of the vessels two propellers are provided propulsion by a 40 MW permanent magnet propulsion motor. DRS again selected a permanent magnet motor for this application, because of the inherently high and broad efficiency rating afforded by this technology [3], [6], ensuring superior fuel economy during all portions of the mission profile. DRS anticipates that CVX will require approximately 11 MW of ship service power. To ensure adequate ship service and propulsion power, the proposed arrangement includes two redundant GTG and four redundant DG sets.

V. Conclusions

This paper has presented a brief history of electric propulsion, with emphasis placed on naval vessel applications, as well as a comprehensive comparison of hybrid and integrated electric drive for a modern naval vessel. HED propulsion was first reviewed, outlining both gear and shaft mounted motor implementations of this propulsion arrangement. Gear mounted systems were identified as being most economical implementation, whereas shaft mounted offered lower operating costs, coupled with reduced propulsion system noise. Next, DRS proposed a notional HED propulsion system for CVX-Class aircraft carriers. The proposed system incorporated shaft mounted propulsion motors for reduced fuel consumption and low noise signature.

After discussion of HED propulsion systems, this paper reviewed gear mounted and shaft coupled IED propulsion systems. IED was identified as being most attractive for large vessels, such as destroyers and aircraft carriers, with directly driven implementations offering the best performance. Gear mounted IED solutions were reviewed and identified as best suited for small vessels. Lastly, DRS' proposed a notional integrated electric propulsion plant for the CVX-Class aircraft carrier. DRS' proposed system included a 13.8 kV distribution to manage the large electric plant, as well as two 40 MW permanent magnet propulsion motors, directly coupled to the propeller line shafts.

For the modern warship, both IED and HED propulsion systems offer significant advantages over conventional mechanical drive. HED is typically best suited for smaller vessels and those applications requiring a power dense solution or low noise signature at low propulsion loads, whereas IED is better suited for large vessels and applications where reductions in propulsion plant noise are desirable at higher speeds or where supporting large electrical loads is required or envisioned to be needed in the future.

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