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Key Requirements for Surface Combatant Electrical Power System and Propulsion System Design

ABSTRACT

This paper explores the impact of ship requirements on the selection of a preferred electrical distribution system and propulsion system on a modern surface combatant. Four different plant architectures are considered: Mechanical Drive, Integrated Power Systems, Hybrid Electric Drive, and Hybrid Electric Drive with Propulsion Derived Ship Service (PDSS) electrical power. Requirements such as sustained speed, endurance, survivability, flexibility including margins and service life allowances, electric load conditions, definition of mission critical equipment, and signatures are discussed. The impacts of these requirements on the four plant architectures are presented. The end goal is to highlight those important requirements that should be investigated and established early (or accommodated via flexibility) to enable a faster maturation of the electric plant and propulsion plant design.

INTRODUCTION

The choice of a ship's architecture for power and propulsion has major implications on the cost, capability and design of a naval surface combatant. Many times the capabilities with large impacts on cost are not well addressed by requirements documents or early ship concept designs. On the other hand, because of its large impact on design, there is often a strong desire to choose the ship's power and propulsion architecture early. If the relationship among capability, design, and cost are not well understood or explored early, there is great risk that the design will undergo considerable churn and rework late in the process as the impacts on cost and capability are better known. To avoid the cost and time delay associated with this rework, the authors recommend conducting studies early in the design process to better define the requirements that drive the size, weight and cost of surface combatant electrical power systems and propulsion systems. This paper identifies these key requirements and how they relate to four different power and propulsion architectures.

The views expressed in this paper are those of the authors and are not necessarily official policy of the U.S. Navy or any other organization.

REQUIREMENTS

The key requirements that drive the size, weight, and cost of surface combatant electrical power systems and propulsion systems are:

- Flexibility
- Sustained speed
- Endurance
- 'Compromised Mobility' Speed
- Survivability
- Low Observable Mode
- Operating and Support Costs

Flexibility

Flexibility is manifested as elements of the ship design that enable ships to remain operationally relevant over their service lives. As detailed by Gantt and Hootman (2009):

"We are driven to design ships not only to solve the capability gaps we understand today, but also to be able to adapt the ship to address future gaps, which are less well-defined during the ship design phase."

"Early incorporation of flexible and adaptable design features as well as common equipment (hardware and software) and interfaces not only should be a goal for the design teams – it also should be direction that is driven into the requirements documentation ("big R" requirements), the specification ("little r' requirements, and the construction contract."

"this flexibility requirement should define a time-based standard in which the platform must be able to modernize its combat capability to deliver credible combat power without disrupting the vessel's availability for operational tasking, whether the vessel is 10, 20, or 40 years into its service life."

Service life allowances (SLAs) are the traditional method for providing some degree of flexibility. SLAs are additional capacity of distributed systems reserved for future modernization and equipment degradation. The traditional methods however, have not generally been sufficient since the end of World War II for ships to achieve their design service life. (Koenig, Nalchajian, and Hootman 2009)

For power and propulsion, an SLA is typically not provided for the propulsion system. An SLA is provided for the ship service electrical load. The traditional SLA may not be sufficient for future surface combatants as more and more electric weapons and high power sensors that are currently not available, but may become necessary during the ship's service life.

Having the visible and credible capability in 15 to 20 years to rapidly upgrade a substantial number of ships to include multiple railguns, lasers, high power electronic warfare systems and high power sensors will likely force potential adversaries to divert resources to counter this potential capability. This diversion of resources will likely occur whether or not we eventually field these weapons. The value of this strategic effect should be better understood.

Sustained speed. Sustained speed is the speed a ship can attain when using 80% of its rated propulsion power at design full load displacement, clean bottom and calm water. The difference between 80% and 100% power accounts for the added resistance due to a fouled bottom and higher sea-state. With a fouled bottom and a higher sea-state, the ship should be capable of achieving the sustained speed with 100% propulsion power. (Naval Sea Systems Command 2011)

Endurance. The endurance requirement directly impacts the size of the fuel tanks of a ship. Presuming that the Navy is committed to having clean fuel compensation ballast tanks, reducing endurance fuel requirements will minimize volume needed for both fuel tanks and clean ballast tanks. Traditionally, endurance requirements have been specified for an economical transit speed of 20 knots. To the designer, this led to optimizing fuel economy at this one speed without consideration for how the ship is employed. In the context of ship power and propulsion, Naval Sea Systems Command (2011) defines endurance and its metrics:

"Endurance refers to the metrics used by the Chief of Naval Operations used to determine the minimum amount of burnable fuel the ship must carry. Endurance is specified by one or more of the following metrics: surge to theater distance, economical transit distance, and operational presence time. The tankage is sized to have sufficient capacity to achieve all of the specified endurance metrics"

"Surge to theater distance is the minimum distance (nautical miles) which a ship can sail without replenishment and using all of its burnable fuel (excluding cargo and aviation fuel), at sustained speed, deep water, and full load displacement, with a ship service operating condition corresponding to a cruise with self defense capability."

"Economical transit distance is the minimum distance (nautical miles) which a ship can sail without replenishment and using all of its burnable fuel (excluding cargo and aviation fuel), at a specified endurance speed, deep water, and full load displacement, with a ship service operating condition corresponding to a cruise with self defense capability."

"Operational presence time is the minimum time in hours that a ship can conduct specified missions with a given speed-time profile, with a ship service operating condition corresponding to the specified missions, without replenishment, and using all of its burnable fuel (excluding cargo and aviation fuel)."

For ships with high power sensors, the operational presence time may be more important than either the economical transit time or surge to theater time. This became evident during the alternative propulsion methods study conducted by the Naval Sea Systems Command (2007).

'Compromised Mobility' Speed

OPNAVINST 9070.1B (CNO 2017) provides policy for establishing survivability requirements. One such policy is

"Ship mission performance degradation resulting from combat damage or accidents must be addressed during tradeoff and effectiveness assessments conducted during ship design, modifications, and overhaul. The focus of these reviews must combine individual functions in a manner that addresses overall system survivability requirements (i.e., susceptibility, vulnerability and recoverability) while minimizing the total ownership cost (TOC)."

The degree to which mobility (propulsion) is allowed to degrade following exposure to a threat (either weapons effect or accident), is a major driver in the propulsion system design.

Historically, most surface combatants have employed twin shafts and sufficient longitudinal separation of the prime movers and reduction gears so that if damage were to occur to the prime mover(s) or reduction gear of one shaft, the other shaft would still be available to ensure a relatively high ship speed. For example, a ship with a 30 knot sustained speed can be expected to achieve over 20 knots on one shaft.

The assumption that the shafting and propellers of both shafts would not be damaged at the same time is based on World War II experience. Torpedoes however, have significantly changed since WWII; this assumption should be verified through analysis and testing.

If the compromised mobility speed is low enough (below about 14 knots), a forward retractable azimuthing thruster is an alternate means to provide propulsion to achieve the compromised mobility speed. With the forward retractable azimuthing thruster, the need for significant longitudinal separation of prime movers is reduced. If the requirement is less than about 14 knots, a forward azimuthing thruster may be feasible which in turn may enable considerable flexibility in the machinery arrangements of the primary propulsion system. This flexibility can be used to minimize arrangeable area consumed by long shafts, and to affordably enable the insertion of parallel midbody in future flights of the ship design.

If the requirement is much greater than 14 knots, than a forward azimuthing thruster probably won't provide the capability. The propulsion units (either electric motors or gas turbines and reduction gears), port and starboard, would have to be separated by a significant amount longitudinally; one shaft would cross midships, thereby complicating ability to add parallel midbody later. The long shaft would consume valuable real estate. Net effect is that the ship would likely become larger and more expensive. In any case, with modern torpedoes as threats, it may not be possible to retain propulsion without using a forward thruster since both the port and starboard shafts may both be damaged.

Survivability

As stated in OPNAVISNT 9070.1B, "The level of protection against the damaging effects of enemy weapons or accidents must be a function of the ship size or type, the POE *(Projected Operating Environment)*, the projected threat environments, the projected mission, and other factors that may be unique to the ship design or acquisition program." The ship requirements should explicitly state the expected residual capability a ship should retain or be able to restore following exposure to a threat.

Equipment that are part of mission critical systems and required to operate through emergency conditions (part of the emergency operating load) are designated as Mission Critical Equipment (MCE). The emergency operating load for surface combatants consists of Emergency Ship Control and selected weapons. The "selected weapons" are not well defined. The list of selected weapons can range from none to everything. Equipment that must operate to support the selected weapons are also considered MCE. Because of the differing amounts of redundancy required for MCE and non-MCE, the definition of what comprises the "selected weapons" can have a major impact on the design of the in-zone architecture and its associated cost. For ships with a zonal architecture (specified for ships greater than 150 meters in length), MCE are provided both zonal survivability and compartment survivability (which must be verified through Vulnerability and Recoverability Analysis).

Low Observable Mode

Lithium-Ion battery-based energy storage today is about one fourth the cost it was in 2012. (St. John 2019) From 2011 to 2015, the energy density of Li-ion batteries has roughly tripled. Goldie-Scot (2019) predicts the cost of Li-Ion battery packs will fall below $100 kWh before 2024 and continue falling. If these trends continue, energy storage has the potential to give surface combatants capabilities that were not possible or affordable ten years ago.

For example, with sufficient energy storage, a surface combatant could, for a short time, shut down all prime movers and still keep some or all of the combat systems operational while moving at a slow, but tactically useful speed. Without any prime movers online, the ship's thermal and acoustic signature would be significantly less. If this capability is desirable, then the requirements for the ship must include this capability.

Operating and Support Costs

Some of the major operating and support cost drivers for a surface combatant are fuel consumption, manpower, and maintenance. The choice of power and propulsion architecture impacts all three of these cost drivers.

POWER AND PROPULSION ARCHITECTURES

Most modern surface combatant power and propulsion architectures fall within one of the following categories:

- Mechanical Drive
- Integrated Power (and Energy) Systems (IPS or IPES)
- Hybrid Drive
- Hybrid Drive with Propulsion Derived Ship Service (PDSS) power

Mechanical Drive. Mechanical Drive surface combatants typically have two shafts with gas turbine prime movers driving a reduction gear and controllable reversible pitch propellers. In some cases, diesels or a combination of diesels and gas turbines are used. A separate electrical distribution system provides electrical power. Primer movers for the electrical generator sets are typically either gas turbines or diesels.

IPS / IPES. IPS and IPES surface combatants typically have two shafts with propulsion motors driving fixed pitch propellers. An integrated electrical system provides electrical power to both propulsion and ship service power. Prime movers for the electrical generator sets are typically either gas turbines or diesels. IPES is a variant of IPS incorporating energy storage and advanced controls.

Hybrid Drive. Hybrid Drive surface combatants have a Mechanical Drive augmented with electric propulsion motors. These motors can drive the same shaft, or different shafts, or electric azimuthing thrusters (Figure 1). If on the same shaft, the cost and complexity of using the motor only for low speeds (mechanical drive in an "OR" configuration) is less than the complexity of using both the motor and mechanical drive at the same time ("AND" configuration)

Hybrid Drive with PDSS A variation of the Hybrid Drive incorporated PDSS. In this configuration, the hybrid motor can also be used to generate electrical power for ship service loads. Typically, the 60 Hz power is generated using power electronics. The integration of a power electronic based source with limited fault current capability increases the complexity (and cost) of the fault detection, localization, and isolation system of a.c. power systems.

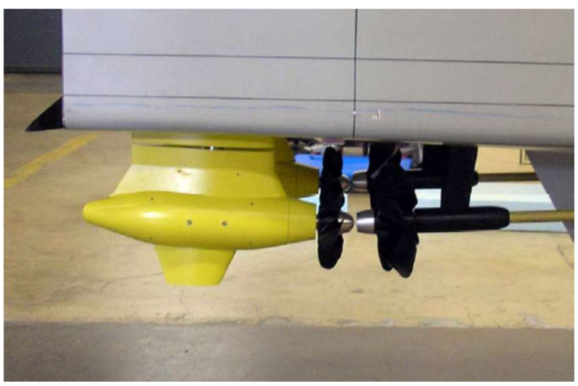

Figure 1: Hybrid Drive with electric azimuthing thruster

IMPACT OF REQUIREMENTS ON ARCHITECTURES

Flexibility

In the coming decades, one of the biggest drivers for flexibility of the power system will be the introduction of high power sensors and electric weapons, many of which will act as pulsed loads. Being able to successfully integrate these future mission systems is challenging because the power and pulse characteristics of these mission loads is currently not well understood. In general, a pulse load that has a peak magnitude a small fraction of the generation capacity reduces the over-all need for energy storage to buffer the pulses; generator sets can safely supply pulse loads that are a small fraction of their rating.

Mechanical Drive

The electrical generation capacity of a mechanical drive ship is generally significantly smaller than for an IPS/IPES ship. Consequently a mechanical drive ship will likely require more energy storage to buffer the pulse dynamics from the generator sets.

If batteries are used for this energy storage, each pulse cycles the energy storage which shortens its life, potentially requiring more frequent replacement.

The SLA for the advanced mission systems is provided by adding additional generation capacity in the electric plant. Predicting the actual service life allowance that will be consumed can be challenging – a number of ships in the past were electrical power limited near the end of their service life. A mechanical drive ship is typically limited by the capacity initially installed.

IPS / IPES

An IPS or IPES ship however, offers the option to increase the ships electric load at the expense of not being able to always provide rated propulsion power. Essentially, the ship's speed (for specific operating conditions) becomes an additional source of SLA for the electric plant if the Navy chooses to use it in that manner.

With an IPS or IPES system, less energy storage is generally required because a greater portion of the pulse energy can come from the prime movers without causing power quality issues. (an MVDC IPES needs even less energy storage than an MVAC IPES). If sufficient propulsion power is present, that propulsion power can be diverted to the pulsed load temporarily to reduce the cycling on the energy storage (and thereby increase the life of the energy storage) as well as the stress on the prime mover.

Hybrid Drive

The power reserved for or supplied to a hybrid drive electric propulsion can be used to support pulsed loads. Because the power generation capacity of a ship with hybrid electric drive will be between the capacity of a mechanical drive and an IPS / IPES system, its ability to support pulsed loads will also fall between the two extremes.

Hybrid Drive with PDSS

The PDSS will somewhat increase the capability to support pulsed mission loads as compared to the Hybrid Drive (without PDSS). The power normally allocated to the hybrid drive and the power generation capacity of the PDSS both can be used to power pulsed mission systems.

Sustained speed

For most ships, propulsion power is roughly proportional to the cube of speed. Table 1 Shows that a notional ship designed for a sustained speed of 30 knots requiring 75 MW of installed propulsion power. In calm water with a clean bottom, the same ship can attain 32.3 knots using 100% of the rated power.

Table 1: Example Propulsion Power vs Speed

Propulsion Power (MW)	Speed (knots)
75.0	32.3
72.8	32
66.2	31
60.0	30
54.2	29
48.8	28
43.7	27
39.1	26
34.7	25
30.7	24
27.0	23
23.7	22
20.6	21
17.8	20

Mechanical Drive

The sustained speed requirement drives the size of the propulsion engines, reduction gear, shafting, and propellers.

For a twin shaft mechanical drive ship (without a combining gear), the number of propulsion prime movers has to be even -- typically 4. This means that choice of prime movers will be somewhat limited.

Surface combatants with a high speed requirement (generally greater than 28 knots), typically use gas turbines due to their power density. The sustained speed power requirement is translated into the total power requirement required by the propulsion gas turbines. Since there are only a limited number of gas turbines on the market, the designer is forced to pick the next larger size, or accept a slightly lower sustained speed requirement. The electric plant is designed to provide the maximum ship service electric load with one generator down for maintenance (N+1 rule where N is the number of generators required to meet the load demand). There are additional survivability separation requirements that typically drive the design to three generator sets, with 50% extra capacity (The +1 in N+1) to account for maintenance. Thus a "traditional" surface combatant would have seven prime movers (4 for propulsion and 3 for electrical generation)

Because of the N+1 rule for mechanical drive ships, as the ship service electrical load increases, the amount of installed prime mover power increases by (N+1)/N if the generator sets are equally sized.

IPS / IPES

The sustained speed power requirement is translated into the power rating required by the propulsion motors and its associated motor drive, shafting, and propellers. Normal practice in the acquisition of motors is that a common frame size is used and the required motor power rating is achieved by making the motor longer or shorter – no need to pick the next larger standard size. Motor drives are increasingly becoming modular: As many modules as needed are integrated to achieve the desired rating. The electrical generation capacity of the ship must be sufficient to provide 100% of the propulsion power and all of the ship service loads required while the ship is operating with 100% propulsion power. (In special cases, the electric load at a lower speed may dominate and determine electrical generation capacity). Often, the optimal power generation design will result in four prime movers, although depending on power needs, prime mover properties and availability, the optimal number can easily vary between 3 and 6.

In an IPS / IPES ship, the power system architecture can be designed to accept an arbitrary number of prime movers (gas turbines or diesels) (either even or odd) thereby increasing the population of prime movers to choose from.

For IPS ships, one has the choice to install a total power of all prime movers to a value less than that needed to supply full power to propulsion, all high power sensors, and all high power loads at the same time. In particular, many weapons fire relatively infrequently, even during combat. Using the previous example, if an IPS ship was initially operating at 30 knots and 16 MW of propulsion power was diverted from propulsion to a weapon, the ship would coast down from 30 knots to about 27 knots, then accelerate back to 30 knots after the engagement is over. If the engagement is very short, the ship may still be coasting down at the end of the engagement and may still be moving greater than 27 knots. Is the cost of installing an additional 16 MW of power worth ensuring the ship speed does not briefly drop below 30 knots?

Note that an IPS ship can be designed to achieve 30 knots and serve the maximum electric load at the same time. The installed power of the IPS plant will still be less than that of a mechanical drive ship because of the mechanical drive N+1 requirement for gensets. An IPS configuration offers the option, but not the obligation, to further reduce the amount of installed capacity to reduce the required machinery volume, weight and cost.

For an IPS / IPES ship, the combined efficiency of the generator, drive, and propulsion motor will likely be less than for a reduction gear at maximum speed. This means that when using traditional shafting arrangements common with mechanical drive ships, an IPS ship will require more prime mover power to achieve the sustained speed requirement.

The loss in transmission efficiency between the prime mover and shafting of an IPS design can be partially or entirely offset at high speeds by allowing the IPS ships to employ more efficient propulsor technologies. The simplest improvement comes from replacing controllable, reversible pitch (CRP) propellers with fixed pitch propellers. The decreased hub size of the fixed pitch propeller has been shown to reduce drag. More substantial improvements that can result in an IPS ship being more efficient at high speed than a mechanical drive ship are possible by using contra-rotating configurations. Contra-rotating propellers increase propulsion efficiency by recovering the energy the first propeller expends in creating a rotational “swirl” in the water. The use of contra-rotating propellers still has technical risk, primarily in the areas of acoustic signatures and if azimuthing thrusters are used, in shock hardening and electro-magnetic signatures. The use of contra rotating propellers does offer the opportunity to reduce the required power for propulsion. Implementing contra-rotating propellers with electric motors is straight-forward; with reduction gears it is complex.

The use of azimuthing thrusters also has the advantage of improving low speed maneuverability as well as reducing drag by eliminating rudders.

At medium and low speeds, where naval ships operate almost all of the time, IPS configurations are generally more fuel-efficient than mechanical drive ships because the prime movers are loaded to operate at much more beneficial specific fuel consumption rates.

Hybrid Drive

For "OR" hybrid ships, the sustained speed requirement drives the size of the propulsion engines, reduction gear, shafting, and propellers in the same way as a mechanical drive ship.

Reduced propulsion power requirements are also achievable in hybrid drives where a mechanical drive is in the hull and the electrically driven azimuthing thruster behind the mechanically driven propellers (see Figure 1).

At low speeds, where naval ships operate much of the time, hybrid drive configurations are generally more fuel-efficient than mechanical drive ships because the prime movers again are loaded to operate at much more beneficial specific fuel consumption rates.

If the hybrid drive is not required operationally and is used primarily for fuel efficiency, then it need not be included in the load estimate for determining the installed generation capacity. Any power generation capacity not used for other loads can be used to power the hybrid motors. Furthermore, the electric motor and drive need only be qualified to Grade B shock requirements. This approach was used on LHD 8 and subsequent LHA 6 class ships. (Dalton, et al. 2002)

The "AND" hybrid drive can reduce the required power from the mechanical drive prime movers and increasing the required capacity of the electric plant. Designing a propulsion motor and its associated drive to be able to efficiently provide its maximum power over a wide speed range is more complex than designing a propulsion motor in the "OR" configuration.

Hybrid Drive with PDSS

If the PDSS can generate power independent of the power applied to the shaft, then the PDSS can be considered part of the ship service power generation system, possibly reducing the number of gensets required. The amount of power reserved for electrical power generation must be subtracted off of the propulsion prime mover rating for purpose of determining sustained speed. This can be useful if one is installing over-sized propulsion gas turbines since the use of CRP propellers enables the shaft to rotate at a minimum RPM, while still providing full control over ship speed.

Endurance

If the endurance speed for the economical transit condition is above about 15 knots, it is hard to identify with certainty which plant will prove best.

The size of the fuel tank is increasingly becoming more important with the requirement for clean compensation tanks. If the operational presence requirement dominates, the Hybrid plants and IPS plants are more favorable. If the surge to theater requirement is most important, then a Hybrid plant or mechanical plant is more favorable. For the economical transit condition, the choice of endurance speed will impact the more favorable configurations. If the speed exceeds the capability of the hybrid plant, then the IPS plant is likely more able to be optimized to have the lowest endurance requirement.

Mechanical Drive

Because a mechanical drive plant typically has higher efficiency at sustained speed as compared to an IPS plant, Mechanical Drive ships can be expected to require less endurance fuel for the surge to theater requirement as compared to IPS / IPES ships (unless the IPS / IPES ships employ efficiency features such as contra-rotation or azimuthing thrusters)

Since the propulsion gas turbines are chosen based on the sustained speed requirement for a mechanical drive plant, the ability to optimize the plant for an endurance speed is reduced unless Combined Diesel and Gas Turbine (CODAG) or Combined Diesel or Gas Turbine (CODOG) configurations are employed. In these cases, the diesel engine rating is chosen based on achieving the endurance speed.

IPS / IPES

In general, because one can mix and match prime movers for an IPS configuration, it should be easier to optimize the IPS plant for a given endurance speed.

If the specified speed time profile emphasizes low speed operation, an IPES / IPS configuration will likely have a longer operational presence time for a given fuel load than a mechanical drive ship.

Hybrid Drive

Hybrid drives have historically been employed in part to improve low speed fuel efficiency; the efficiency of the electric propulsion motor and associated generator sets is better than the propulsion prime movers operating at very low power levels. Hence hybrid drives would be expected to require less endurance fuel than mechanical drive ships in the operational presence condition.

Hybrid Drive with PDSS

Adding a PDSS to a hybrid drive promises to improve fuel efficiency at speeds higher than what the hybrid drive can achieve while acting as a motor. The PDSS adds additional load to the propulsion gas turbine, improving its specific fuel consumption, while allowing operation with one less ship service generator set. If the operational profile has significant time in this speed range, then the PDSS will help reduce the required endurance fuel for the operational presence condition.

'Compromised Mobility' Speed

Mechanical Drive

A twin shaft mechanical drive ship should be able to achieve a relatively high compromised mobility speed if both shafts are not damaged at the same time. Otherwise, a forward propulsor will be required which will likely limit the compromised mobility speed to something less than 14 knots. With the forward propulsor, the need for longitudinal separation of the prime movers and reduction gears of the two shafts are reduced because the driving requirement becomes machinery arrangements rather than survivability.

IPS / IPES

In terms of the propulsion motor and shafting, IPS / IPES configurations are impacted by the compromised mobility requirements much like the mechanical drive configurations. The differences are due to the increased machinery arrangement flexibility of an IPS / IPES plant over a mechanical drive ship. With a forward propulsor, it may be possible to locate both propulsion motors in the same water-tight subdivision which may not be possible for two sets of reduction gears and prime movers for the mechanical drive ship.

The second concern is locating the generator sets so that sufficient power can be generated to serve both propulsion and ship service loads following damage.

Hybrid Drive

The impact is almost identical as for mechanical drive.

Hybrid Drive with PDSS

The impact is almost identical as for mechanical drive.

Survivability

All of the considered power and propulsion architectures can be designed to provide MCE with zonal and compartment survivability. The differences in capability is that following damage, the different architectures may have differing amounts of surviving electrical power capability to power these loads.

Mechanical Drive

Mechanical drive ships usually have the lowest amount of installed power generation capacity and often fewer generator sets. While a mechanical drive ship is expected to provide power to all MCE with a single generator offline, they may not have sufficient capacity to power all MCE with more than one generator offline.

IPS / IPES

Since an IPES configuration will typically have more gensets than a mechanical drive ship and the highest overall amount of installed generation capacity, the availability of electrical power should be the greatest on an IPS / IPES Ship following damage.

Hybrid Drive

The amount of surviving electrical generation capacity of a hybrid drive plant would be similar to a mechanical drive plant.

Hybrid Drive with PDSS

If the PDSS results in additional sources of power as compared to a mechanical drive configuration, then the hybrid drive with PDSS will likely have somewhat more electrical generation capacity than a mechanical drive configuration, but less than an IPS / IPES configuration.

Low Observable Mode

Mechanical Drive

A mechanical drive ship does not provide many additional opportunities to minimize IR or acoustic signatures.

IPS / IPES

Since fewer prime movers will likely be online at any one time with an IPES as compared to a mechanical drive system, and the prime movers that are on are operating at higher efficiency, the IR signature of an IPES ship should be lower than for a mechanical drive ship under many conditions.

One design option that is available to IPES ships and hybrid ships and not available to mechanical drive ships is providing sufficient energy storage and power management software to enable operating for periods of time at low speeds with no prime movers on line. This could be done to minimize both acoustic and Infra-red signatures to enable tactics that otherwise would not be possible. Is this of value?

Hybrid Drive

Hybrid drives can be acoustically quieter than mechanical drive ships at low speeds. Similarly, the IR signature can be lower when fewer prime movers are online.

Hybrid Drive with PDSS

PDSS enables fewer prime movers to be online for certain operating conditions than hybrid drive without PDSS.

Operating and Support Costs

Mechanical Drive

Normally, a mechanical drive ship will operate with a minimum of three gas turbines online: 1 for propulsion and 2 for ship service power. All of these gas turbines may be operating at very low power levels which leads to high fuel consumption and excessive wear on the engines.

IPS / IPES

With IPS and hybrid configurations, this can be reduced to two gas turbines, where the particular units chosen for operation can be properly loaded (ideally between about 50% and about 90%) In this regard, the IPS configurations would normally have greater flexibility in loading as compared to a hybrid drive. If sufficient energy storage is included in the design, IPES ships could operate continuously with one generator set online and mechanical drive ships with two online.

Since the prime movers are typically the maintenance driver in the electrical and propulsion systems, and operating hours is the key driver to prime mover maintenance, having fewer prime movers online results in less overall maintenance.

Assuming future surface combatants will have operating profiles (speed – time plots) similar to today's surface combatants, an IPS ship will consume less fuel in a year than an equivalent mechanical drive ship. An IPS and hybrid drive ship will likely consume similar amounts of fuel depending on details of ship configurations and the operating profile.

Hybrid Drive

An IPS and hybrid drive ship will likely consume similar amounts of fuel depending on details of ship configurations and the operating profile.

Hybrid Drive with PDSS

PDSS will likely have improved fuel efficiency over hybrid drive without PDSS due to the ability to operate propulsion prime movers at a higher loading and keep a ship service generator offline. Similarly, PDSS will likely result in fewer total operational hours on all the prime movers, thereby reducing maintenance costs.

OTHER CONSIDERATIONS

Technical Maturity

The propulsion and electrical distribution system of any future surface combatant, whether mechanical drive, hybrid drive, or IPES, will require development and integration. In general, prime movers will be off-the shelf, although prime movers not already in the Navy's inventory will have to be qualified; some design modifications may result. Generators, switchgear, cabling, reduction gears, propulsion motors, propulsion motor drives, shafting, shaft bearings, and propellers are all custom made to standard off-the shelf design families. The design tools, design methods, and production methods are all well understood such that these items can be purchased with confidence with fixed price contracts.

Risks that are common to mechanical drive with associated power system and IPES systems:

- Design and implementation of control systems.
- Maintaining power quality on the power bus in the presence of modern loads
- Supporting pulse loads
- Integrating energy storage
- Survivability of twin shafts
- Controlling common mode currents due to proliferation of power electronics

Since the electrical distribution system of a mechanical drive ship will likely be MVAC due to the size of the ship service electric load, there really aren't any unique risks of a basic MVAC IPES system and a mechanical drive system that must support the same set of loads.

There are risks associated with incorporating azimuthing thrusters or contra-rotation if the benefits from these technologies are desired. These technologies are not practical with mechanical drive, so these risks (and opportunities) are unique to IPES and Hybrid solutions.

For hybrid configurations with PDSS an additional risk exists in integrating the PDSS with the fault detection, localization, and isolation system since the PDSS is limited in its ability to provide fault current.

IPES systems incorporating MVDC promise to be smaller, lighter, more efficient, and potentially less costly than equivalent MVAC IPES solutions. Additional risk areas for MVDC include

- Methods for fault detection, localization, and isolation
- MVDC Switchgear, cabling systems, bus pipe development

- Equipment specifications including qualification methods

- MVDC bus stability through controls

Acquisition Cost

Making definitive statements of relative acquisition cost among the different power and propulsion options is difficult because some cost areas are less and other cost options are more for the different options. In recent studies, cost estimates based on material cost elements had differences that were less than the margin of estimating error. Estimating labor hour differences is even more challenging. It is not clear whether installing an IPS / IPES system would be more or less costly than installing a mechanical drive system. At this time, it is too close to call.

RECOMMENDED STUDIES

A number of unknowns can be resolved independent of the particular details of a surface ship acquisition. The authors recommend the following generalized studies be conducted:

a. Survivability of twin shafts when subjected to damage from modern torpedoes.
b. Value of operating without any prime movers online for limited periods of time.
c. Modifications to commercial pods needed to meet naval surface ship requirements.
d. Viability of using forward propulsors for low speed operations where signatures are important.

Additionally, in conducting an AOA, the operational usefulness of different values of the requirements described above should be evaluated in addition to understanding the particular details of their implementation in each of the power and propulsions architectures.

CONCLUSION

The factors that would make an IPS/IPES solution preferred over a Mechanical Drive solution include

i. Minimizing operating and support costs is important

ii. The maximum margined ship service power load with SLA is large (> ~10 MW) and/or includes large pulse loads

iii. Maximizing on-station time is important

iv. The ship has an operational profile similar to today's surface combatants

v. One wants the option to trade ship speed for supporting future high power loads

vi. One wants to preserve the option to install multiple high power loads

vii. Controlling the IR signature and/or acoustic signature is important

The factors that would make a mechanical drive or hybrid solution preferred over an IPS / IPES Solution include:

i. The maximum margined ship service power load with SLA is small (< ~ 8 MW) and does not include large pulse loads

ii. The ship has an operational profile that emphasizes high speed operation

iii. One doesn't expect to install multiple newer higher power sensors and electric weapons over the ship's service life. Growth will be limited to the specified SLA

iv. IR and acoustic signatures are of lesser importance

The risks of an IPES solution are primarily in the integration of energy storage and the development of advanced controls. MVDC solutions also have additional risks, primarily in fault detection, localization, and isolation, development of military grade hardware, and bus stability.

The risks of a mechanical drive solution are ensuring power quality is maintained on the bus and the development of advanced controls if pulse weapons and sensors are incorporated. If energy storage is incorporated into the mechanical drive system, then the integration of this energy storage is an additional risk.

The increasing use of power electronics within the power systems and loads (independent of a mechanical drive or IPES) also has introduced the management of common mode currents as a risk in all future electrical distribution system designs.

The primary risk of hybrid drives is the development of advanced controls. For hybrid drives with PDSS, the integration of the PDSS with fault detection, localization, and isolation is also a risk.

No matter what the final decision is as to the electrical power and propulsion architecture, advanced controls, at least some energy storage, and power electronics will likely be part of the solution. The electric plant control, machinery plant control, and combat system control systems will require integration. The successful design and integration of the total ship system should be supported by a robust digital engineering environment where control systems, systems and equipment are tested first in a virtual environment and then in a combined virtual and physical environment (Power Hardware in the Loop and Control Hardware in the Loop). An integrated test facility should be part of the design effort.

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