Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-45902

Integrating A Hybrid Electric Drive Propulsion System with the Existing DDG 51 Class Machinery Control System

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ABSTRACT

The destroyers of the USS Arleigh Burke Class all have 4 propulsion gas turbines and 3 gas turbine generators (GTGs). A typical at-sea "condition 3" operating profile consists of having 2 gas turbine generators running at approximately 50% capacity, and one propulsion gas turbine online at low to intermediate ship speeds. Having 2 GTGs online at all times at 50% load each provides the obvious advantage of maintaining all electric loads should one GTG shut down unexpectedly. This luxury does come at the cost of fuel efficiency, as gas turbines efficiency improves continuously as they move away from idle.

On the propulsion end, a single gas turbine is capable of generating enough horsepower to propel the ship at speeds in excess of 20 knots. Depending upon the specific mission that the destroyer may be on, however, quite a bit of operating profile may be at speeds below 15 knots where the LM2500 is operating at less than 20% capacity. In this range of operation specific fuel consumption ratios are also relatively low.

The proposed Hybrid Electric Drive (HED) system has the potential to address both of these inefficient ranges of operation. By installing one 2000 horsepower electric motor on each shaft, the electric motors can be used to propel the ship at speeds below 14 knots (projected) while running the GTGs up to 90% operating range where they are most efficient. The LM2500 is shut down completely at this range, and the potential fuel savings in this configuration is substantial.

While there are many engineering challenges with installing such a HED system on board an in-service DDG, the focus of this paper is on how to integrate HED with the existing Machinery Control System (MCS). Such challenges include interfacing MCS to the HED supervisory controller, developing a new HED control interface for the propulsion control operator, integrating HED into the existing shaft speed control algorithm, transitioning to and from HED propulsion, and updating data logging to include HED. Managing the interface between current electric load, changing electric loads, and current available HED power will also be addressed.

INTRODUCTION

The USS Arleigh Burke (DDG 51) Class of Destroyers has perhaps been the most successful US shipbuilding program since the 1940s. 60 of the originally planned 62 DDGs have been commissioned since 1991. While the last of those ships will be commissioned as planned in 2012, it has been decided that additional DDG 51 Class ships will be built. The US Navy describes these destroyers as “warships that provide multi-mission offensive and defensive capabilities”. Some of these missions require the 30+ knots that her 4 LM2500 gas turbine propulsion plant can provide. Other missions that these ships support only require low ship speeds for long periods of time. Whether or not this low speed mission profile was envisioned 25 years ago or not, the DDGs were not equipped with any sort of fuel efficient low speed “trolling” motor. Thus, even while only running 1 gas turbine for propulsion, fuel consumption rates are relatively high in this mode of operation.

In an effort to improve fuel economy at low ship speeds, it has been proposed that the excess capacity from 2 online gas turbine generators (GTGs) normally running be used to drive 1 or 2 electric motors designed to propel a DDG without the use of any of the 4 LM2500 propulsion gas turbines (GTMs). On FLT 2A DDGs, each GTG is rated at 3 Megawatts (MW). That is approximately equivalent to a typical entire ship service load. Each GTG typically operates at 50% load so that the loss of a single generator does not cause the loss of ship's power. This also means that, theoretically, there is another 3MW available to operate additional electric loads. In this case, it is being proposed that two 1.5 MW electric motors be coupled to the reduction gear and utilized for low speed non-critical operations. In a Hybrid Electric Drive (HED) configuration, the projected potential savings in the range of 0-13 knots is projected to be in the range of approximately 150 to 200 gallons per hour. Thus, while there are many technical challenges that lie ahead in integrating HED with the current propulsion and electric plant, the potential fuel savings are substantial.

In addition, it has been proposed that at higher speeds these electric drive motors could be used to generate ship service electricity from the LM2500 main propulsion engines, operating with a single online generator to pick up transient loads. In this mode of operation, called propulsion derived ship service (PDSS), one of the two normally online GTGs would be turned off. Comparing a normal trail shaft configuration with a single GTM and two GTGs online to a proposed PDSS configuration of a single GTM which also provides ship service and a single generator, the potential savings is much less substantial. It should be noted that during less critical missions/operations, some DDGs are willing to operate in single GTG mode in order to save fuel now. Because of this, the amount of fuel that could be saved employing a PDSS mode of operation is much less substantial than it is utilizing electric drive mode. Thus, the focus of near term Navy efforts (and of this paper) is HED mode of operation.

As an initial proof of concept, a single electric motor is going to be added to the single shaft at the Land-Based Engineering Site (LBES) in Philadelphia in 2011. Assuming success at LBES, it is currently planned to then install this set up on a single shaft on the target demonstration ship, the DDG 103, in 2012. The focus of this paper is a discussion on how to interface this new Hybrid Electric Drive system to the existing Machinery Control System (MCS) in an acceptable operational manner while minimizing cost. The MCS on the DDG 103 is largely made up of hard pushbuttons. There are currently very limited color graphics capabilities. Since this is set to be a temporary installation on the DDG 103, it is desired that this change be purely a software modification if at all possible. That means using the existing color graphics for control in ways that it is not currently used. The shaft speed control algorithm will need to be modified and extensively tested to account for this new mode of propulsion plant operation. Communications methodologies between MCS and the new HED local controller will need to be formulated. Data logging will need to be modified to account for new alarms and status changes. It is also a requirement that HED does not put cyclical loads on the electric plant. Due to typical ship rolling, a single shaft HED implementation would indeed likely put cyclical loads on the electric plant, as the current shaft speed control algorithm attempts to maintain an ordered shaft speed. Ship pitching is another possible source of cyclical electric loads. Thus some sort of constant power mode meshed with the desire to maintain shaft and ship speed will need to be developed.

There are many other challenges facing such a HED implementation. They include, but are not limited to, interfacing an electric motor to the Main Reduction Gear, modifying the network to accommodate new users and additional network traffic, ship arrangement modifications, switchboard modifications, load shed logic modifications, and the design of the motor and local supervisory controller itself. They are all beyond the scope of this paper.

PROPULSION AND ELECTRIC MODES OF OPERATION ON THE DDG 51 CLASS OF SHIPS

DDG 51 class ships all have 4 propulsion gas turbines coupled via 2 reduction gear and shafts to 2 controllable pitch propellers. This configuration is capable of propelling the 500+ foot destroyer in excess of 30 knots. This controllable pitch propeller system is designed such that pitch is moved from a zero thrust position at "all stop" (0 knots) to either the ahead or astern directions. Pitch angle is also referred to in "feet of pitch". This refers to how many feet the blade would move in one rotation. An excellent analogy is to think about how far a wood screw would cut into a block of wood with one complete rotation. When the blade is in a neutral position, the shaft is rotating but is not providing any forward thrust. At all stop, the gas turbine(s) are operating at idle. Shaft speed is dependent upon the number of gas turbines online. While the actual horsepower produced is dependent upon ambient air inlet temperature, using an approximation of 200-250 horsepower per turbine on line is a reasonable approximation. With all 4 engines online, shaft speeds at all stop are approximately 60 RPM. Once throttle position is increased, pitch angle increases, engines remain at idle, and shaft speeds decrease. Once pitch is at "100%" (an operationally efficient blade angle), engine speed demand is increased. Shaft speed, and thus ship speed, then increases further. Empirical sea trial data also shows that 4 engines at idle produce enough power to propel the ship at approximately 10 knots. Since 4 LM2500 engines at idle produce approximately 200-250 HP each, or about 1% of its Navy-rated full power, it takes at only about 1% of ship's full power to produce a useful ship speed range. LBES data confirms that in the case of the LM2500s it takes about 10% the fuel used at full power to produce 1% of the full rated power. Power produced is relatively linear for every gallon of fuel burned after that idle point.

During critical operations, such as underway replenishment or pulling into or out of port, all 4 propulsion gas turbines are online for redundancy. Once out of such critical operation scenarios, 3 of the 4 gas turbines are frequently shut down. The most fuel efficient manner in which to operate is on this single propulsion gas turbine due to the amount of fuel it takes to get a gas turbine to idle at low power production.

Frequently, DDGs are in a mode of operation whereby they are essentially loitering on station. In order to maintain positive steering control, a ship typically needs to maintain a speed of only 5 knots. In fact, empirical sea trial data shows us that a single LM2500 at idle providing a mere 200 horsepower or so is sufficient to provide the horsepower required to move the ship at 5 knots. Unfortunately, this means that the LM2500 is operating in the range that it is least efficient. Ideally, there would be another means to turn the shaft at such low power requirements.

The DDG 79-AF class of ships has three 3-Megawatt (MW) Allison 9140 gas turbine generator sets to provide ship's electrical power. They are typically designed to run with 2 generators at half power. Should one generator trip offline, the second generator can carry the ship's electric load while the third standby generator is brought online. Because they have been shown to be very reliable, the gas turbine generators are often operated in a single generator mode in order to increase fuel economy. Since they are considered to be extremely reliable, it means that there is a potential to have 3MW of additional power available for electric motor propulsion. If the smaller gas turbine generator is more fuel efficient producing 2.5 MW (or about 3000 horsepower, conservatively accounting for electric motor losses) via an efficient electric motor than is the larger LM2500 producing 3000 HP in a range where it is not thermally efficient, the potential exists to save fuel.

While the focus of this paper is how to integrate such an electric motor to the existing Machinery Control System, readily available LBES fuel consumption data allow us to quickly see about how much fuel could be saved by such a HED implementation. DDGs frequently operate at 5 knots, which is considered to be the minimum speed required keeping positive steering. If 2.5 MW is about the maximum available generator power given current average ship loads, empirical data shows that approximately 12 knots is the maximum speed that such a HED system could provide. So that is a second point worth checking for fuel savings.

A quick look previous sea trial propulsion data and LBES Allison 9140 fuel consumption data appears to show quite promising potential fuel savings. In order to provide enough power for 5 knots, LBES Allison 9140 LBES data shows that adding 150 KW (approximately 200 HP) adds only 12 gallons per hour to the GTG fuel consumption. Even a 25% loss through the motor and reduction gear means that only 15 gallons per hour is required to troll at 5 knots. At 5 knots, sea trial data has shown LM2500 fuel consumption data to be about 150 gallons per hour, or ten times that amount. At 12 knots, several sea trial data samples show LM2500 fuel consumption to be near 400 gallons per hour, producing 3000 horsepower. A 2 GTGs providing 2500 KW to one or two HED electric motors would require an additional 200 gallons per hour based upon LBES Allison 9140 data. This represents a 200 gallon per hour fuel savings in this configuration. So while these are quick looks, and the business case for Hybrid Electric Drive is beyond the scope of this paper, the potential fuel savings are very real.

TESTING AT THE DDG 51 CLASS LAND-BASED ENGINEERING SITE IN PHILADELPHIA

Since 1988, propulsion and electric plant testing has taken place at the DDG 51 Class Land-Based Engineering Site (LBES) in Philadelphia. On the propulsion side, this test site has 2 LM2500 Propulsion Gas Turbine Modules coupled to the same reduction gear that steps down power turbine speeds of up to 3600 RPM to 168 Shaft RPM. This load is absorbed by a water brake. On the electric plant side, 2 Electric Plant Gas Turbine Generators and 2 Switchboards feed load banks capable of absorbing in excess of 6 megawatts of power. Over the past 20 years, these propulsion and electric plant gas turbines have been interfaced (both via hardwiring and networking) with 4 different generations of machinery control systems and 3 different network configurations from two different ship classes. LBES also has the capability of simulating the second shaft that is on each DDG, along with simulating various auxiliary and damage control sensors. A complete list of LBES uses and capabilities is certainly beyond the scope of this paper.

The current plan is to bring a single electric motor to LBES and connect it to the existing reduction gear. The electric motor would be fed by the existing LBES switchboard. The electric motor controller will be networked via the existing scaled down version of shipboard network. The existing Machinery Control System will be modified in order to interface the operator to HED in a manner described below.

INTERFACING HYBRID ELECTRIC DRIVE WITH THE MACHINERY CONTROL SYSTEM

The current Machinery Control System architecture on the target ship class consists of two local Shaft Control Units (SCUs), one Propulsion Auxiliary Control Console (PACC, the normal propulsion operating station), one Electric Plant Control Console (EPCC), one Engineering Officer of the Watch (EOOW) data monitoring and logging console, and seven Damage Control Workstations (DCWs). All MCS information is available at all consoles and workstations. The SCUs and EPCC are hardwired to the plant, with the SCUs having an additional Ethernet interface to each LM2500 engine controller.

The current MCS consoles have hardwired pushbuttons cut into steel consoles, and modifying the consoles to add new hard pushbuttons and indicators would be an expensive proposition. In order to provide the operator insight to and control of the HED system, the most cost effective change would be to modify the MCS color graphics screens on the Shaft Control Units (SCUs) and Propulsion Auxiliary Control Console (PACC). Such a similar interface modification has been done this way before. The DDG 78 was the first ship to get a Redundant Independent Mechanical Starting System (RIMSS), which is essentially a small gas turbine started with a battery that can be used to start a generator without the use of high pressure or bleed air. Modifying the original EPCC console with several new hard pushbuttons would also have been expensive and time consuming. Thus, that successful model is being followed. Color graphics screens have subsequently been added to all DDG 83-AF MCS consoles. If the concept of operations allows for sufficient operator interface via the MCS color graphics applications available on the DDG 83-AF consoles, then a “software only” change to MCS would be possible. Emergency stop functionality may or may not be done via a 28 volt closed contact system.

In order to interface MCS to the local HED controller, status and control messages will be sent back and forth over the shipboard Fiber Optic Data Multiplex System (FODMS), a network that also has hardwired interfaces to various flooding and fire sensors, firemain valve control and indication, and other auxiliary systems. An Interface Design Document describes the frequency of communications, data error checking, and bit by bit message content. This communications schema and data content is described the subsequent section.

COMMUNICATIONS FLOW VIA FODMS

Currently, the DDG 51 Class Machinery Control System consoles are divided into propulsion plant and electric plant control consoles, with both being independently monitored by qualified propulsion and electric plant operators in the Central Control Station (CCS). The first challenge will be to provide the propulsion plant console operators information and control of the HED via the shipboard data and control network, the Fiber Optic Data Multiplex System (FODMS). The MCS consoles on the DDG 83-AF currently interface to FODMS via redundant NATO STANAG 4156 interfaces. However, MCS interfaces with Ethernet-based Damage Control Workstations (DCWs). Thus a communications schema between Ethernet-based devices and MCS already exists and would be utilized for the new MCS-HED communications interface.

Current MCS console to console communications update at a rate of 2 Hz. This data rate makes sense in this new communications interface, as the shaft speed control algorithm is only updated at a rate of 2 Hz. Hybrid Electric Drive controls are implemented across a network of interconnected hardware and software components. Primary devices in this architecture are the Shaft Control Unit (SCU), an interface controller between the local motor controller, and the motor controller itself. The Shaft Control Unit is the DDG-51 MCS propulsion console and is the topmost controls component.

The Shaft Control Unit is the propulsion control console of the DDG-51’s machinery control system. Responsibilities of the SCU include processing of sensed propulsion plant data, remote control of equipment, thrust and pitch control, and interfacing with the plant operator. This console is directly connected to the propulsion plant and has visibility into all of the plant signals and data. This console is modified to communicate with the SCS by way of the DDG-51 class shipboard network, namely the Fiber Optic Data Multiplexing System (FODMS). Modifications also include calculation of HED power available, implementation of the over-arching state machine, and integration with the ships propulsion control algorithms.

The local supervisory controller is the component of HED controls that lies logically between MCS and the motor controller. For the purposes of this paper, the local controllers and motor itself are being treated as a “black box”. The interface between MCS and that HED black box are described below.

The messages between all components of the HED system are similar in nature. These messages generally consist of a header, payload, a date and time, and a checksum. The headers contain such information as size, source, and sink. Payload data uses 16 bit word format and carry analog, discrete, ASCII, and calculated data values. The date and time data are synchronized to ship’s clock and the checksums are 2’s compliment. Figure 1 is a sample MCS – SCS data message.

Item Name	Word Position Message / Body	Type/Size	Range	Scaling/Offset
Standard Header	0 / -			
EPS ON Command	2 / 0	bit 0	0 = not ON 1 = EPS ON	N/A
EPS OFF Command		bit 1	0 = not OFF 1 = EPS OFF	N/A
Breaker Open Command		bit 2	1 = open the HED breakers	N/A
Breaker Close Command		bit 3	1 = close the HED breakers	N/A
(x31) SPARES	3 / 1	(x31) words	-	-
EPS Horsepower Command	34 / 32	AN	0-2200 HP	x0.53724 = HP
EPS Available Power	35 / 33	AN	0-1500 kW	x0.3663 = kW
Shaft RPM	36 / 34	AN	0-200 SRPM	x0.04884 = SRPM
Standard Footer				

Item Name	Word Pos Msg / Body	Type/ Size	Range	Scaling/ Offset	Low Fault	Low Alarm	High Alarm	High Fault
Sensor Values – Other, from the SCS:								
Horsepower Limit Parameter	52 / 50	AN	0-2200 HP	x0.5372 = HP	N/A	N/A	N/A	N/A
Speed Limit Parameter	53 / 51	AN	0-1100 RPM	x0.2686 = RPM	N/A	N/A	N/A	N/A
Torque Limit Parameter	54 / 52	AN	0-26,000 ft-lbs	x6.349 = ftlbs	N/A	N/A	N/A	N/A

Figure 1 – Sample MCS-SCS Data Message

MONITORING AND CONTROL VIA THE EXISTING GRAPHICAL UNIT INTERFACE (DDG 83-AF)

Currently, the DDG-51 MCS exposes a graphical HMI as an option for monitoring and controlling both the electric and propulsion plants. This will be the main method of controlling Hybrid Electric Drive. The nature of this schema is “soft” and no hardware modifications for control will be necessary. This software runs on a separate processor within the MCS consoles and interfaces with a primary MCS processor via a shared memory interface. An operator will be able to enter and exit HED mode as well as monitor system permissives and operating parameters from these graphics screens. Figure 2 depicts a notional screen. Values displayed are MCS permissives such as valid communications with other system nodes and propulsion plant permissives, engineering data, and system state data. Command buttons are also present.

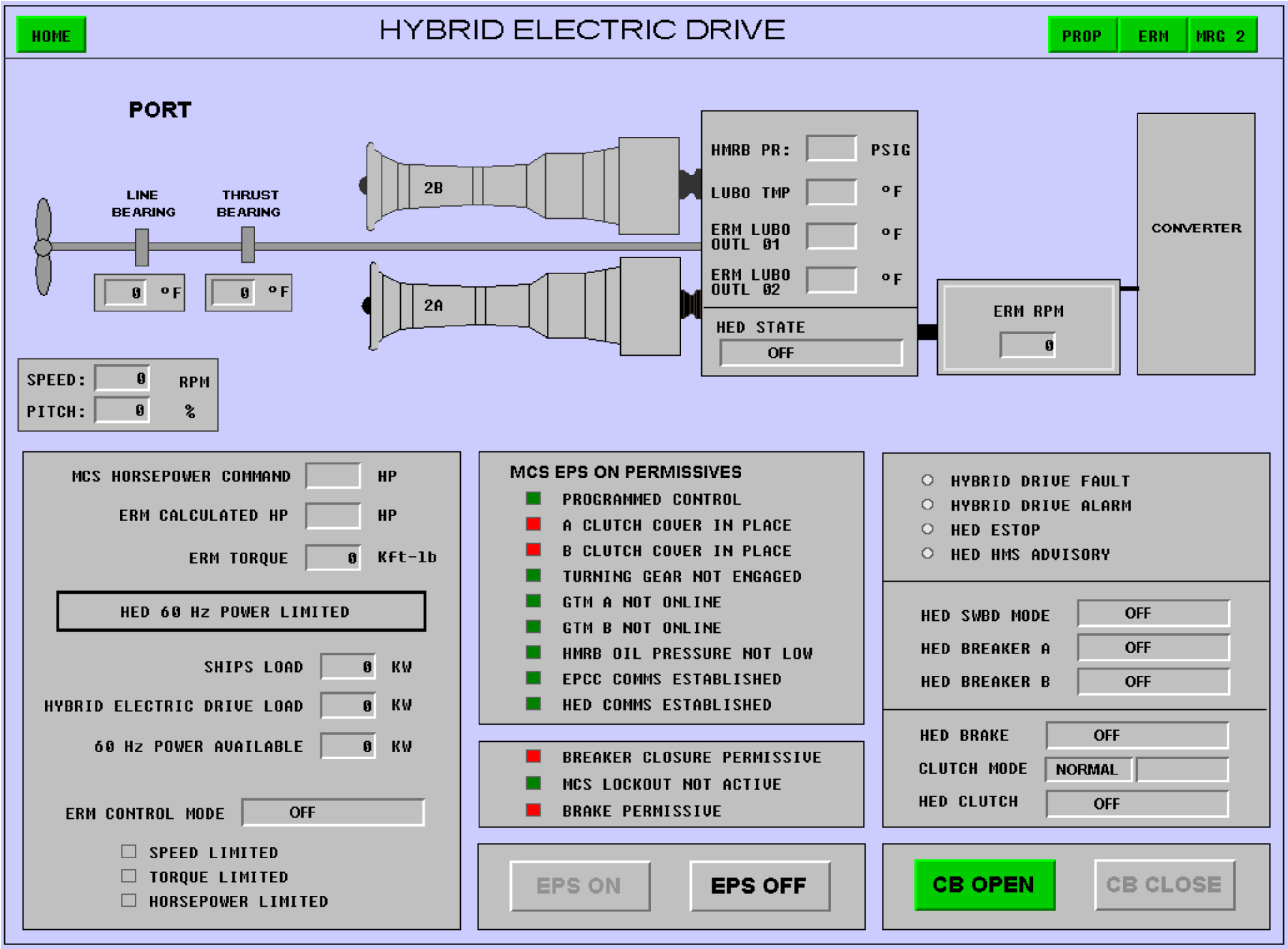

Figure 2 – Notional Graphics Screen

The MCS software on the primary processor will also be modified in order to facilitate running in Hybrid mode and monitor additional parameters that are not shown on the graphics screen. Such parameters need not be monitored during operation from the graphics screen but may be instrumental in troubleshooting casualties. The notional screen in Figure 3 shows a summary grouping of selected signals as well as individual analog signals selected for display on the bottom 9 lines of the screen.

INTERFACING HED TO THE CURRENT SHAFT SPEED CONTROL ALGORITHM

The current shaft speed control algorithm is designed to automatically take throttle inputs from the bridge, central control station, and local control console. The algorithm modifies pitch settings and horsepower commands and the net result is a ship speed that is approximately linear with throttle movement. It also automatically cuts horsepower when pitch travels through zero thrust pitch settings during ahead to astern or astern to ahead operations, and boosts horsepower during increasing ahead transitions above what would be required at steady state in order to improve ship response. There are currently 3 normal plant configurations: full power (all 4 engines online), split plant (one GTM per shaft), and trail shaft mode with one driving GTM and the other shaft "wind-milling".

Hybrid Electric Drive mode will then add a fourth mode of operation. It is most likely that it will be more efficient to run HED in a split plant mode, vice having one electric motor online and the other shaft trailing. However, for this first proof of concept only one shaft on the DDG 103 will be getting HED. It will be no doubt interesting to see if having HED online on one shaft with a GTM online on the other shaft leads to reasonably steady shaft speed control or not, as response to changing horsepower demands from the electric motor will no doubt be different than the GTM response.

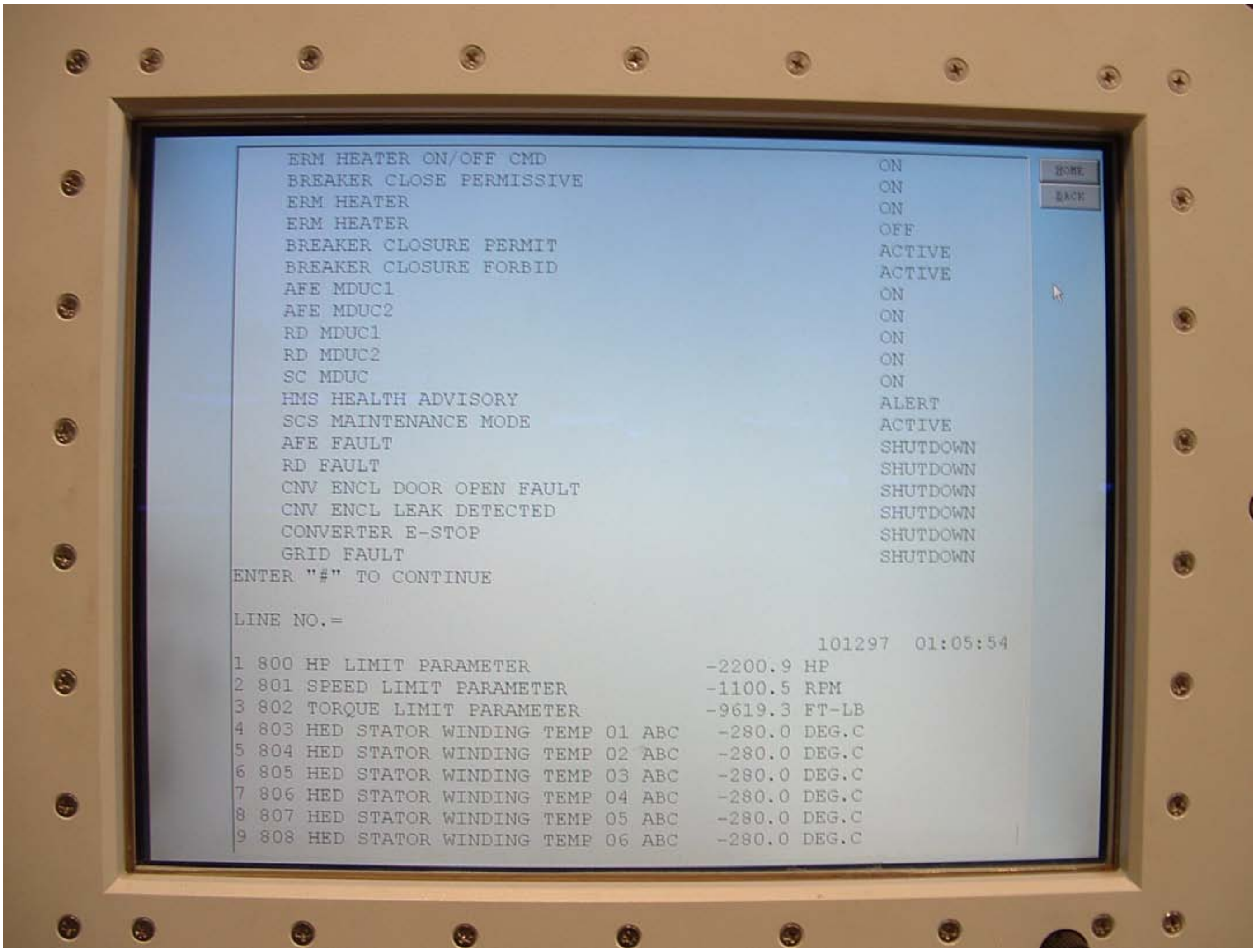

Figure 3 - Summary Grouping of Selected Signals

In this mode, 2 GTGs are driving both ship service and 2 electric motors at low ship speeds. RPM and Pitch schedule could remain the same as it is now, whereby constant HP is demanded and pitch essentially ramps to 100% at 7-10 knots. It is unclear whether or not the HED vendors would provide a different more fuel efficient schedule or if the existing pitch schedules would be used. However, if new RPM and Pitch Control schedules are provided by the HED vendor for electric drive operation, they can be added. Note, if there are 3 engines ONLINE, the shaft with 2 engines ONLINE utilize a full power schedule and the second shaft operates on a split plant schedule. This state is typically only achieved when transitioning briefly from split plant to full power or full power to split plant modes.

Adding an electric drive mode would add a 5th mode to shaft operation. It would have to be determined as to what the limitations were on the electric motor concerning when it could be “clutched” in or out of driving mode. Such limitations would be maximum shaft speed for clutching in and out. A Concept of Operations would be necessary as well. For example, would the shaft be turning at idle speed at “all stop” when shifting into electric drive mode? Would this mode only be used during condition 3 steaming?

In all likelihood, the SCUs would limit throttle input to approximately 4.0 (Limits to a little over 3000 HP in both directions according to trail shaft driving schedule, 2.92 Ahead and -1.4 Astern) PCL in the ahead direction and a TBD value in the astern direction. The command and control values correlating to this PCL value are then sent to the electric motor interface (provided by the vendor). The specific behavior and limits of these data items will be discussed in interface development coordination with the vendor. It is still to be defined whether or not the SCU needs to limit the ramp rate of the demanded horsepower or whether the electric motor interface would limit the ramp rate in order to minimize the current draw from the switchboard interface.

It would be reasonable to check with the vendor to see if there are optimum electric motor speeds at which to operate.

It is possible that the shaft even turn at 1 single speed with only pitch being modified if it would enable more efficient operation. Based on the operating range of the electric motor, it is possible that the identical RPM and Pitch schedule would be used. A slightly different RPM and Pitch schedule designed to maximize GTG fuel efficiency and ship speed in electric drive mode could also be developed.

It is unclear at this time whether or not it would be desirable to add a function at the SCUs to detect if an electric motor were to trip offline due to the loss of a generator or some other reason. The current design specifies that during unknown and non standard plant configurations a minimum horsepower value of approximately 200 HP be issued. The SCU could automatically start a LM2500 if a loss of electric motor were detected. Determining whether or not such a function would be needed would most likely be derived from the Con-Ops. It is assumed that any function designed to trip an electric motor offline would come from the load-shed logic in the switchboards. However, it is possible that this function could be moved to the SCUs in advance of reaching a load-shed condition. Such casualty control scenarios should probably be addressed in a separate white paper.

IMPLEMENTATION AND TESTING AT LBES

In order to test changes to MCS, a message simulator would first be developed to prove that each bit in the interface messages being sent to and from MCS to HED is being processed properly. In this way, the control and status messages defined a future interface design specification can be tested prior to receiving any actual HED equipment. A MCS message emulator could also be developed and delivered to the HED vendor(s) in order to provide a way for those vendors to perform initial message testing and troubleshooting.

LBES also maintains a complete simulation of the propulsion and electric plant that could theoretically be modified to add electric motors to each shaft for additional simulation based testing. Both analog and discrete I/O signals that compose the plant interfaces to MCS are electrically stimulated according to plant operation profiles. This method will be used for both the new DDG 111 Machinery Control System testing and the DDG 51 Modernization testing efforts in 2009 and 2010. The message emulator and plant simulation hardware will be interconnected via an Ethernet interface. This will allow electrical feedback into the MCS system based on demands from the MCS to HED message and facilitate the ability to fully test the software at LBES. This is a more significant effort than developing the message emulators, but would provide a more robust test and would greatly enhance the confidence in the Machinery Controls Interface with HED.

It is unclear if the HED control system with the communications module can be separated from the HED electric generator/motor and be sent to LBES prior to sending the entire HED unit. It would be beneficial to perform such integration testing in advance of receiving the HED unit as there would be less impact to other currently scheduled LBES. At that point, interfacing MCS to HED should be assured to be a success. Mechanically interfacing HED to the switchboards and MRG are beyond the scope of this paper.

CONCLUSIONS

The concept of Hybrid Electric Drive is certainly very appealing from a fuel economy perspective. From 0 to about 12 knots, projected fuel economy savings ranges from about 150 to 200 gallons per hour. Challenges in making HED a reality include physical arrangement, the reduction gear interface, the electric plant interface, the network interface, and the Machinery Control System interface. Each of these interfaces themselves would be worthy of a technical paper such as this paper discussing MCS to HED interface. MCS to HED interface challenges include creating the network interface message in each direction, new HED status and alarm messages to the operator, color graphics representation and control interface, data logging, shaft speed control interface, the electric plant “power availability” interface, and engine state logic interface. While those MCS to HED interface challenges are considerable, there is currently a clear path forward to the successful integration of the DDG 51 Class Machinery Control System to Hybrid Electric Drive both at LBES, on the DDG 103, and on future implementations.