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U.S. NAVY AEGIS DESTROYER HYBRID ELECTRIC DRIVE

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SYNOPSIS

Energy has a direct impact on warfighting effectiveness and energy security has become a strategic as well as an operational imperative for the world's navies. The U.S. Navy is committed to ensure that the execution of our critical missions is not dependent on petroleum-based energy resources. One of the ways of achieving this is by the early adoption of new technologies that reduce our exposure to energy volatility. New technologies are required to improve the fuel efficiency of Navy ships to increase endurance, enhance operational flexibility and support forward presence and distributed operations while reducing the vulnerability inherent in a long supply line tether. This paper reviews the background supporting the Hybrid Electric Drive initiative for DDG 51 Class guided-missile destroyers, presents an approach to leverage the significant Navy investment in integrated power systems technologies to support potential increases in future weapon systems electrical power requirements, and discusses system integration challenges of incorporating new technologies within the constraints of an existing machinery plant design.

Authors' Biographies

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INTRODUCTION

In 2006 the U.S. Department of Defence's (DoD) Defence Science Board (DSB) created a Task Force to examine the department's Energy Strategy. Citing significant risks to both our nation and our military forces, the Task Force was challenged to find opportunities to reduce DoD's energy demand, identify institutional obstacles to their implementation, and assess their potential commercial and security benefits to the nation. Recognizing the increasing scarcity, volatility, and environmental impact of petroleum-based energy resources, the U.S. Navy initiated studies in 2007 to assess the viability of installing a Hybrid Electric Drive (HED) system in DDG 51 Arleigh Burke Class Aegis guided-missile destroyers to reduce fuel consumption through electric propulsion and later began to evaluate increased capacity in available ship service power generation. Since being introduced into the Fleet, DDG 51 destroyers have seen a continued increase operational tempo, accounting for an excess of forty-percent of the U.S. Navy's surface ship fuel consumption. Fuel savings from the HED system will be achieved by utilizing fewer gas turbines for propulsion and ship service power generation while also loading gas turbines at their optimal operating condition.

The U.S. Navy's recent request to truncate the DDG 1000 Zumwalt Class destroyer program and restart production of the DDG 51 destroyers to expand warfighting capacity and capability in areas needed by Combatant Commanders presents a unique challenge for the Science and Technology community. The DDG 51 Class was developed in incremental flights, with upgraded technology and capability built into subsequent ships. The departure baseline configuration for new surface combatants added to the DDG 51 Class includes 9 megawatts (MW) of electrical power for mission and support systems. In contrast, the DDG 1000 Class design provides up to 78 MW using an Integrated Power System (IPS) that manages power between propulsion, mission, and support systems loads. Technology advancements resulting from significant investment from the U.S. Navy and its allied partners in power and propulsion systems provides an opportunity to integrate an energy efficient plant architecture and increase available ship service power generation for the DDG 51 Class. The Royal Navy has gained experience in electric drive technology with the acquisition of the Type 45 Destroyer with IPS and with the Combined Diesel-Electric and Gas Turbine powering the Type 23 Frigate. Similarly, the U.S. Navy has acquired knowledge with the recent demonstration of its first hybrid gas turbine-electric propulsion system in USS MAKIN ISLAND (LHD 8). Despite these technological advances in electric drive applications, significant system integration challenges remain within the constraints of the existing DDG 51 Class design.

The DDG 51 Class multi-mission destroyers will represent the majority of the U.S. Navy surface combatant force over the next several decades, conducting missions against air, surface, and sub-surface threats. In order to continue to pace the threat throughout their expected service life, Aegis Destroyers will likely need to meet increasing electrical power demands for future sensors and weapons. These increased demands may impact the ship's existing power plant architecture. As the scope and technological sophistication of ballistic and anti-ship cruise missiles increases, enhanced sensor and weapon system capabilities will be required. Further, the evolution of asymmetric threats to naval forces will continue to require new technology solutions for lethal and non-lethal shipboard defence applications. An innovative approach will be required to reduce fuel consumption and satisfy increased electrical power demands for advanced sensors and future weapons in the DDG 51 Class and future U.S. Navy surface combatants.

DISCUSSION

As oil prices rose to historic levels in July 2008, reaching a peak of $147 per barrel, Navy Department senior leadership expressed an interest in accelerating an acquisition program for HED back-fit for DDG 51 Class destroyers and pursuing its application for CG 47 Class cruisers. Acceleration would permit the Navy to start capitalizing on the strong return on investment sooner than planned and make a meaningful contribution to the U.S. Navy's goal of reducing dependence on foreign and non-renewable sources of energy. Oil prices have declined in response to the drop in world oil demand and slow economic growth resulting from the global financial crisis; however, the U.S. Navy has not lost momentum in its efforts to increase energy efficiency and has developed a Task Force charged with transforming its energy posture. Plans are underway to accelerate the demonstration of HED capability in a DDG 51 Class destroyer, and HED has been established as a top priority within the U.S. Navy's energy task force. An acquisition strategy will be required for a formal U.S. Navy program and, if funded, such a strategy could be developed to permit full production of an HED system with Initial Operational Capability (IOC) within the 2010-2015 Future Years Defence Program (FYDP).

Senior Navy leadership has also expressed an interest in evaluating HED for new construction ship design as a means of expanding the trade space if additional electric power generation is required to satisfy increased electrical power demands for advanced sensors and future weapons. As is the case with most advanced technologies like HED, the innovation is in the application. If enhanced air and missile defence capabilities are required prior to fielding of the Next Generation Cruiser, CG(X), Aegis Cruisers and Destroyers may require modifications to incorporate advanced sensors beyond the capability of the current SPY-1 radar [1], driving additional electrical power requirements. Increasing power demands are also projected to enable the introduction of future weapon systems, as identified in Figure 1.

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1 O'Rourke, R., 'Navy DDG-1000 and DDG-51 Destroyer Programs: Background, Oversight Issues, and Options for Congress', CRS Report for Congress, RL32109, 14 November 2008

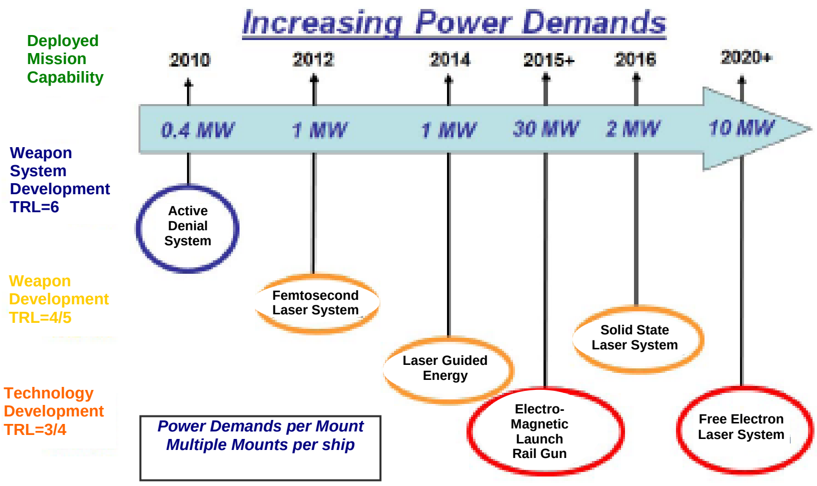

FIG.1 - INCREASING WEAPON SYSTEM POWER DEMANDS

Several emerging directed energy and electric weapon technologies will be introduced over the next decade to enhance mission capability. Active Denial System (ADS) and Laser Weapon System (LaWS) are two directed energy capabilities of particular interest for today's Fleet of Aegis Cruisers and Destroyers. ADS is a weapon developed as an Advanced Concept Technology Demonstrator (ACTD) to solve non-lethal counter-personnel challenges for the military [2]. Advancements in next-generation active denial technology, which reduces the size of current ADS prototypes, may be suitable for maritime applications such as security and counter-piracy operations. LaWS will provide a directed energy engagement element to augment the existing Mk 15 Close-In Weapon System (CIWS) with defensive capability to counter several asymmetric threats and extend the effective CIWS range and provide enhanced lethality [3].

INITIAL CONCEPT FEASIBILITY AND TRANSITION TO PRODUCTION

DDG 51 Class ships currently employ LM-2500 Gas Turbines Main (GTM) engines exclusively for propulsion and 501K Gas Turbine Generators (GTGs) exclusively for electrical power generation. Operational profiles show that the DDG 51 Class spends the majority of its operating time at less than 14kts [4]. Light turbine loading at slower speeds places the LM-2500s in an inefficient region of their Specific Fuel Consumption (SFC) curves over a substantial portion of their operating hours. Similarly, the normal configuration of the electric plant is to have two GTGs on-line for redundancy, resulting in light loading of the GTGs.

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[2] Scarber, K., 'Overview of the DoD Non-Lethal Weapons Program', Intelligence Oversight Journal, Vol 1, Issue 2, pp 4-5 (July 2008)

[3] Kiel, D., et al., 'A Vision for Directed Energy and Electric Weapons In the Current and Future Navy', Proceedings, ASNE Fuel Tank to Target: Building the Electric Fighting Ship Symposium, 25-26 June 2007

[4] Clayton, D., Doyle T., 'A Fuel Savings Cross-Connect for the DDG-51', Proceedings, ASNE Advanced Naval Propulsion Symposium, 30-31 October 2006

In 2007, the U.S. Navy sponsored two industry concept feasibility studies to determine if an affordable, technically viable HED system could be produced for back-fit applications into DDG 51 Class Destroyers. The first study focused on utilizing a 1.2 MW bi-directional electric propulsion/generation drive system, attached to the existing propeller shafts [5]. Superconducting homopolar, permanent magnet axial flux, and permanent magnet transverse flux direct-drive motor technologies were evaluated as part of the initial industry concept study. The second industry study focused on utilizing two permanent magnet motor/generators, rated at 1.14 MWs, mechanically connected to existing couplings of each Main Reduction Gear (MRG) [6]. Both studies concluded that HED systems for DDG 51 Class destroyers could be operated for ship propulsion at low ship speeds, where the required shaft power is relatively low, and as a generator for propulsion-derived ship service at higher ship speeds.

The U.S. Navy also performed an independent energy efficiency study and conducted trade space exploration using the SeaQuest computational model to prioritize technology investments [7]. Criteria, including return on investment, reduction in fuel consumption throughout the DDG 51 Class expected service life, non-recurring engineering costs, impact on availability, in addition to a comparison of competing architectures, were considered in the analysis. This evaluation reduced the field of 10 conceptual designs down to three leading solutions requiring more detailed analysis. In 2008, the Navy defined requirements for a Proof of Concept (PoC) system consisting of 1.5MW Permanent Magnet Motors (PMM) connected to each MRG at the lower intermediate speed shaftline, controlled by adjustable speed drives. The PoC design leverages technology from DDG 1000 Class and U.S. Navy Electric Ships Office (ESO) developments consisting of a PMM and Power Electronics Modules (PEMs) similar to those designed for DDG 1000 electric propulsion and Integrated Fight Through Power Systems. See Figure 2.

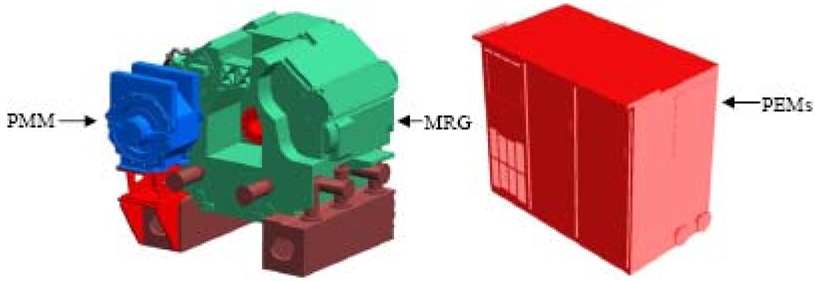

FIG.2 - PROOF OF CONCEPT PERMANENT MAGNET MOTOR AND POWER ELECTRONICS MODULES

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[5] McCoy, T., et al., ‘Hybrid Electric Drive for DDG 51 Class Destroyers’, Naval Engineers Journal, Vol 119, Issue 2, pp 83-91 (November 2007)

[6] Reed, G., et al., ‘Economic Benefits of Hybrid Electric Drive Propulsion for DDG-51 Class Ships’, Proceedings, ASME Turbo Expo: Power for Land, Sea, and Air Symposium, 9-13 June 2008

[7] Robinson, M., et al., ‘Intelligent Tools Used in the Design of Navy Ships’, Naval Engineers Journal, Vol 120, Issue 1, pp 41-49 (May 2008)

For the initial PoC phase, a PMM design was selected as a leading motor candidate because of the physical arrangement constraints defined by the existing DDG 51 Class design and its demonstrated commercial performance in harsh conditions, such as offshore drilling rigs. It is important to note that alternate motor designs and other compact power conversion technologies will be evaluated for DDG 51 Class application before the HED system enters full production. Candidate technologies include designs whose performance characteristics are understood over a range of heavy industrial and military applications, such as the induction motors incorporated into USS MAKIN ISLAND (LHD 8). It is envisioned that an expanded competitive prototype plan will be introduced to the PoC phase to further reduce technical risk, validate designs, evaluate manufacturing processes, refine requirements, and accelerate fielding within the 2010-2015 FYDP. Technology refresh can be made possible through an open architecture business model [8] where interfaces are defined and specified by the U.S. Navy's ESO, which will result in standard and open interfaces, competitive module development, technologically refreshable systems, and more affordable systems.

In order to prudently manage risk for the PoC phase, a "build-a-little, test-a-little" strategy for system development and production was adopted, as depicted in Figure 3. Increment 1 consists of an Electric Propulsion System (EPS) mode where, at low ship speeds (<14 knots), the PMM provides EPS operation. In this mode, all four LM-2500 main engines can be shut down and significant fuel savings realized while the ship is motoring.

Increment 2 will add a Propulsion Derived Ship Service (PDSS) electric power mode that, when ship speed exceeds 14 knots, generates electricity and places power back on the distribution bus with the PMM now acting as a generator. Current DDG 51 Class engineering operating procedures require the ship to maintain at least two GTGs on-line at all times to reduce the risk of losing ship service and mission power resulting from a faulted condition or electrical/mechanical failure. Light loading, resulting from operating GTGs in parallel for redundancy results in poor operating efficiency, significantly increasing DDG 51 Class fuel consumption. Increment 2 enables the engineering plant to be configured with a single 501K ship service generator on line at speeds above 14kts, thus achieving additional fuel savings.

Increment 3, leveraging investment from the Navy's Office of Naval Research (ONR), will incorporate an energy storage capability in the future where advanced marine battery modules, when mature, would provide an Uninterrupted Power Supply (UPS), thus enabling single ship service gas turbine generator operations throughout the entire mission speed-time profile, without sacrificing the requirement for two separate sources of ship service power. The energy storage capacity would meet ship electric power requirements until off-line generators could be started, thereby avoiding "dark ship start" and enhancing quality of ship service power.

[8] NAVSEA 05D/Ser 349, "Next Generation Integrated Power System NGIPS Technology Development Roadmap", 30 November 2007

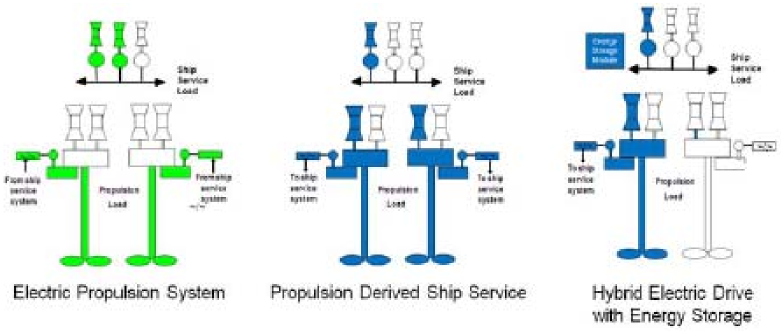

FIG.3 - HYBRID ELECTRIC DRIVE MODES OF OPERATION

Material procurement commenced for Increment 1 in 2009 with factory testing and delivery to the Navy's Land Based Engineering Site (LBES) in Philadelphia, Pennsylvania scheduled for 2010. U.S. Navy personnel in Philadelphia provide Research, Development, Test and Evaluation (RDT&E) and in-service engineering for ship propulsion and electrical power generation systems, utilizing the LBES in the Richard C. Cunningham engineering complex for testing of IPS technologies and architectures and the DDG 51 Class propulsion plant. Demonstration at LBES will consist of rigorous integration testing with the laboratory's Machinery Control System (MCS), MRG, and electrical distribution system prior to sea trial demonstration in an in-service DDG 51 Class ship. The at-sea demonstration for Increment 1 will evaluate the system in a dynamic environment that cannot be simulated ashore; i.e., propeller loading and un-loading, and actual shipboard electrical system characteristics. This land-based and at-sea testing and evaluation is intended to prove the HED concept in order to de-risk future system acquisition programs.

MEETING THE CHALLENGES

Significant system integration challenges remain to incorporate a HED system within the constraints of an existing DDG 51 Class machinery plant design. The PoC system will serve to demonstrate the ability to effectively interface with the existing DDG 51 Class MCS, MRG, and electrical distribution system.

The proposed controls architecture for HED will have minimal impact on the operator during propulsion mode, enabling operation in much the same manner as standard propulsion. Throughout the PoC phase, a balanced assessment of impacts to the existing DDG 51 Class MCS versus required automation functions for operation is being considered for the controls architecture. MCS algorithms and interfaces from the HED Supervisory Control System (SCS) to MCS and Shaft Control Units (SCUs) will be required to demonstrate HED capability. Computer program and equipment changes will be minimized during the PoC phase while maximizing system functionality for improved fuel economy. A measured approach to retiring MCS risks while ensuring minimal change from present shipboard Concept of Operations (CONOPS) will be required to accelerate the introduction of HED. The successful demonstration of propulsion mode operation will provide the foundation for additional MCS changes required to support additional electrical power generation capacity. Proposed HED controls architecture incorporated into the existing DDG 51 Class MCS is provided at Figure 4.

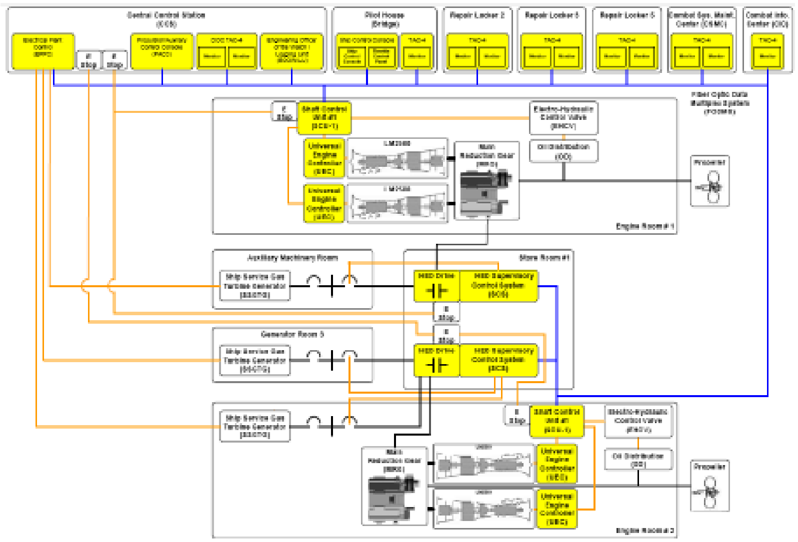

FIG.4 - PROOF OF CONCEPT SYSTEM CONTROL BLOCK DIAGRAM

Selection of the MRG as the HED motor interface presents technical challenges because of the precise tolerances of the MRG's design. For the PoC system, the HED motor will be connected to the MRG at the lower intermediate speed shaftline (Figure 5). Extensive analysis will be performed during the PoC phase to ensure the mounting location of the HED motor does not impact the MRG's mission-critical propulsion plant operation. To this end, the Navy has specified an overrunning clutch with manual lock-in and lock-out modes to ensure the HED motor can be manually disconnected in the event of an engineering plant casualty. Additional analysis is underway to assess the effects of the motor on alternating torque, short circuit torque, impacts to snubber settings, in addition to any changes from the original MRG torsional analysis. Following successful demonstration of the HED PoC system and incorporation into a full production program, the HED system will be analyzed for stress under a shock load using advanced computational analysis.

FIG.5 - PROOF OF CONCEPT MECHANICAL INTERFACE TO MRG LOWER INTERMEDIATE SPEED SHAFTLINE

Interfacing with the existing electrical distribution system, with minimal changes to installed equipment, is required to control the cost, complexity, and installation duration for HED. HED will need to interface with the ship service distribution system to enable propulsion and generation modes of operation without impacting continuity of electrical power to vital loads. In the EPS mode of operation, HED will draw electrical power from the ship service distribution system while supplying electrical power in PDSS mode. Initial ship integration assessments identified spare connectors within the existing switchboards as the rating of the 1.14MW PMM was within the switchboard main bus rating. Subsequent PoC design and requirements definition for a 1.5MW PMM have driven the need for a free-standing switchboard enclosure, containing both breakers and breaker controls, increasing the scope of the installation. If increasing power demands drive additional electrical power generation requirements beyond the capacity limits of the existing ship service distribution system, further assessment of shipboard space constraints, and existing design margins of the DDG 51 Class will be required.

CONCLUSION

System integration and technology development challenges to reduce fuel consumption while balancing the need to evaluate mission requirements for additional electrical power generation are not insignificant, however adoption of innovative technologies such as HED will be required to transform the U.S. Navy's energy posture and pace the threats facing the Fleet over the next several decades. Since it is always desirable to keep technological risk in the Scientific Research and Technology Development domain, we intend to leverage investments from the U.S. Navy's ONR, and Small Business Innovation Research (SBIR) programs to develop and transition technologies capable of reducing fuel consumption, improving power conversion efficiency, and increase installed power generation density for U.S. Navy surface combatants. Technology insertion opportunities for HED currently include 62 Aegis Destroyers (DDG 51-112) and 22 Aegis Cruisers (CG 52-73), under the cognizance of the Naval Sea Systems Command Surface Warfare Directorate. As additional DDG 51 Class Destroyers are authorized for construction in subsequent fiscal years and future U.S. Navy surface combatants are indentified in long-range plans for construction, HED should not only be considered for applications to reduce U.S. Navy dependence on petroleum-based resources, but should also be considered within the trade space as an effective alternative to deliver additional electrical power for future warfighting requirements.

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