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LHD 8: A Step Toward the All Electric Warship

ABSTRACT

The recently commissioned *Iwo Jima* (LHD 7) is the last ship with conventional steam propulsion that the U.S. Navy plans to build. The LHD 8 is the next ship of the class and will be built as a modified repeat design of the LHD 7. The key modifications are steam propulsion being replaced with a hybrid propulsion system of main gas turbine engines augmented with auxiliary propulsion motors and electric powered auxiliaries replacing those powered by steam. The LHD 8 will also be the first USN surface ship to implement a 4160 VAC Zonal Electrical Distribution System (AC ZEDS) as well as the integrated power system concept for electrical power generation, distribution and propulsion. These modifications embody the intent of the all electric warship concept for the future U.S. Navy. This paper presents the constraints and issues involved in the design process by addressing major design impacts and significant design concerns. This text explores the design options within the available trade space and illustrates specifically how the fleet / mission requirements, LHD 7 hull design and propulsion shafting constraints, schedule and funding drove the propulsion system design.

INTRODUCTION

The 40,500 ton 844 ft ships of the *Wasp* (LHD 1) class of amphibious assault ships (Figure 1) are designed to support Marine Corps air and amphibious assaults against defended positions ashore. The propulsion plant for the first seven ships of the Wasp class consists of two independent steam boilers and two 35,000 hp steam turbine engines capable of driving the ship at over 20 knots. This basic steam propulsion approach was adopted from the earlier, circa 1960’s, steam propulsion plant of the *Tarawa* (LHA 1) class. In the early 1990s the U.S. Navy made a general decision to phase out conventionally powered steam ships due to the high cost of maintenance and manning. During construction of the LHD 5, 6 & 7, the Navy conducted a global search to replace the steam plant with alternative power systems. At that time a General Electric LM2500 gas turbine engine (25,000 hp) was the only gas turbine engine qualified for propulsion of U.S. Navy ships and inadequate by itself to replace a 35,000 hp steam turbine plant.

FIGURE 1 - Amphibious Assault Ship (LHD 2 – *Essex*)

Because gas turbine engine ducting must be routed through the island structure, gas turbine propulsion for an LHD requires a tremendous amount of internal volume that may displace equipment in many existing spaces. Studies have shown that although two gas turbine engines per shaft would provide ample power, they would not fit in the existing machinery spaces without major impacts to the surrounding spaces and the engine ducting would severely impact the ship arrangements. With commercial development of the General Electric LM2500+ gas turbine engine (35,000 hp), it became conceivable to fit a single gas turbine engine into a LHD at power levels comparable to the steam turbine plant it would replace. Although conceptual studies were conducted to fit LHD 7 with one LM2500+ gas turbine engine per shaft, the ship was too far into construction to make such a major change. Accordingly, *Iwo Jima* (LHD 7) is the last ship in the U.S. Navy to be built with a conventional steam plant and LHD 8 will be the first ship in the U.S. Navy to use an LM2500+ gas turbine.

PROPULSION PLANT DESIGN HISTORY

In preparation for the design and construction of LHD 8, the U.S. Navy initiated a series of feasibility studies (References 1 and 2) aimed at developing a gas turbine propulsion concept and reducing Total Ownership Costs (TOC) over the expected 40 year service life of the ship. Early results of this study showed that TOC could be drastically reduced simply through the predicted reduction in crew size of at least 80 personnel and decreased maintenance requirements associated with the removal of steam turbine engines and boilers. To minimize design and construction costs, a number of constraints were placed on the design:

- Maintain the existing shaft line rake and skew of the steam propulsion plant to retain the same *Wasp* (LHD 1) class hull hydrodynamic characteristics
- Limit design changes to the second stage of the reduction gear to maintain the manufacturing lead time needed to support the ship construction schedule
- No Marine Corps missions could be degraded
- Minimize the impact to adjacent non-machinery spaces
- Allow only reasonable machinery arrangement changes

The amphibious assault ship operating profile is such that over 75 % of the underway time the ship requires less than 10,000 hp for propulsion to travel at speeds up to twelve knots. Because a single 35,000 hp gas turbine engine is lightly loaded at this power level, the specific fuel consumption of a gas turbine plant is very unattractive and well off its most fuel-efficient design point over much of the ship's operating profile. Although these feasibility studies were not predicated on supplementing the gas turbine engines with an electric propulsion system, their analysis did indicate that significant fuel savings could be realized by augmenting the gas turbine propulsion with electric propulsion. As a result, propulsion motors were integrated with the gas turbine engines at a relatively modest 1600 hp per shaft, which is capable of driving the ship to roughly six knots under ideal wind and sea conditions. Another recommendation from these studies was to retain a small auxiliary boiler for heating and hotel services. This design feature ensured that the 450 VAC electric plant would essentially be maintained at roughly the same size as previous ships in the class by simply replacing the same number of steam turbine generators with diesel generators of comparable power level and density. Although the TOC savings were sufficient to justify the conversion to gas turbine propulsion in manpower and maintenance reductions alone without electric propulsion, the addition of an electric propulsion system enhanced those savings.

The design concept for the LHD 8 was further refined to totally eliminate all shipboard steam heating for spaces, laundry, cooking and other hotel services, resulting in a greatly increased electric plant capacity. Consequently, the generation and distribution system voltage was increased to 4160 VAC to meet the additional load demand for electric heating on a cold day. With the removal of the steam auxiliaries, the worst case load demand changed from a mission scenario of debarking on a 90^0 F day to a cruise condition on a 10^0 F day. It was then realized that the ship had as much as 8 MW of excess generating capacity under typical climatic conditions of a 70^0 F day (Figure 2).

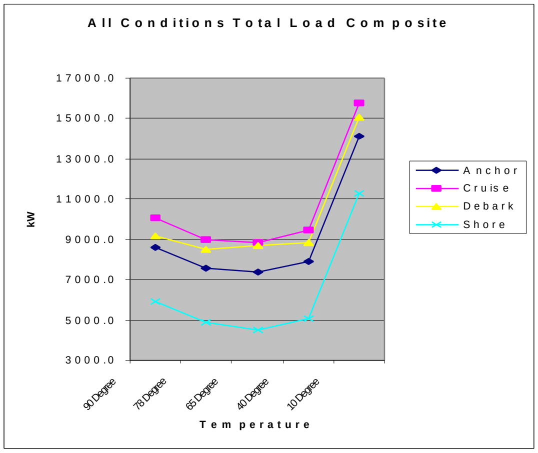


FIGURE 2 - Predicted LHD 8 ship service power demand loading curves without anticipated service life load growth margin

This excess capacity could support electric propulsion considerably larger than the 1600 hp propulsion motors originally planned anytime it was warmer than the extreme design condition of a 10^0 F day. Since the propulsion motors are not mission essential (the ship can fulfill all mission requirements using the gas turbine engines alone), larger propulsion motors could be incorporated without requiring an increase in the total electric plant generating capacity. Accordingly, follow-on study determined the optimal propulsion motor rating to be 5000 hp per shaft, which was subsequently incorporated into the final design.

PROPULSION PLANT DESIGN

The propulsion system for each of the two shafts of the LHD 8 consists of a single main gas turbine engine (LM2500+ at 35,000 hp) and an auxiliary propulsion motor (5000 hp) driving a two-stage reduction gear into a controllable pitch propeller (CPP) (Figures 3 and 4). The gas turbine engines drive the reduction gear through an overrunning self-synchronizing clutch. The first stage reduction gear casing is modified from the LHD 7 design to accept the single gas turbine engine and propulsion motor input, in lieu of the high and low pressure steam turbine engines. The single gas turbine engine input pinion splits into two locked power train drives. The propulsion motor drives through a self-synchronizing clutch into one of the two locked train first stage reduction gears. The existing shaft rake and skew were retained and modifications to the second stage reduction gear have been minimized to only that necessary to fit the CPP hydraulic oil distribution box. The length of the gas turbine engine module in the machinery rooms required moving the reduction gear several feet aft from the prior ship design location. This was beneficial since it eliminated one section of line shafting.

While the reduction gear ratios for the gas turbine engines and propulsion motors are identical, the maximum shaft speed of 180 rpm from the gas turbine engine is twice that from the propulsion motor at 90 rpm. Propulsion is provided from either the gas turbine engine or the propulsion motor, but not both simultaneously. Transitioning from propulsion motor to gas turbine engine drive and back is allowed over the entire speed / power range of the propulsion motor.

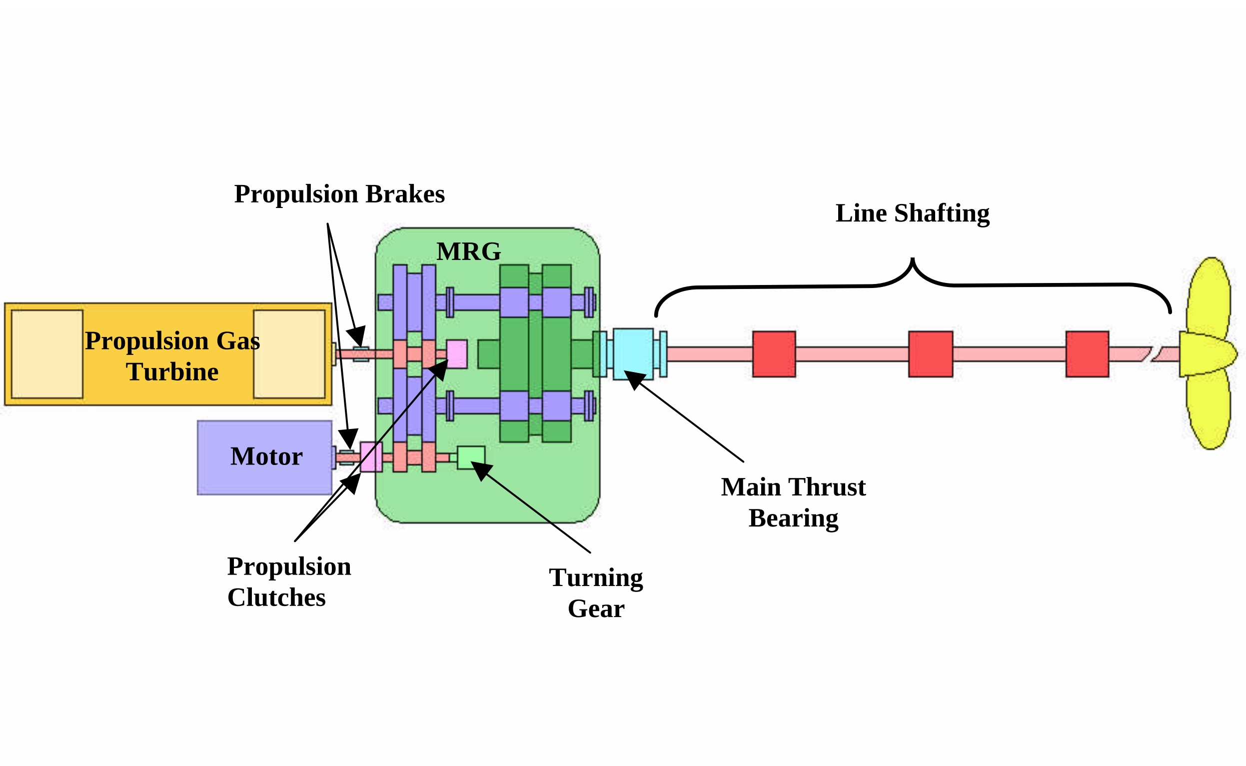


FIGURE 3 - Conceptual diagram of shaft propulsion power train arrangement for LHD 8

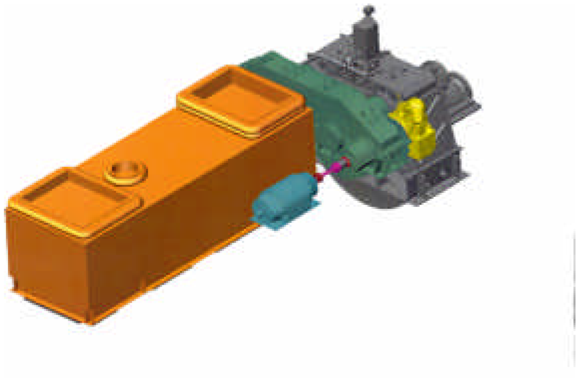


FIGURE 4 - Sketch of shaft propulsion power train design concept for LHD 8

ELECTRIC PLANT DESIGN HISTORY

During the LHD 8 feasibility studies several options for the electric plant were explored that were based on ship construction cost, life cycle cost, survivability, maintainability and feasibility of the design to support the load increase from the removal of steam and incorporation of electric heaters and auxiliaries. As shown in the load analysis summary (Table 1) for each design condition, the worst case scenario was during a cruise condition on a 10^0 F day when approximately 19 MW of power was required to operate the ship. In comparison, a 90^0 F day cruise condition requires only 11 MW of power.

Table 1 - Predicted electrical load analysis summary with anticipated service life growth margin

DAY TEMP	ANCHOR	CRUISE	DEBARK
^{0}F	MW	MW	MW
10	16.6	18.6	17.4
90	10.0	11.5	11.0

Although a traditional U.S. Navy 450 VAC electrical power distribution system was initially considered for LHD 8, the operating configuration of such an electric plant was much too awkward to be practical. In a 450 VAC power distribution system no more than two 2.5 MW generators can be paralleled due to the maximum interruptible fault current capacity of standard 450 VAC

U.S. Navy circuit breakers. This limitation would require ship's force to operate too many separate electric plants (at least three) to support the maximum power demand. This added complexity was deemed unacceptable.

The only practical alternative to a 450 VAC power system was to increase the power generation and distribution system voltage to reduce the operating and fault currents to a level which existing switcher could handle. Because the U.S. Navy has design and operational experience with 4160 VAC power systems and U.S. Navy qualified 4160 VAC circuit breakers exist, this voltage level was selected as the low risk choice. A 4160 VAC electric plant design allowed six 4 MW diesel generators, sufficient to power all margined loads, to fit into the proposed engineering spaces within the LHD 8. Also, the electric plant offered maximum operational flexibility by being able to parallel up to five generators, or all but the standby generator, without exceeding the maximum interruptible fault current capacity of the 4160 VAC U.S. Navy circuit breakers.

Since most loads on the ship are derived from 450 VAC, a power distribution system architecture was needed for routing the 4160 VAC power, converting the 4160 VAC power to 450 VAC, and distributing the 450 VAC power. After reviewing several previous U.S. Navy electric plant designs as well as looking at current and future electric plant designs, an AC Zonal Electrical Distribution System (AC ZEDS) was selected. This application of AC ZEDS is based on partial and full system designs implemented on DDG 51 Flight IIA class destroyers and LPD 17 class amphibious assault ships, respectively and includes using multifunction monitors (MFM III) to enhance the response to multiple faults from battle damage weapon effect scenarios. When compared to radial distribution system architectures of previous classes of ships, AC ZEDS provides an electric plant that weighs less and is both highly survivable and recoverable from battle damage faults.

ELECTRIC PLANT DESIGN

The configuration of the AC ZEDS architecture is a 4160 VAC power generation and primary power distribution system for zone to zone power distribution as well as 450 VAC secondary power distribution for supplying power to loads within each of the fire / electrical zones (Figure 5). The 4160 VAC primary power distribution consists of two longitudinal buses located port and starboard in a high and low orientation in the ship to enhance survivability. Each of the longitudinal buses consists of four switchboards and the associated interconnecting cable. Eight transformers are used to connect the primary power distribution switchboards to the 450 VAC secondary power distribution systems. The six diesel generators are installed with two located in each forward and aft main machinery room (MMR) space and one located in each forward and aft generator room. Each generator has an associated switchboard capable of feeding power to switchboards on either the port or starboard longitudinal bus. This permits independent operation of 4160 VAC generation and power distribution system as port and starboard electric plants. This electric plant configuration establishes two sources of power throughout the ship and provides the flexibility to align generators as required for each electric plant. It should be noted that each section of the electric plant is isolated by circuit breakers to ensure maximum protection and survivability to isolate any damaged sections of the bus and reconfigure the electric plant to maintain or restore power as quickly as possible. The electric propulsion system may be powered from a dedicated generator in each MMR or from either longitudinal bus.

Each switchboard on the port and starboard buses connects to a 3.5 MVA, 4160 VAC / 450 VAC ship service step down transformer located within that electrical zone to power ship service loads in the local zones via the 450 VAC secondary power distribution system. Each of these ship service transformers has an associated 450 VAC ship service distribution switchboard that feeds multiple ship service load centers to power ship service loads in the local zones. These load centers are either in the same electrical zone or in the adjacent electrical zones as the ship service transformer and associated switchboard. Each load center then feeds the ship service loads within its respective electrical zone. Vital loads are provided normal and alternate power sources via automatic bus transfer (ABT) devices that are provided power from load centers connected to switchboards fed from the port and starboard buses.

Forward and aft 4160 VAC shore power receptacles are provided from three of the 4160 VAC switchboards, two amidships and one aft. The shore power distribution system is centerline oriented to support either port or the starboard connections to the ship from the pier. Shore power connections at 4160 VAC were chosen over the traditional 450 VAC shore power connections for the following reasons:

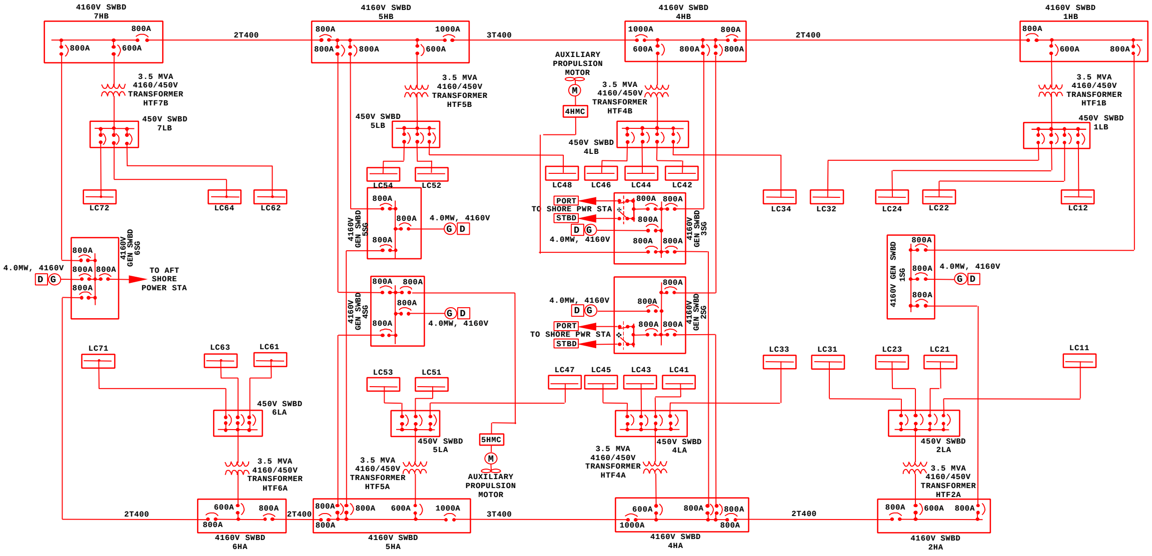
- Supplying 13 MW of shore power on a 10º F day at 4160 VAC would only require three versus over fifty shore power cables, connection boxes and switchboard circuit breakers at the 450 VAC design.

` - Shore power at 450 VAC would have required either large, heavy transformers to convert the 450 VAC to 4160 VAC for compatibility with the port and starboard longitudinal busses, or extensive cabling to each of the eight 450 VAC distribution system zonal load centers and an awkward power transfer procedure

- The piers likely to be used by LHD 8 in her eventual home port are not capable of providing 13 MW of 450 VAC power to a single ship. Piers in LHD 8's eventual home port will have to be upgraded regardless of the shore power voltage. Installing a shore power connection to provide 13 MW of shore power would be considerably cheaper at 4160 VAC than at 450 VAC.

AUXILIARY PROPULSION SYSTEM (APS) DESIGN HISTORY

As previously indicated the initial feasibility studies introduced the auxiliary propulsion motor design concept for ship loitering capability with a relatively modest 1,600 hp per shaft. This was accomplished by fitting two 800 hp propulsion motors at 450 VAC atop the second stage reduction gear and driving into pinions meshing with the first stage reduction gear train. When the generation and distribution of the electric plant was increased from 450 VAC to 4160 VAC, the propulsion motor size was increased from 1,600 hp to 2,000 hp. This occurred because a propulsion motor with a higher voltage rating could fit in the same machinery space footprint and the increased size of the electric plant could provide more power. Further study on the type and size of propulsion motor recommended the use of a single speed AC induction motor since an AC synchronous motor, a DC motor or any two speed motor would be significantly larger as shown in Table 2 (Reference 3). AC permanent magnet and super conductive motors were also considered as propulsion motors, but were deemed far too developmental in terms of risk, cost and schedule impact at the power level required.



NOTES: 1) ALL LOAD CENTERS ARE 2000A
2) “*”, “◆”, “✠” , “❖” = INTERLOCKED
3) ALL 4160V CABLE TO BE TYPE LS5KV

FIGURE 5 - Electric plant one line diagram design concept

TABLE 2
COMPARISON OF PROPULSION MOTOR TYPE OPTIONS

MOTOR TYPES	RELATIVE SIZE	RELATIVE COST	RELATIVE RISK
DC	max dia	near min	min
AC SYNC	near max dia	near min	min
AC INDUC	near min dia	min	min
AC PM	near min dia	near max	near max
AC SUPER-C	min dia	max	max

Additional analysis (Reference 4) confirmed that the optimal propulsion motor size was between 3000 hp to 5000 hp and indicated a slight improvement in investment return with a 5000 hp propulsion motor. A 5,000 hp propulsion motor was also the appropriate size based on the largest frame size AC induction motor that would physically fit without major impacts to the reduction gear design and having a power demand within the capacity of one diesel generator. With 75% of the ship’s operating profile and a ship speed of over 12 knots possible with the 5,000 hp propulsion motors, the loiter motor title was no longer appropriate. Once the decision was made to go forward with the 5,000 hp design, the propulsion motor and associated drive was renamed more appropriately as the auxiliary propulsion system. To accommodate the larger size of the 5000 hp propulsion motor, a separate foundation was added adjacent to the gas turbine engine foundation. In this arrangement the size of the propulsion motor became restricted to that which would fit between the edge of the gas turbine engine module enclosure and input shaft centerline of the reduction gear.

The initial APS design concept required the shaft to be spinning before energizing the propulsion motor because the limited starting torque of a relatively small single speed induction motor was not sufficient to start a stopped shaft. Normally this would entail the gas turbine engine powering the shaft, but the shaft could spin without shaft input power if the ship happened to have sufficient speed to cause water windmilling of the propeller.

The single speed aspect of the propulsion motor also caused a concern for CPP blade cavitation. Since the propulsion motor would only operate at a nominal rated speed of 1800 RPM, altering the blade pitch angle of the propeller controlled ship speed. At lower ship speeds and minimal thrust there was a risk of cavitation on the suction side of the propeller blades. Also, since transitions were required “on-the-fly” from gas turbine engine to propulsion motor, speed matching and synchronization had to be accomplished by manipulating gas turbine engine speed only since the propulsion motor speed was fixed.

To minimize propulsion motor inrush currents and avoid having to dedicate up to three generators to provide start-up torque for even an unloaded propulsion motor, a reduced voltage (soft) start concept was incorporated into the original design. All of these design issues were considered manageable, except for the inability of the propulsion motor to start a stopped shaft.

The next design iteration provided the APS with the capability to “pick-up” a stopped shaft and thereby allows the APS to operate independently from the gas turbine engine. While adding this capability would not reduce operating costs, this feature was highly desired by the ship operators during the fleet review of the APS design and its operation. The near proximity of the propulsion motor to the gas turbine engine meant a larger propulsion motor frame size beyond the 5000 hp for an AC induction motor was not possible. This ruled out using 5000 hp DC motors, even though DC motors could more easily develop the requisite starting torque.

Other design approaches of moving the propulsion motor foundation farther from the gas turbine engine to accommodate a larger AC induction motor frame to develop more starting torque would increase the propulsion motor pinion size. The associated loss of mechanical advantage from such a change would offset any increase in propulsion motor starting torque. Of course, changing the gear ratio (smaller pinion) to provide more mechanical advantage at startup would lower the full rated shaft speed. However, a gear ratio change would not be acceptable since the propulsion motor would be unable to reach its full rated load capacity at full or even maximum propeller blade pitch angle. A torque assist motor option using a hydraulic motor to break the static friction of the bearings to reduce the starting torque requirement for the propulsion motor was also considered. This unconventional concept would also require soft motor starting for the torque assist motor and an additional clutched drive interface with the reduction gear. The torque assist motor approach was not considered practical since it would require more design lead time for additional gear redesign than was available.

If the 5000 hp AC induction motor were capable of developing rated torque at zero speed, it would be able to start a stopped shaft. The design option of full voltage starting was quickly dismissed because the high inrush currents dictated that at least four of the six ship service generators need to be dedicated to the propulsion motor for starting. Low voltage starting was not feasible either since it could not develop the required starting torque. A variable speed drive (VSD), provided the capability of developing full rated torque at start-up within the power capability of a single generator. However, VSD power electronics cabinets are relatively large and difficult to locate in an existing ship design with limited space available. Moreover, in order to maintain the power quality requirements for the ship service bus, VSDs typically require large phase shifting transformers and perhaps large passive filters.

After considerable study, as indicated by Tables 3 and 4, the VSD design option was chosen as the method to achieve the required propulsion motor start-up torque because it is affordable and an acceptable machinery arrangement was identified. Despite the significant impact of VSD on ship arrangements, it is the best means of developing the required propulsion motor torque and maintaining acceptable power quality from the primary power distribution system or powering from a single dedicated generator. The VSD solution was also chosen to help solve the potential propeller cavitation problem by providing the capability of lowering the propeller speed as power is decreased, which was not possible from a single speed propulsion motor. The capability to vary shaft speed also allowed flexibility in controlling the transitions between the gas turbine engine and APS to include the propulsion motor as well gas turbine engine.

AUXILIARY PROPULSION SYSTEM DESIGN OPTIONS

Once VSDs were chosen as the propulsion motor drive, a final study was undertaken to determine the range of design solutions possible as depicted in Table 5 (Reference 6). With regard to the VSD size,

TABLE 3
PERFORMANCE COMPARISON OF PROPULSION MOTOR STARTING OPTIONS

MOTOR STARTING OPTIONS	MOTOR DESIGN BASIS IN CURRENT	MOTOR DIAMTR FIT AT 5000 HP	QTY OF 4 MW GEN SETS	MIL SPEC PWR QUAL W/2 GEN SETS 50% LOADED
Full Voltage Starting	**6 x rated**	**probably**	**six**	**yes**
Low Voltage Starting (r, xfmr or soft)*	**not applicable since unable to develop required torque to turn a stopped shaft**			
Variable Speed Control (PWM)	**1 x rated**	**yes**	**one**	**yes**
Torque Assist Motor With Low Voltage Starting	**2 - 3 x rated**	**probably**	**at least two**	**yes**

*** indicates resistance, transformer and power electronics soft starting methods**

TABLE 4
IMPACT COMPARISON OF PROPULSION MOTOR STARTING OPTIONS

MOTOR STARTING OPTIONS	SYS SIZE	SYS WT	SYS COST	SYS RISK
Full Voltage Starting	1 x	1 x	1 x	none
Low Voltage Starting (r, xfmr or soft)*	2 – 3 x	2 – 3 x	2 – 3 x	not feasible
Variable Speed Control (PWM)	3 – 4 x	3 – 4 x	4 – 5 x	minimal
Torque Assist Motor With Low Voltage Starting	1.5 x	1.5 x	2 – 3 x	high

*** indicates resistance, transformer and power electronics soft starting methods**

TABLE 5*
COMPARISON OF APS DESIGN OPTIONS+

APS OPTIONS	COST	SIZE	IHD - THD VOLTS	IN-RUSH CURRENT CONCERN	RISK	TOTAL
6 pulse w/filters	4	3	< 1 - < 1	no	1	8
12 pulse w/o filters	3	2	1.6 - 2.5	yes	3	8
24 pulse w/o filters	2	1	0.7 – 1.3	yes	2	5
Active rectifier	1	4	na	no	unsat	na

*** a rating of greater value means better performance**
+ the MIL spec power quality requirement is individual and total harmonic distortion in terms of voltage of 3 % IHD and 5 % THD

transformerless designs are expected to result in lower converter size, but need further evaluation to ensure that the motor insulation system will not be stressed. A six-pulse rectifier requires substantial filtering to achieve the level of power quality required on a naval ship. Passive filtering is space intensive and active filtering would require development. A pulse width modulated (PWM) rectifier or active front end converter is feasible, but would also require development. For VSD designs incorporating transformers, twelve, eighteen and twenty-four pulse rectifier designs could provide adequate power quality performance without filters. Unfortunately, a very large single propulsion transformer would be difficult to arrange within the limited height of the machinery spaces. Although a split design option consisting of two propulsion transformers equal to the rating of the required single transformer is possible, this option may be just as difficult to locate within the machinery spaces due to the additional switchgear necessary for two transformer connections. The actual selection of VSD topology and technology will be left to the shipbuilder / vendor team during the detail design.

By functioning as a non-mission essential propulsion system, the APS can be commercial-off-the-shelf (COTS) based and obviate some demanding military requirements, such as Grade A shock qualification. This requirement to remain fully operational after a shock event has been one of the key reasons preventing the application of modern COTS power electronics based AC electric propulsion systems in naval ships. However, the APS still requires Grade B shock qualification of not injuring or being a safety hazard to personnel or causing other damage that results in the failure of any Grade A shock qualified equipment. Similarly, the APS has no acoustic or other survivability performance requirements since it is designated as non-mission essential.

Typically, the U.S. Navy requires that a propulsion system for each shaft be located within a single machinery room to minimize its vulnerability. This ensures that damage outside a machinery compartment, other than to the shafts or their bearings, does not disable an entire propulsion system. In the case of the APS, no such requirement limits its arrangement to within a single machinery space. As previously mentioned, incorporation of the VSD required a lot of space to locate equipment enclosures for power electronic cabinets and perhaps transformers and filters. The existing hull design did not allow locating all the required APS equipment in the forward MMR. Normally this would be an unacceptable design, but since the APS is not mission essential, all of the APS equipment, except the propulsion motor, was preliminarily located in the adjacent AMR as indicated in the notional machinery arrangements (Figures 6 and 7).

PROPULSION SYSTEM CONCEPT OF OPERATIONS

The propulsion system concept of operations (CONOPS) was developed by the ship design team (Reference 7) ahead of the system specifications as guidelines for defining the overall propulsion system performance and APS system design, interface and control requirements. This was a necessary starting point since there were no mission requirements and TOC reduction goals are not firm performance requirements. The propulsion system CONOPS was also used to develop APS purchase specifications and factory, dockside and sea trails requirements. The propulsion system CONOPS will likely continue to be used as a basis for developing Machinery Control System (MCS) hardware and software requirements as well as Engineering Operating Station (EOS) operating procedures and technical instruction manuals.

The basic propulsion system CONOPS to describe the overall propulsion system performance is as follows:

- Power quality criteria

Integrated Generation and Propulsion Mode - MIL-STD-1399 power quality must be retained under worst case conditions of two generators operating to support ship service loads equal to the rating of one generator during APS ship propulsion loading (evaluated in terms of harmonic content and frequency and voltage response to ramp loading to rated propulsion power and step unloading from rated propulsion power)

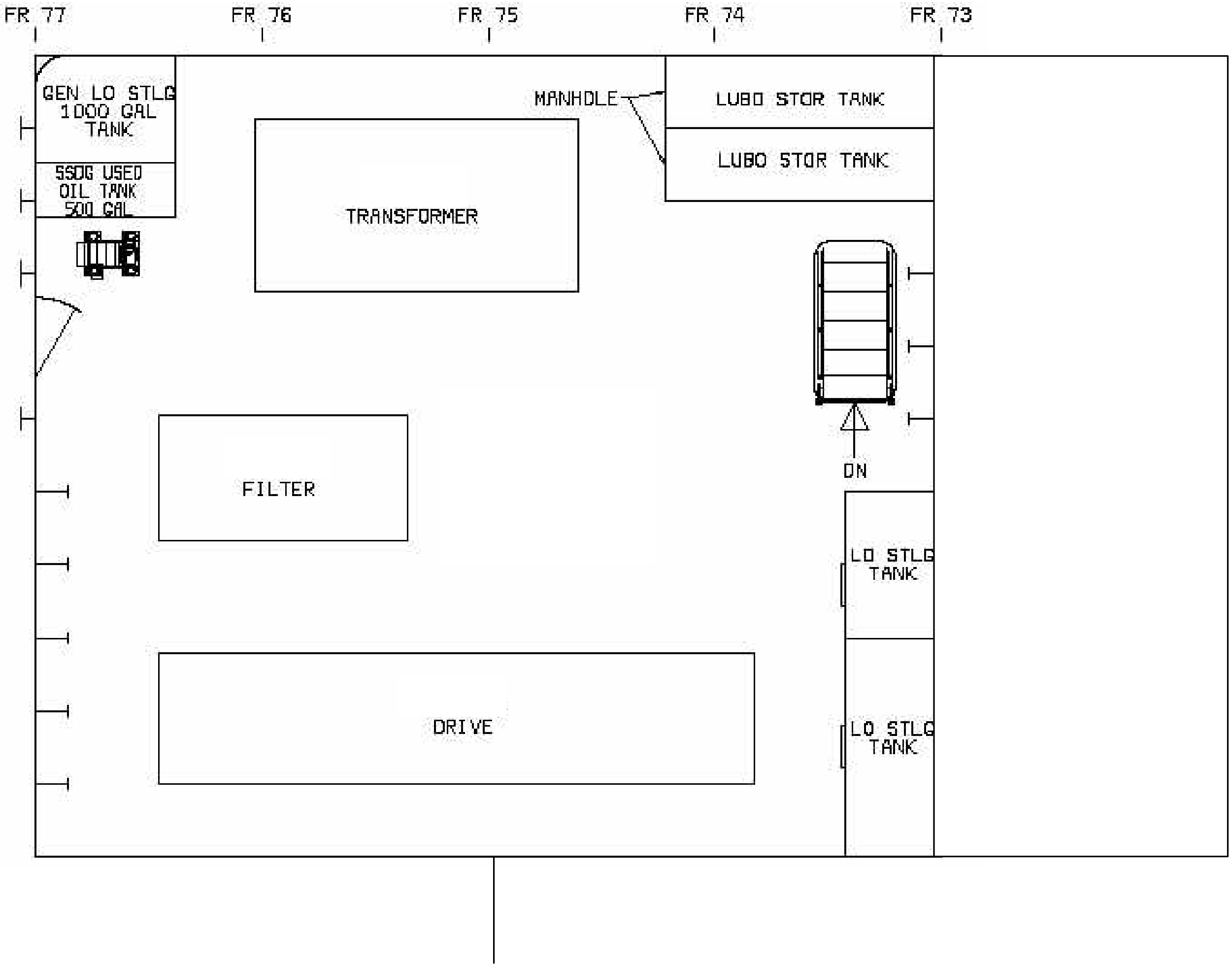


FIGURE 6 - Notional forward APS machinery arrangement in AMR for LHD 8

  - Dedicated Generator Mode - no specific power quality requirements, except that the generator must be compatible with APS ship propulsion loading in regard to not causing excessive heating of the generator rotor due to harmonic currents present
- Power management philosophy
  - Integrated Generation and Propulsion Mode - Ship service power has priority over ship propulsion power so manual load shedding has to be invoked or additional generators have to be placed on-line to provide more power for ship propulsion
  - Dedicated Generator Mode - No restrictions on power usage
- Gas turbine engine and APS capabilities and response characteristics
  - Each shaft may be powered by either gas turbine engine or APS, but not both simultaneously

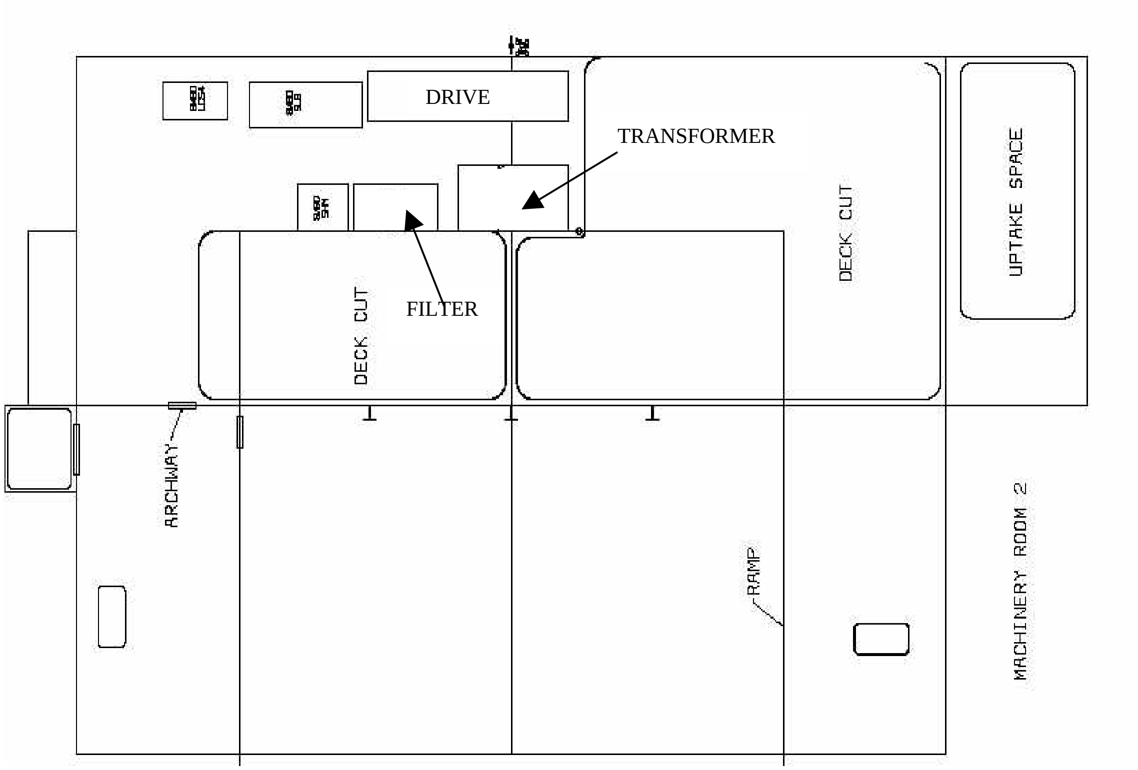


FIGURE 7 - Notional aft APS machinery arrangement in MMR 2 for LHD 8

- The APS will be capable of turning a dead shaft
- Gas turbine engine ship propulsion capability is from a minimum shaft speed corresponding to the gas turbine engine idle speed to full rated shaft speed of 180 rpm
- APS ship propulsion capability is from a minimal shaft speed of 55 rpm, which matches the gas turbine engine idle speed (1050 rpm) and retains the same propeller blade pitch angle for both operational modes of propulsion, to a maximum shaft speed corresponding to the rated propulsion motor speed (1800 rpm)
- Each shaft may be powered by either gas turbine engine or APS, but if one shaft is powered by the gas turbine and the other shaft is powered by the APS, the shaft powered by the gas turbine engine may not be operated at shaft speeds beyond the capability of the APS to prevent overspeeding the propulsion motor on the shaft powered by the APS
- Crashback by the gas turbine engine or APS is performed by reversing the propeller blade pitch angle, but the power of the APS is limited to the power available from that ship service bus if in the integrated generation and propulsion mode

- APS control, local and remote
    - Control is normally remote from either the bridge or EOS
    - Local control always requires knowledge of the propeller blade pitch angle and, if in the integrated generation and prolusion mode, the quantity of generators operating
- Recommended APS configurations for maximum propulsion capability or maximum fuel economy
    - Integrated generation and propulsion plant mode provides the most economical operation
    - Dedicated generator mode provides the maximum maneuverability operation
- Propulsion plant transitions from gas turbine engine to APS and from APS to gas turbine engine
    - Propulsion transition from gas turbine engine to APS must be made within the capability of the APS and power transfer from the gas turbine engine to the APS does not occur until the gas turbine engine is shutdown since the APS is applied by an overrunning clutch
    - Propulsion transition from APS to gas turbine engine may be made at any shaft speed within the capability of the APS and power transfer from the APS to the gas turbine engine does not occur until the propulsion motor is commanded to a slower speed than the gas turbine engine is providing since the gas turbine engine is applied by an overrunning clutch

APS CONTROL

The present design provides for normal control of the electric plant and APS (Figure 8) from a Machinery Control System (MCS). The MCS will also provide remote monitoring and remote control of propulsion, auxiliary, fuel, fuel fill and transfer, damage control, and ballast systems. The MCS includes multi-function workstations, data acquisition units and local operating panels, which communicate with each other via a fiber-optic MCS-LAN. The MCS remotely controls and monitors all aspects of the electric plant and APS. The MCS also incorporates a power management system that prevents inadvertent ship service load shedding or overloading of diesel generators. This ensures optimum utilization of the power available from the on-line diesel generators when an APS is connected into a ship service bus. The MCS monitors on-line generating capacity for each ship service bus, ship service loads per ship service bus, APS load per ship service bus or dedicated generator and shaft propulsion power control lever position. When the shaft propulsion power control lever is moved to a position that would require more power to the APS than the on-line generators are capable of delivering from a ship service bus, power to the ships service loads are maintained while the MCS automatically limits the APS power to the highest level possible within the full rated capacity of the on-line generators. Similarly, when the power demand from the ships service loads increases and causes the total power demand (ships service and APS) to exceed the capacity of the on-line generators, the MCS automatically reduces the power delivered to the APS. Likewise, when the generating capacity decreases, the MCS automatically reduces the power available to the APS. Whenever MCS is limiting the power demand of the APS, an alarm is initiated to indicate that the MCS is limiting power to the APS and that additional generators should be placed on-line or load shedding applied. When additional generating capacity is brought on-line, either manually or automatically, or load shedding is manually invoked; the MCS automatically increases the power delivered to the APS to the ordered command for shaft propulsion unless power limiting continues to occur.

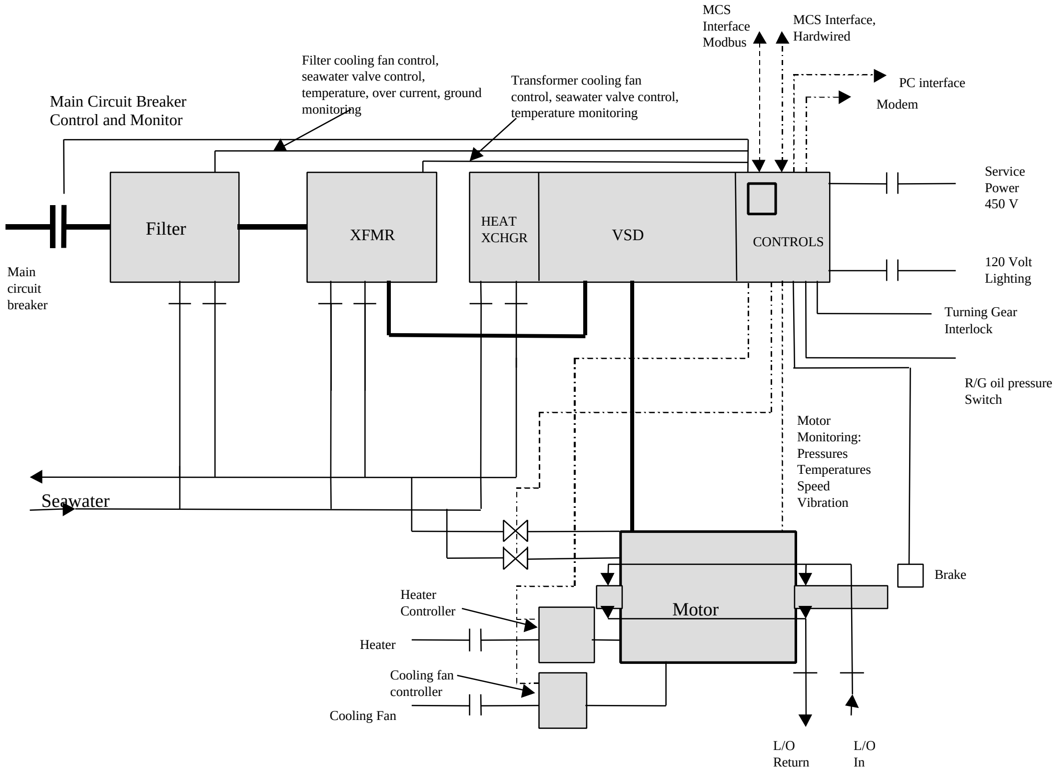


FIGURE 8 - APS control diagram design concept for LHD 8

Present day COTS variable speed drive systems are designed for remote control through a data interface protocol. Most also include a local operating panel for control, monitoring and troubleshooting. The APS will utilize this local operator interface as a secondary control station in the event the MCS or data interface is inoperable. The VSD will also incorporate an interface port for a portable computer (laptop) as a backup to the local operator panel. Except for propeller blade pitch angle and power available, either of these two local control methods will allow the operator to completely control the APS including such functions as breaker closure, cooling water valve sequencing, motor vibration monitoring and component fault diagnosis.

CONCLUSIONS

Through the elimination of the steam plant and the incorporation of main gas turbine propulsion with auxiliary electric propulsion, the LHD 8 will have significant TOC savings as compared to earlier ships of the *Wasp* (LHD 1) class. These savings are principally through the reduction of crew by over 80 personnel and significant improvements in propulsion plant efficiency. The incorporation of the APS enables fuel efficient diesel generator to provide propulsion power at low speeds when gas turbine engines are least efficient. Feedback from fleet operators led to incorporating a VSD to start a stopped shaft using the APS alone. LHD 8 also includes an AC ZEDS featuring a 4160 VAC power generation and primary distribution system and a 450 VAC secondary distribution system. The AC ZEDS provides a more survivable and reconfigurable power distribution system with less weight than a traditional radial distribution system. A modern MCS will integrate control of the APS and AC ZEDS and provide the LHD 8 with significant capability to monitor and control the propulsion and electric plant. In summary, although eliminating steam and reducing TOC was the motivation for changing the propulsion and electrical plant on LHD 8, the resulting design, based on sound engineering and economic analysis, is a significant step toward the all electric ship for the U.S. Navy.

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BIOGRAPHIES

Mr. Dalton (MSEE – University of Miami, Florida – ’75) has been with NAVSEA for over fourteen years of his past 28 years in the marine industry. He began his government service with the US Department of Transportation – Maritime Administration and then worked for the commercial firms of Gibbs & Cox, Inc., Rosenblatt & Sons, Inc. and Advanced Marine Enterprises, Inc. and Frank E. Basil, Inc. before returning to government service with NAVSEA in 1987. Mr. Dalton has been involved with typical ship service electric plant design support as well as various integrated electric plant ship designs throughout his career. In particular, he has been supporting the Integrated Power System (IPS) developmental program over the past seven years. His initial duties for IPS program office were technical review and oversight of the Full Scale Advanced Development (FSAD) testing phase of IPS at the land based test site (LBES) facility of Naval Surface Warfare Center – Ship Systems Engineering Service (NSWC-SSES) in Philadelphia, PA. He presently serves in the IPS program office as the Assistant Program Manager for Mission Interface Loads in an effort to provide the combat system with the type, quality, quantity and survivability of power required from the IPS architecture.

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