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DESIGNING ALL ELECTRIC SHIPS

Capt. Norbert H. Doerry[1] and Howard Fireman[2]

ABSTRACT

The Integrated Power System (IPS) offers the naval architect considerable flexibility to achieve mission requirements at minimum cost. This flexibility results from the ability to separate the prime movers from the propulsion train, maximize efficiency of prime movers and propulsors, and optimize the number and rating of prime movers. Unfortunately, many naval architects are unfamiliar with how to exploit this flexibility, resulting in unfavorable comparisons with mechanical drive alternatives. This paper will provide guidance for selecting the number and rating of IPS modules and incorporating these modules into the design of ships. Often, the resulting general arrangements for an optimally designed IPS ship will differ significantly from an optimally designed mechanical drive ship.

KEY WORDS

Electric; power; ship; design; motor; system; architecture

NOMENCLATURE

ADG	Auxiliary Diesel Generator
AIM	Advanced Induction Motor
ASSET	Advanced Surface Ship Evaluation Tool
ATG	Auxiliary Gas Turbine Generator
CM	Corrective Maintenance
CONOPS	Concept of Operations
DFM	Diesel Fuel Marine
DRM	Design Reference Mission
EPLA	Electric Plant Load Analysis
ESM	Energy Storage Module
ESWBS	Expanded Ship Work Breakdown Structure
ILS	Integrated Logistics Support
IFTP	Integrated Fight Through Power
IPS	Integrated Power System
LEAPS	Leading Edge Architecture for Prototyping Systems
MBT	Manual Bus Transfer
MDG	Main Diesel Generator
MLDT	Mean Logistic Delay Time
MTBF	Mean Time Between Failure
MTG	Main Gas Turbine Generator
MTTR	Mean Time To Repair
NAVSEA	Naval Sea Systems Command
NCETL	Naval Concept Essential Task List
ONR	Office of Naval Research
OPNAV	Office of the Chief of Naval Operations
PCM	Power Conversion Module
PCON	Power Control Module

[1] Naval Sea Systems Command, U. S. Navy
[2] Naval Sea Systems Command, U. S. Navy

PDM	Power Distribution Module
PF	Power Factor
PGM	Power Generation Module
PM	Preventative Maintenance
PMM	Propulsion Motor Module
PMMS	Permanent Magnet Motor System
PWM	Pulse Width Modulated
QOS	Quality of Service
SDM	Ship Design Manager
SSCM	Ship Service Converter Module
SSIM	Ship Service Inverter Module
TSCE	Total Ship Computing Environment
UNTL	Universal Navy Task List
ZEDS	Zonal Electrical Distribution System

INTRODUCTION

Over the past twenty years or more, the U.S. Navy has invested considerable resources developing electrical power technology and design practices for naval warship applications. In addition to replacing steam with electricity for auxiliary applications, the Navy has recently incorporated Integrated Power System (IPS) technology into ship programs such as *Makin Island* (LHD 8), *Lewis and Clark* (T-AKE 1), DDX, and CVN 21. Unfortunately, the authors have observed that few Naval Architects, particularly those engaged in concept and preliminary design, have the requisite education and training to properly exploit the design and construction opportunities facilitated by IPS. This paper will detail the electric warship design process, highlighting the opportunities available to the designer, and detailing some of the design subtleties associated with the selection of prime movers, bus voltages, and propulsion motors. The paper concludes with recommendations for future work.

ELECTRIC WARSHIP DESIGN PROCESS

The generalized design process for designing electric warships is fundamentally the same as for conventional ship design. The differences are largely due to the added flexibility that an Integrated Power System (IPS) can provide the ship designer. Taking advantage of this flexibility may require additional design work that may not ordinarily be accomplished in a conventional design. The basic steps in this design process are:

- Analyze requirements
- Allocate requirements to mission systems
- Develop initial Concept of Operations (CONOPS)
- Assign mission systems to ship zones
- Develop derived requirements for ship systems
- Develop distributed system architectures
- Calculate distributed system component ratings
- Synthesize the ship
- Evaluate total ship mission effectiveness
- Iterate until total ship mission effectiveness requirements are met

Analyze Requirements

Figure 1 is an idealized systems engineering process and it is typically interpreted to be serial and iterative. In practical application, all of the components occur concurrently. Additionally, the feedback loop from Synthesis-to-Requirements Analysis is more than just verification. In practice, the systems engineering process as applied to ship design proceeds with the following parallel efforts:

- The Operational Requirements, Policy, Practices, Customs, and Statutory Requirements are analyzed and allocated to functional components (to include humans). These functional components become configuration items. The probability that each requirement will change over the life cycle of the product is assessed and functions allocated in an attempt to isolate the impact of likely changing requirements.

- The configuration items are synthesized by selecting / designing system architectures and associated hardware / software / humanware system elements. The Ship Design Manager's (SDM's) design organization is generally aligned with these system architectures and there is a clear definition of responsibility for each. (NAVSEA 2004)
- The selection of hardware / software / humanware system elements during synthesis results in the creation of derived requirements. Typically these derived requirements include specific details for elements such as the distributed systems onboard ship (electrical power, compressed air, sewage, potable water, etc.).
- The derived requirements generated during synthesis feed back to the Requirements Analysis Block (In addition to verification that the design and the developed product meet the requirements). Feedback regarding functional analysis and allocation may develop additional configuration items (or change existing configuration items) to fulfill the derived requirements. These new configuration items are then synthesized which in turn may create even more derived requirements. The process continues until the Synthesis loop does not create any additional derived requirements and the design is verified to satisfy all direct, derived, and statutory requirements.

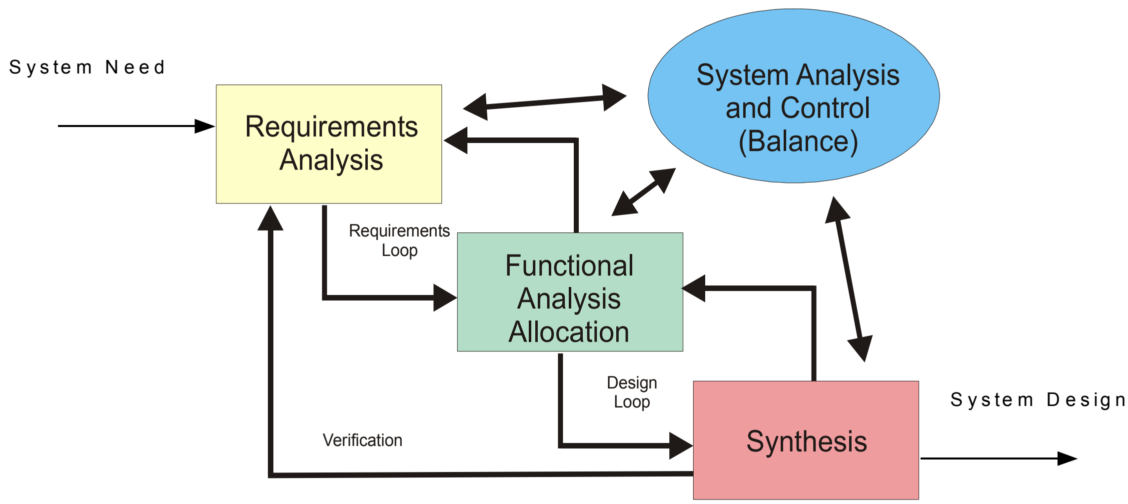


Figure 1: The Classical Systems Engineering Process

Allocate Requirements to Mission Systems

Each ship type has requirements specific to that ship type. Requirements that are specific to Surface Combatants include:

- maximum speed, endurance, speed-time profiles
- weapon systems, guns, missiles, torpedoes, small arms
- sensor systems, radar, sonar, electronic intelligence (ELINT)
- self defense systems, electronic countermeasures, chaff, torpedo decoys
- aircraft and support activities
- on board training systems
- signature characteristics, magnetic, airborne and structure-borne noise, radar cross section, infrared
- shock and vibration
- survivability, redundancy, compartmentation, damage control
- Military Specifications and Standards
- American Bureau of Shipping Naval Vessel Rules
- margin policies

All requirements are not of equal importance. In any acquisition, there are requirements, which, if not met or exceeded, will be totally unacceptable programmatically, and **there** are requirements which are subordinate and more flexible.

To reduce the time required to allocate capabilities to systems and then synthesize the system solution, the authors propose the creation of a library of "System Packages" to map tasks from the Universal Navy Task List (UNTL) (Chief of Naval Operations 2001). These "System Packages" would consist of:

- Capability Performance
  - UNTL Capabilities satisfied by this System Package
  - Measures the System Package can achieve for specific conditions
- Hardware Descriptions
  - Expanded Ship Work Breakdown Structure (ESWBS) code + Nomenclature
  - Geometric + mass properties for the entire package or for each of several sub-packages (if needed)
  - Distributed systems needs
  - Ship arrangement considerations
  - Integrated Logistic Support (ILS) needs
- Software
  - Amount of Total Ship Computing Environment (TSCE) re-use code required
  - Amount of new TSCE code required
  - Other TSCE requirements
- Manpower
  - Watch-standing Skill Objects and manhours
  - Maintenance (Preventative (PM) and Corrective (CM) Skill Objects and manhours

For some capabilities, incorporation of the applicable System Package from the library of packages into a design would be sufficient to ensure all requisite mission equipment are included. Of course, the distributed system needs of the System Packages levy additional derived requirements that must in turn be allocated and synthesized.

Other capabilities are a function of multiple System Packages and the manner in which they are integrated to form a total ship solution. The library of packages can help in managing the collection and configuration of the multiple packages for each iteration. The library does not address how to integrate the packages to achieve the desired capabilities. To simplify integration, zonal design offers opportunities to the naval architect.

Develop Initial Concept of Operations

During this stage of the design process an initial Concept of Operations (CONOPS) is developed to document how the concept and its mission systems are intended to be used to fulfill the concept's missions. The CONOPS is used in developing the Electrical Plant Load Analysis by identifying which systems and subsystems are needed to be online for different design conditions. The selection of the number of power supplies, their rating, inherent reliability and signature performance are all influenced by the CONOPS and will drive the overall ship design. The CONOPS is also used in the evaluation of Total Ship Mission Effectiveness.

Assign Mission Systems Elements to Ship Zones

Zonal Design enables the naval architect to assign mission functions to specific zones of the ship in a manner that can reduce ship complexity, enhance survivability, and reduce the number of design iterations required to integrate a ship.

A zone is a geographic region of the ship. The boundaries of the zone can be arbitrary, but to maximize survivability, the zones of multiple distributed systems as well as damage control zones should be aligned. For shipboard distributed systems, this typically means the zone boundaries are the exterior skin of the ship and selected transverse watertight bulkheads. The zone boundaries may rise above the watertight bulkheads into the superstructure, or the superstructure may be composed of one or more zones independent of the zones within the hull.

The size of a zone is a compromise between increased survivability and cost. In general, damage from threats that are not over-matching should be limited to one or two adjacent zones. However, zones should not be so large that a significant amount of mission system equipment will remain undamaged, but inoperative due to a lack of required services from damaged distributed systems. For most combatants, about 6 or 7 zones is a good starting point, resulting in each zone being roughly 15% of the length of the ship.

For mission systems, zonal survivability is the ability of a mission system, when experiencing internal faults due to damage or equipment failure confined to adjacent zones, to continue its function, perhaps at a somewhat lower level of performance, with the surviving equipment in undamaged zones. Zonal survivability assures the impact of damage does not propagate outside the adjacent zones in which damage is experienced. Zonal survivability requires sufficient damage control features to prevent the spreading of damage via fire or flooding to zones that were not initially damaged.

To implement zonal design, the authors propose a Naval Concept Essential Task List (NCETL) be defined as the cumulative list of tasks that a concept is designed to accomplish under the specific set of conditions and to the assigned measures. The NCETL should employ the tasks, conditions, and measures defined in the Universal Navy Task List (UNTL) to the greatest extent practical. This should not be difficult with respect to tasks and conditions. However, the measures defined in the UNTL may not be sufficient to characterize a ship concept and may require augmentation.

The naval architect starts with the NCETL and chooses mission system packages to achieve the NCETL capabilities. These packages, or elements of the packages, are assigned to different zones of the ship. For the capabilities that are required to have zonal survivability, redundant packages, or redundant elements of the packages, must be assigned to different non-adjacent zones. This assignment of functions and associated equipment to different zones at the earliest stages of design is the key feature of zonal ship design.

When combined with zonal distributed systems design, this consistent approach to mission system design assures a minimum level of zonal survivability while minimizing design iterations in the earliest stages of design. Contrast zonal design with the current design methodology consisting of many synthesize, analyze, and correct design iterations.

Develop Derived Requirements for Ship Systems

Before the ship designers and engineers get too far down into the actual design process, a very important part of the process must occur. The naval ship design process is complex and with many requirements. These requirements come from many sources. The sources include OPNAV Capabilities Documents, OPNAV instructions, Navy Policies, Regulatory Bodies, American Bureau of Shipping Naval Vessel Rules, Mil-Stds, Mil-Specs, Other Government Standards, etc. The ship design team must embrace the process of developing the derived requirements that are applicable to the various ship systems. The process is tedious and requires full systems analysis. The results of this analysis will result in system tradeoff discussions as well as the prioritization of requirements. In some cases, the analysis will highlight conflicts and requirements that do not have a linkage to anything in the hierarchy of the system. In all cases, the system engineers must understand and make the best total system design. The final results of this process must result in a system specification that the ship design can reference and use downstream in the development of the final ship specification.

Develop Distributed System Architectures

During this stage of the ship design process, the major elements of the distributed systems are assigned to zones and the number and type of longitudinal buses are selected. As described earlier, the distributed system needs of the mission system packages are derived requirements that must in turn be analyzed, allocated, and synthesized. The use of zonal distributed systems as described in (Doerry 2005) ensures the zonal survivability of the mission systems is not compromised by un-survivable supporting systems.

Zonal distributed systems also help reduce ship design complexity by limiting the number of distribution elements that cross a space without servicing the space. In zonal distribution systems, only longitudinal mains run fore and aft. Feeders generally run port or starboard and up or down. By careful location of the longitudinal mains, perhaps even using dedicated utility trunks, the number of spaces that must be “crossed” to reach the end user can be minimized.

Calculate Distributed System Component Ratings

Properly sizing the different elements of the distributed systems is based on the flow-down of all the derived requirements. Generally, a database of all the loads for a given distributed system is created. These loads, plus design margin and service life margin, are amalgamated in some manner to develop required ratings for the distributed system elements. Typically, all the loads are not expected to require their maximum use of the distributed system commodity at the same. Thus, the required rating for the distributed system element is a fraction of the connected load, the sum of all the individual loads served. Each distributed system has its own method for determining the proper fraction of the connected that should be used for sizing distributed system elements.

Synthesize Ship

The next step in zonal ship design is wrapping a ship hull around all of the zones. This hull is analyzed to ensure it "balances" in terms of all of the naval architecture requirements such as volume and area analysis, stability, resistance and powering, and structural strength. Figure 2 graphically depicts the process starting with defining the desired concept capabilities in the NCETL, allocating these capabilities to System Packages, assigning the system packages to zones, identifying derived requirements for distributed support systems, synthesizing the distributed support systems, analyzing the total ship performance, and making any needed adjustments to the zonal system packages .

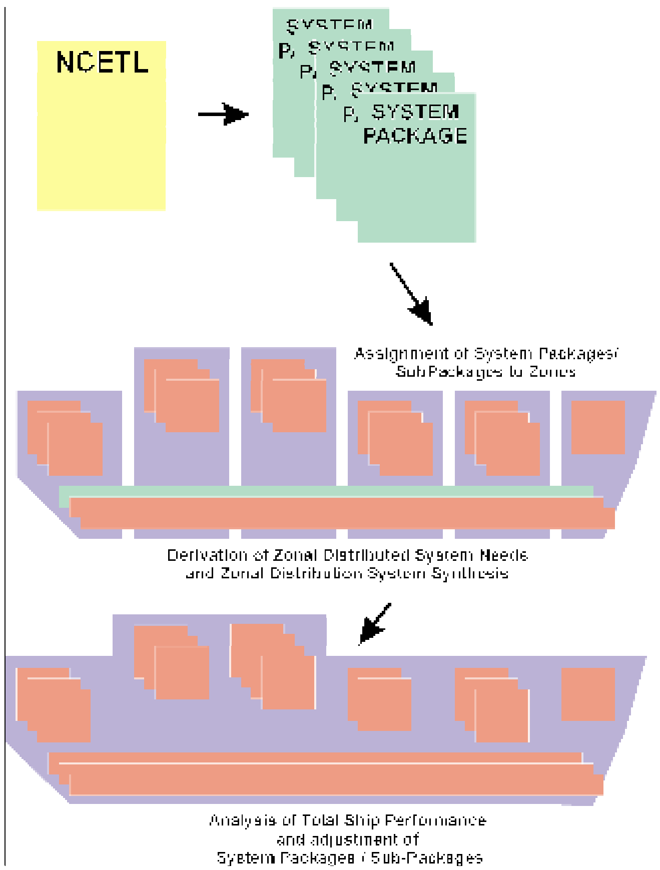


Figure 2: Zonal Ship Design Process

In balancing the ship, system packages / sub-packages and/or distributed system elements may have to be moved from zones with volume and/or area deficits to zones with available volume or area. When relocating packages, the naval architect must ensure that zonal survivability is considered.

Evaluate Total Ship Mission Effectiveness

The ship design process is not complete. The total ship mission effectiveness must be assessed. Along the ship design timeline, the critical path in the design process is obtaining timely feedback on how well the design satisfies the requirements. During the analysis phase several key assessments are done. They include:

- Cost vs. capability
- Signatures analysis
- Speed vs. electric power availability
- Ship survivability

- Total warfare assessment
- Satisfying all naval architecture limits (weight, KG, v-lines, etc.)
- Design margins
- etc.

Iterate until Total Ship Mission Effectiveness Requirements Are Met

Typically in the early phases of the design continuum several aspects of mission effectiveness are not satisfied, thus necessitating modifications to the ship design and a repeat of the analysis. In many cases, derived requirements may have to be reallocated, requiring additional functional allocation iterations. This process repeats at least until all of the ship requirements are met. If additional time remains, additional iterations may be explored to optimize cost and capability while reducing risk.

IPS ARCHITECTURE

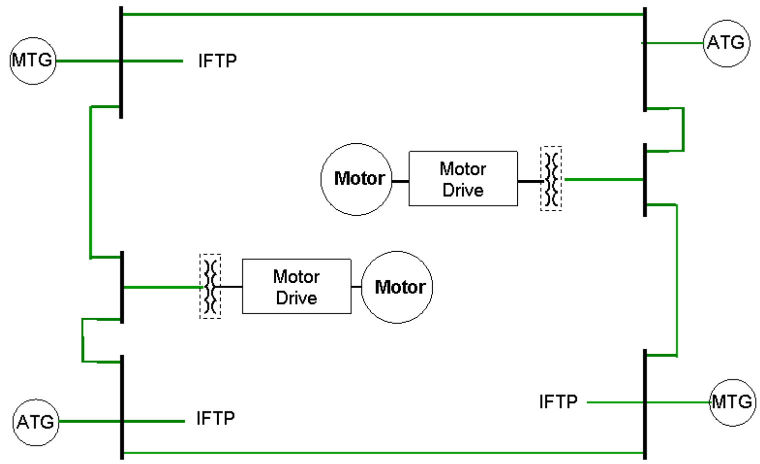
The basic IPS architecture described by Doerry and Davis (1994) and Doerry et al (1996) is generally common among all recent electric warship designs. The actual interface standards however, continue to evolve. The following sections will describe the basic IPS Topology and detail each of the module types and provide the design guidance for the synthesis of the IPS. The basic IPS module types are:

- Power Generation Modules (PGM)
- Power Distribution Modules (PDM)
- Power Conversion Modules (PCM)
- Energy Storage Modules (ESM)
- Power Loads
- Propulsion Motor Modules (PMM)
- Power Control Modules (PCON)

IPS Topology

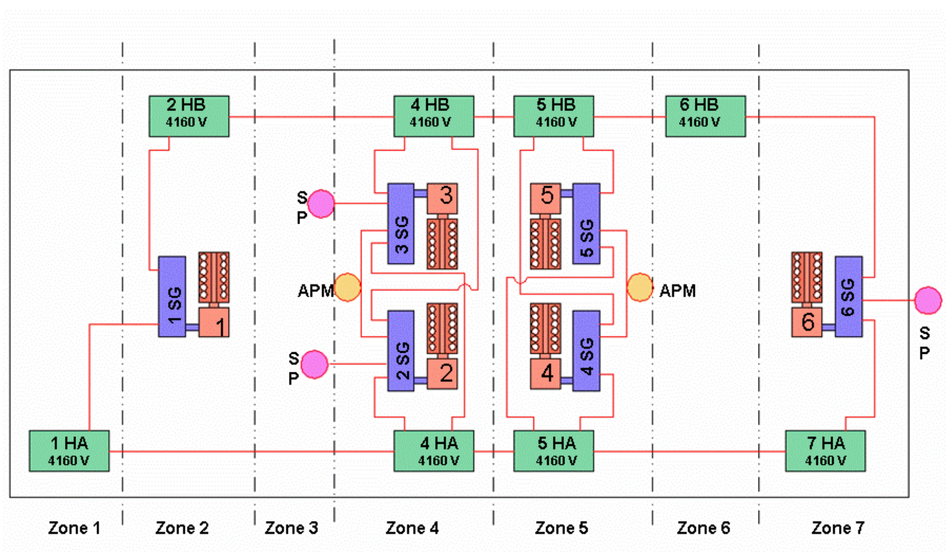
Most IPS configurations feature similar characteristics. Power Generation Modules provide power to a High Voltage (4.16 kV to 13.8 kV) 3 phase ac power distribution module (Figure 3). Propulsion Motor Modules and High Power Loads (generally larger than 500 kW, but sometimes smaller) are provided power directly from the High Voltage PDM. For ships with an AC Zonal Distribution System (AC ZEDS), the High Voltage PDM is normally configured as a port and starboard bus. For ships with a DC Zonal Distribution System, also known as Integrated Fight Through Power (IFTP), the small number of modules connected to the High Voltage PDM generally results in a ring bus being most economical.

For AC ZEDS systems (Figure 4), loads are fed power from one or more load centers. Each Load Center is provided power from a transformer from the same zone or an adjacent zone. To ensure zonal survivability, for loads provided two sources of power from two load centers, the associated load centers are connected to transformers on opposite buses and are not connected to transformers in the same adjacent zone.



MTG = Main Gas Turbine Generator
ATG = Auxiliary Gas Turbine Generator
IFTP = Integrated Fight Through Power

Figure 3: Notional High Voltage AC Distribution System



APM = Auxiliary Propulsion Motor
SP = Shore Power
SG = Generator Switchboard
HA/HB = High Voltage Bus Switchboard

Figure 4: Notional AC-Zonal Distribution System

For IFTP Systems (Figure 5), three Power Conversion Modules PCM-4s are presently used to convert the High Voltage AC power to DC Power for the port and starboard buses. Normally one PCM-4 provides power to each bus, with the third PCM-4 on standby. Within each zone, PCM-1s are located in each electrical zone to protect and segment the port and starboard buses. The PCM-1s provide power to the PCM-2s and PCM-3s which in turn provide power to AC and DC loads. The various Power Conversion Modules (PCM-1, PCM-2, PCM-3, and PCM-4) are described in detail below.

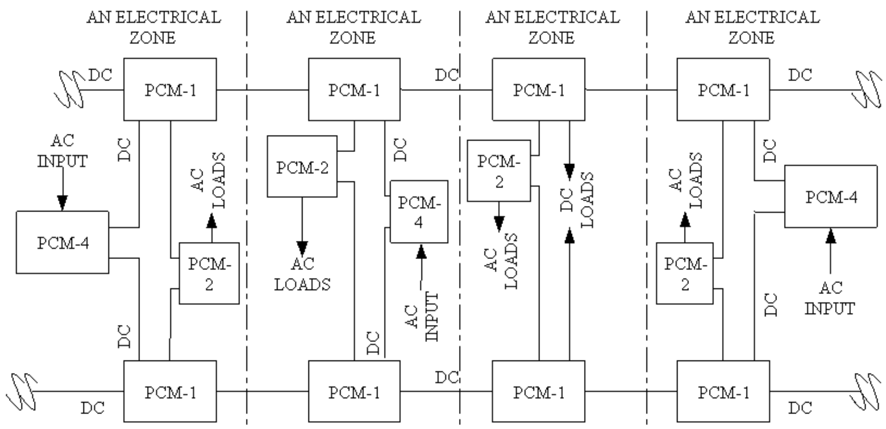


Figure 5: Notional DC-Zonal Distribution System

IPS Modules

Power Generation Modules (PGM). A Power Generation Module converts fuel into electrical power that is transferred to one or more Power Distribution Modules. A Power Generation Module also exchanges control and information signals with System Control Modules and may interface with other distributed systems such as seawater system, fuel service system, intakes, and exhaust.

A Power Generation Module typically consists of either a gas turbine or a diesel engine, a generator, possibly power electronics, auxiliary support submodules and module controls. Other possible technologies include solar cells, fuel cells, or other direct energy conversion concepts.

Most ships will typically have at least two different types of PGMs. Generally the PGMs with the higher rating are called Main Turbine Generators (MTG) or Main Diesel Generators (MDG) while the smaller are called the Auxiliary Turbine Generators (ATG) or Auxiliary Diesel Generators (ADG).

IPS offers the ship designer the ability to better match the performance of a gas turbine to the operating conditions. Specifically, the maximum power that a gas turbine can produce without degrading reliability is a function of ambient air temperature. At low temperature, a gas turbine is capable of producing considerably more power than at higher temperatures. In the past, the Navy has rated gas turbines with a single maximum “flat rating” power rating that fell somewhere between the maximum commercial rating at low ambient air temperature and the maximum commercial rating at 100°F. See Figure 6. The improved reliability achieved by operating considerably lower than the commercial rating (“tent rating curve”) in lower ambient air temperatures offset the reduction in reliability by exceeding the commercial rating at high temperatures. Since the power needed to achieve a given speed is not dependent on ambient air temperature, a constant rating for mechanical drive makes sense.

For IPS Ships however, the total electric load is also dependent on temperature. Electric heating loads currently are significantly greater on cold days than the air conditioning loads on warm days. Table 1 shows that the difference in electrical load between the 10°F and 90°F day for LHD 8 is on the order of 7 MW. As can be seen in Figure 6, the Flat Rating Curvefor this particular gas turbine is roughly the same as the Tent Rating Curve at 90°F. At 10°F however, the Tent

Rating Curve is significantly greater than the Flat Rating Curve. If the ship configuration includes two of these large gas turbines, then the remaining power generation modules can be lower in rating then if the Flat Rating Curve were used. Please note that this extra power at lower temperatures does not come free. If the ship operates in an ambient air temperature above 90°F, the gas turbines may not be able to generate sufficient power to achieve the ship's maximum speed.

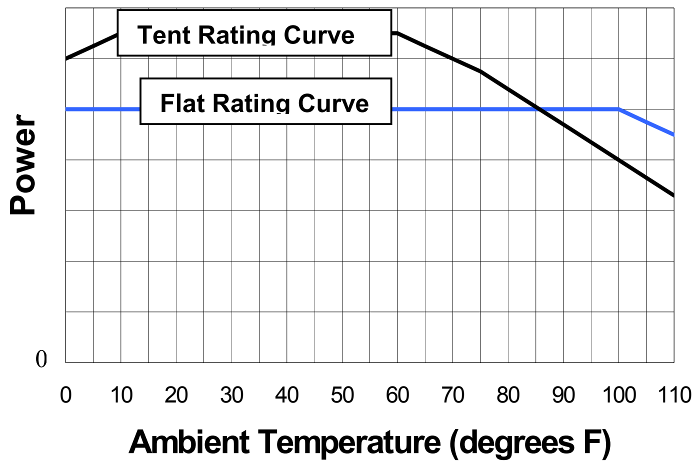


Figure 6: Gas Turbine Power Ratings

TABLE 1: SHIP SERVICE ELECTRIC POWER LOAD REQUIREMENTS EXAMPLE

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

The rating of a medium speed diesel is not impacted significantly by the ambient temperature. Medium speed diesels larger than about 2 MW however, are limited in the amount of overload they can support, typically only 10%. This limited overload capability requires careful integration of Propulsion Motor Module controls, the system protection algorithms in the Power Distribution Modules, the Power Control Software (PCON), and the Power Generation Module controls to ensure that loss of one PGM will not result in cascading overloading and tripping offline of remaining online PGMs.

Designing a power system that requires paralleling gas turbine and diesel generators requires special attention. The transient response of a diesel engine is typically faster than a gas turbine, particularly if the gas turbine has an independent power turbine. This means that in a step load change, the diesel will react faster than the gas turbine, possibly resulting in the diesel overloading and tripping off-line. Appropriate modeling and simulation during preliminary design is necessary to ensure the power system behaves as desired.

Power Generation Modules typically produce 3 phase 60 Hz power. The standard voltages generated are 450 VAC, 4.16 kV, and 13.8 kV. Naval power systems generating 450 VAC are called low voltage systems, while those generating power between 4.16 kV and 13.8 kV are high voltage systems (U. S. Navy high power systems correspond to medium voltage systems in terrestrial power systems). Some high voltage systems employ non-standard voltages such as 6.6 kV, 6.9 kV and 7.2 kV. The selection of voltage is based on the availability of circuit breakers of sufficient rating both for normal operation and fault current interruptions. Table 2 shows typical limits for the power rating of the largest generator or load in the power system. Table 3 shows the typical limits for the total amount of generation that can be paralleled at once (a .95 Power Factor (PF) is used if most of the load is propulsion or DC Zonal Electrical Distribution, otherwise a .80 PF is used). In many ship designs, split plant operation is used at higher power levels, thereby doubling the total ship power generation capacity limits shown in Table 3. In practice, one can purchase non-standard circuit breakers with somewhat larger current capacity for a significant increase in cost and complexity (For example, 4000 amp high voltage (terrestrial medium voltage) breakers are available, but require forced air cooling). Likewise, the total amount of generation can be adjusted somewhat by either generator design to limit fault current (the table assumes maximum fault current rating is 8 times rated current based on derating the maximum fault current by 20% and a 16% subtransient reactance of the generators) or paying substantially more for circuit breakers with higher fault current interrupt capability. Additionally, at a cost of extra control system complexity, other work-arounds are possible to increase the allowable bus MVA shown in Table 3.

TABLE 2: LARGEST GENERATOR OR LOAD VS. VOLTAGE BASED ON CIRCUIT BREAKER LIMITS

Voltage Level	Breaker Rating (amps)	MVA	MW @.95 PF	MW @.80 PF
450	4000	3.1	3.0	2.5
4160	3500	25.2	24.0	20.2
6900	3500	41.8	39.7	33.5
13800	3500	83.7	79.5	66.9

TABLE 3: MAXIMUM BUS POWER BASED ON FAULT CURRENT INTERRUPTION CAPABILITY

Voltage Level	Typical maximum Fault Current (amps)	Approx Bus MVA allowable	Approx Bus MW allowable @.95 PF	Approx Bus MW allowable @.80 PF
450	85000	8	8	7
4160	47000	42	40	34
6900	39000	58	55	47
13800	68000	203	193	163

The sum of the ratings of all PGMs must be greater than or equal to the maximum predicted margined load (both ship service and propulsion) plus service life allowance for ship service loads. Additionally, the sum of all PGM ratings less the rating of the largest rated PGM must be greater than the maximum predicated margined ship service load plus service life allowance.

In past studies, the optimal number of “normal use” PGMs for most configurations has generally been between 4 and 6. An even number of “large” PGMs generally simplifies the high voltage system design by allowing an even loading in a split plant configuration. For bus voltages lower than 13.8 kV, a split plant configuration may be required do address fault current limitations on the circuit breakers when all PGMs are online. If an odd number of large PGMs is used, it may be beneficial to choose a system voltage of 13.8 kV or to choose PMMs with dual motors, such that one motor on each shaft can be driven by a stand-alone “large” PGM.

The “Small” PGMs should generally be sized to supply power to all of the uninterruptible (DC ZEDs only) and short-term interruptible loads. For AC ZEDs systems, all uninterruptible loads must be provided with dedicated Uninterruptible Power Supplies. If energy storage modules are employed, the rating of the “Small” PGM can be reduced by the rating of the Energy Storage Module.

Because many of the PGMs require electrical power to start, many ship configurations will include at least two small (250 KW to 500 KW) emergency diesel generators to provide the initial power needed to start the larger PGMs. These emergency diesel generators may be connected directly into the ship service system instead of providing power through the high voltage bus.

Power Distribution Modules (PDM). A Power Distribution Module transfers electrical power between other Modules. It can also provide fault current protection as well as provide different power system configurations. A Power Distribution

Module exchanges control and information signals with System Control Modules and may interface with other distributed systems such as the chill water system, and ventilation systems.
Power Distribution Modules typically consists of cables, switchgear, load centers, power panels, load monitoring equipment and fault protection equipment. In designing a power system, a naval power system designer must be prepared to make the following choices:

- High voltage bus voltage
- AC versus DC zonal electrical distribution system
- For AC ZEDS, whether to use high voltage buses or 450 VAC buses.

The initial selection for the High Voltage Bus is based on the characteristics of the available circuit breakers. Figure 7 provides the initial voltages to consider based on the sum of the ratings of all the PGMs. Table 2 provides an additional constraint for the minimum system voltage based on the size of the largest individual PGM or load. In general, the system voltage should be allowable from both Figure 7 and Table 2. For example a 78 MW system with the largest load being a 35 MW Motor should employ either a 6.9 kV or a 13.8 kV bus because of the unavailability of a 4.16kV breaker for the 35 MW Motor. For this example, a 13.8 kV system may be preferred to simplify the shore power connection (Navy bases are currently being upgraded to provide 450 VAC, 4.16 kV, and 13.8 kV shore power connections) If an odd number of large PGMs (greater than 18 MW) are used, the inability to balance generation in the split plant configuration may force one to use a higher voltage (typically 13.8 kV).

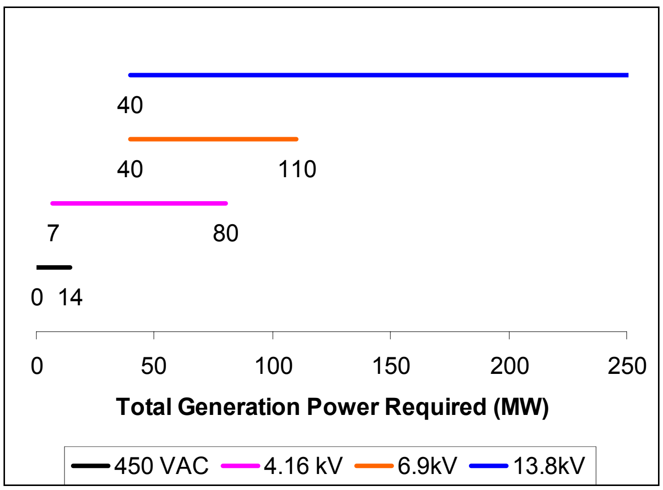


Figure 7: Recommended Bus Voltage for Given Total Generation Power Required

The selection of propulsion motor module may also have an impact on the selection of the bus voltage. Motors based on commercially available drives typically use 4.16 kV to simplify both the insulation system in the motor, and to simplify the motor drive. If power is not generated at 4.16 kV, then large, expensive, and heavy transformers are needed to lower the generation voltage to that needed by the drive unit. On the positive side, using the transformer enables one to reduce the harmonic distortion on the high voltage bus. With minimal filtering, an AC Zonal Distribution system may be capable of providing the requisite power quality and quality of service.

If directly connected to the 4.16 kV bus, a conventional controlled rectifier on the front end of a motor drive will cause significant harmonic distortion on the 4.16 kV bus. Because the ship service loads will likely not work properly with the harmonic distortion, a 4.16 kV bus will likely either need harmonic filtering, or some other form of isolation, such as a DC Distribution system. If harmonic filtering is not included, the PGMs must be designed to handle the harmonic rich currents (adding weight and cost). In the future, the use of higher technology rectifiers, such as Pulse Width Modulated (PWM) rectifiers, will reduce the amount of harmonics induced on the high voltage bus. These advanced rectifiers will likely cost more, but the total ship impact cost will likely be reduced.

The choice of whether to use AC or DC zonal distribution should be based on the power quality of the high voltage bus (which largely depends on the PMM choice) and on the amount of un-interruptible ship service loads. If the Power Quality of the high voltage bus is good enough such that loads can receive power, meeting the Navy's MIL-STD-1399 section 300A interface standard (NAVSEA 1987) and if the amount of un-interruptible ship service loads is small, then an AC Zonal Electrical Distribution System (with local Uninterruptible Power Supplies for uninterruptible loads) will likely be the most cost effective system. Otherwise, a DC Zonal Electrical Distribution System, otherwise known as IFTP, is likely the best solution.

The use of modeling and simulation is critical during early ship Preliminary Design to identify the most cost effective way to manage the high voltage harmonics, short circuit currents, and transformer inrush currents; choose the most appropriate voltage for the high voltage bus; and select an AC or DC zonal electrical distribution systems.

Power Conversion Modules (PCM). A Power Conversion Module converts electrical power from the form of one Power Distribution Functional Module to the form of another Power Distribution Module. Power may be transferred only to and from Power Distribution Modules. A Power Conversion Module exchanges control and information signals with System Control Modules and may interface with other distributed systems such as the chill water system and ventilation systems.

A Power Conversion Module typically consists of a solid state power converter and/or a transformer. Another possibility is a motor-generator set. The power conversion equipment associated with generators and motors are, however, part of the Power Generation and Power Load Modules, respectively. In some cases, a Power Conversion Module may include switchgear functionality normally associated with a Power Distribution Module.

In the development of IPS, several different types of PCMs are given specific nomenclature:

PCM-1: Convert 1000 VDC to 800 VDC and provide fault current protection. To provide improved reliability and scalability for different shipboard zones, a PCM-1 is typically composed of a control unit, an enclosure with a distribution section, and multiple lower power Ship Service Conversion Modules (SSCMs). The available ratings of the SSCMs are not currently consistent among PCM-1 vendors and SSCMs are not interoperable with those of a different vendor. A PCM-1 may be air cooled, fresh water cooled, or chill water cooled. To facilitate dark ship startup, PCM-1s are provided a short term air cooled rating.

PCM-2: Convert 800 to 1000 VDC to 450 VAC at 60 Hz and provide fault current protection. To provide reliability and scalability for different shipboard zones, a PCM-2 is typically composed of a control unit, an enclosure with a distribution section, and multiple lower power Ship Service Inverter Modules (SSIMs).

PCM-3: Convert 800 to 1000 VDC to 270 VDC and provide fault current protection. PCM-3s are very similar to PCM-1 and can share a significant amount of hardware and software components. The SSCMs may differ to optimize efficiency in converting to a lower voltage. Some PCM-3 SSCMs may be programmable to provide other DC voltage such as 155 VDC that may be required by load equipment.

PCM-4: Convert 60 Hz AC Power (4.16KV to 13.8KV) into 800 to 1000 VDC. PCM-4s are typically composed of a 60 Hz transformer, a controlled rectifier and a filter.

Within the naval power system design community, there is currently debate as to the best method for determining the required rating for power conversion modules. Essentially, there are three basic methods (each having variations) proposed. The *first* method employs load factors which are multipliers to all the loads served by the power conversion device. The Power Conversion Device must have a rating greater than the sum of the product of each connected load multiplied by its load factor. Establishing realistic non-conservative load factors and adjusting the analysis to account for special operating conditions are challenges for using this method. Historically, load factors as applied within the Electric Plant Load Analysis (EPLA) have been used to size generator sets. The *second* method employs a demand factor obtained from a graph in MS18299 (NAVSEA 1987A) which returns a Demand Factor based on the total connected load (measured in amps) for 450 VAC loads. The Demand Factor is applied directly to the total connected load to determine the rating. Historically, Demand Factors have been applied to the sizing of feeder cables, feeder breakers, and load centers. Perhaps coincidently, Load Factor analysis and Demand Factor analysis have historically returned similar results.

John Amy (2005) proposes another method based on representing electric loads as probability density functions and determining both an expected value for electric load and a standard deviation. With this method, one can establish a required PCM rating to achieve any level of risk for meeting the electrical power demand. At any stage of design, rating the PCMS to meet the anticipated load with 95% probability is likely sufficient. Since the difference between the expected value and the 95% probability value is in effect a design margin, this method provides an engineered approach to establishing at least a portion of the design margin. Furthermore, as a design progresses and more is known about the loads, the standard deviation

of the probability density functions can be expected to decrease, resulting in a smaller difference between the expected value and the 95% probability value, thereby shrinking the required design margin.
Within the naval power system community, there is also debate as to whether an N+1 rule should apply to the SSCMs and SSIMs comprising PCM-1, PCM-2 and PCM-3. An N+1 rule requires an additional (+1) SSCM or SSIM over the number (N) required to meet the demand. The additional SSCM or SSIM serves as a backup in case one of the others becomes inoperative. From a quality of Service Perspective, one would not need to provide an N+1 SSCM/SSIM if any of the following conditions were true:

- The Mean Time Between Failure (MTBF) of the SSCM or SSIM was on the order of 30,000 hours or more (failure did not occur often)
- Sufficient load could be shifted to another PCM to prevent overloading of remaining SSCMs or SSIMs (N+1 on a zonal level rather than on a PCM level)
- The Mean Time to Repair (MTTR) and Mean Logistic Delay Time (MLDT) of the SSCM or SSIM was less than 5 minutes and the reduction in PCM capacity could be accommodated by shutting down long-term interrupt loads.

In AC Zonal systems, transformers serve as PCMs, but are generally not designated as such. These transformers are often integrated with switchboards on both the high voltage (4160 VAC or 13.8KV VAC) and the low voltage side (450 VAC). Based on circuit breaker limitations on the 450 VAC side, the maximum rating for a zonal transformer is 2.5 MW. In an AC Zonal system, a transformer may serve load centers in more than one zone. Since larger transformers are more cost effective per unit of power, many zonal ac systems employ the minimum even number of transformers with a rating typically between 2 and 2.5 MW.

Energy Storage Modules (ESM). An Energy Storage Module stores energy. It receives the energy electrically from and delivers the energy electrically to a Power Distribution Module. An Energy Storage Module exchanges control and information signals with System Control Modules and may interface with other distributed systems such as the chill water system and ventilation systems.

An Energy Storage Module can be based on a host of technologies to include batteries, flywheels, superconducting magnetic energy storage (SMES), and ultra-capacitors. Energy Storage modules will often include significant power conversion electronics to interface with the Power Distribution Module. The power rating and energy capacity of an ESM will depend on the intended application that will usually fall into one of the following categories:

- Low Power (~250 KW) for 2 to 10 seconds: Provide hold-up power to uninterruptible loads while traditional electro-mechanical switchgear isolates faults. Also protects uninterruptible loads from normal system transients.
- Medium Power (~500 KW) for 5 to 10 minutes: Provide hold up power for uninterruptible and short term interruptible loads to enable single engine cruise operation. The ESM provides power while a standby PGM starts should an online PGM shut down unexpectedly.
- Low Power (~250 KW) for 15 to 30 minutes: Provide emergency starting for PGMs in a dark ship start condition.
- High Power (MW) for seconds: Provide pulse power to advanced combat systems such as rail gun Pulse Forming Networks (PFN), high powered lasers, and advanced radars.

Although the advantages of an ESM are known, a shipboard qualified ESM has not yet been developed. Theoretically, a single ESM architecture employing common and scalable hardware and software elements could be employed to meet all of the above categories.

Power Loads. Power Loads are the end users of the electrical power. In designing the power system to meet the demands of the Power Loads, the following information about each load on the ship is needed:

- Description: Includes the name and ESWBS number for the load
- Physical location: Typically described in terms of a compartment and Electrical Zone
- Connected load and Power Factor: The Name Plate rating of a load. Typically assumed to be the maximum continuous power that the load can draw from the power system.
- Load Factors for different Operating Conditions and temperatures: Load Factors are multipliers applied to each of the Connected Loads to determine how much generation is required on average for the specified operating

condition and temperature. Redundant Standby equipment are assumed to be off (Load Factor equals zero) for sizing generation equipment.

- Zonal Load Factors for different Operating Conditions and temperatures: Zonal Load Factors are multipliers applied to each of the Connected Loads to determine the sizing of zonal power conversion equipment. Standby Equipment are assumed to be on for sizing zonal distribution equipment.
- Relationship with other loads: It is important to know which other loads are functionally redundant to the given load to prevent common-mode failures. Likewise, it is also important to know which other loads are required to operate as a group to achieve a mission capability to maximize the probability that all the required loads are provided power.
- Quality of Service requirement: Loads are categorized into one of three Quality of Service (QOS) categories: Un-interruptible, Short-Term Interrupt, and Long-Term Interrupt. Un-interruptible loads can not tolerate power interruptions of 2 seconds or more. Short-Term Interrupt loads can tolerate power interruptions of 2 seconds, but can not tolerate power interruptions of 5 minutes duration. Long Term Interrupt loads can tolerate power interruptions of 5 minutes. The QOS category is important for the sizing of Power Distribution Equipment, as well as for determining the optimal sizing of Power Generation and Energy Storage Modules.
- Survivability requirements: Non-redundant mission system loads, and damage control loads required to contain damage to directly impacted loads generally require survivable redundant sources of power to enable their restoration following battle damage. Other loads can generally rely on zonal survivability to provide the requisite level of survivability.
- Controls Interface to Power Control Module: Most loads do not directly interact with the Power Control Module. Some larger loads do communicate with the Power Control Module to ensure sufficient generation capacity is online before the load starts. Other loads may request a shutdown command to enable an orderly shutdown before power is turned off by the distribution system.

Most of the information listed above is typically captured in a database and reported via an Electric Plant Load Analysis (EPLA) that is evolved through out the design process.

During the design process, power loads are assigned to power panels and load centers (Power Distribution Modules). The information described above for each load is used to calculate the required ratings of each IPS Module and the level and type of redundancy that must be provided.

Propulsion Motor Modules (PMM). Propulsion Motor Modules are in reality Power Loads. PMMs are treated differently from other loads primarily because their rating is typically a large fraction of the installed power generation capacity necessitating a much tighter controls interface than with other loads. With present day Motor Drive technology, PMMs typically insert relatively large current harmonics into the power system that must be dealt with through careful power systems engineering.

Propulsion Motor Modules typically consist of an electric motor, an associated drive, and related auxiliaries (lube oil, cooling water, etc). With the exception of podded propulsors, a PMM typically does not include the thrust bearing, shafting, or propeller. A PMM may include a transformer to interface with the power distribution modules. These transformers may be employed to lower the voltage to a level required by the Motor Drive and/or to decrease the amount of harmonics injected into the power system.

For near term ship designs, Advanced Induction Motors (AIM) and Permanent Magnet Motor Systems (PMMS) are the preferred technologies that provide the best cost vs capability. Permanent magnet motors generally have a greater power density, but cost more and have a limited industrial base. In the past, synchronous motors and DC motors have been used, but currently they are generally not as cost effective as AIMS or permanent magnet motors. In the future, superconducting motors and superconducting homopolar motors may become producible, reliable and cost effective enough for shipboard applications.

Motor Drive technology has advanced considerably in the past ten years and is anticipated to continue to advance in coming years. Older technologies such as cycloconverters and load commutated inverters are currently being superseded by high power pulse width modulated (PWM) converters, multi-level converters, and resonant pole converters. These new drives offer better efficiency, higher power density, and potentially lower cost.

Power Control Modules (PCON). The Power Control Module consists of the software necessary to coordinate the behavior of the other modules. The PCON Software may reside in other modules, or may reside in an external distributed computer system. The PCON Software will interact with the human operators through a Human-Computer Interface that will typically be part of a ship-wide monitoring and control system. The primary functions of the PCON software are remote control, remote monitoring, resource management, survivability, and quality of service. Operator training functions may also be incorporated into PCON software.

IPS DESIGN OPPORTUNITES

Electric Warships offer a fundamental shift in what is today's traditional weapon systems. The introduction of an electric naval force will open future naval ships to fully exploit the power of electricity. Electric warships unlock propulsion power for use in intermittent electric weapons and advanced sensors.

Support High Power Mission Systems

The introduction of IPS into future naval ships designs will result in a surface combatant fleet with superior mission performance, superior survivability, and reduced cost to the Navy. Since all power generated is literally available for ship service needs, this power could be made available to support the introduction of many new technology weapons into the fleet. They include electromagnetic guns, electromagnetic launchers, and free electron laser weapons.

The generation of electric power along with power storage devices will be the next revolution in warship design. As these new warfare technologies transition to the future surface combatants, many of the traditional ship design integration issues will change. As conventional kinematic weapons phase out, traditional ship systems that support shipboard magazines, weapons handling, ship safety and protection systems will also phase out

Reduce Number of Prime Movers

A review of the ships in the US Navy reveals that significant reductions in the total number and types of prime movers in the fleet are possible in the future with the introduction of an IPS architecture into new ship designs.

For example an LPD 17 ship design has 4 medium speed diesel prime movers (total 40,800 HP) along with 5 diesel generators (total 12,500 KW) that equates to 9 rotating machines with the equivalent of 43 MW of total ship power. With today's technology developed in the DDX program and in the early IPS program in the 1990s, a new design LPD could be configured with a higher power IPS configuration using only four prime movers and having considerable commonality with the DDX. This compact power plant could meet all the LPD 17 needs and improve ship performance with potential for increased payload and/or higher sustained speed.

In determining the minimum number of prime movers to use for a given application, the naval architect must judicially select appropriate PGM ratings and plant lineups to ensure sufficient Quality of Service to support the ship's Concept of Operation.

Improve Efficiency of Prime Movers

Through the integration of ship service electrical power and propulsion power, the overall system efficiency of an IPS configuration can be considerably higher than for an equivalent mechanical drive design. The overall efficiency of a mechanical drive ship can suffer because the propulsion prime movers are inefficient at low ship speed With the introduction of integrated plants, the ship service and propulsion loads are managed off the same distributed system. This improves ships fuel conservation/efficiency along with the opportunity to improve MTBF of the total system.

It must be noted that for a ship that operates most of the time near its maximum speed, and has a relatively small ship service electrical load, a mechanical drive plant may prove to be more economical than an IPS plant. These characteristics though, are not typical for most naval warships. Similarly, ships with the propulsion load considerably larger than the ship service load and operate infrequently at the maximum speed may benefit from a hybrid plant where the smaller PGMs produce power for ship service and low speed propulsion, and mechanical drive boast engines provide high speed operation. *Makin Island*, LHD 8, is an example of the latter configuration (Dalton et al. 2002).

Improve Efficiency of Propulsors

The integration of an IPS system in a ship design offers the naval architect a new tool in the propulsion system design. The propulsion shaft line can be simplified with the removal of the traditional controllable pitch propeller (CPP) system. CPPs are currently the state of the practice for major surface combatants in world navies. Naval architects now can investigate the use of contra-rotating propellers or POD Propulsion. A NATO study (NATO NIAG NG6-SG/4 2001) concluded that POD Propulsion is well established in merchant ships where its proven advantages have provided the impetus for an increased number of podded drives. NATO also concluded that a possible contentious point is the behavior of a POD in a combat environment (vulnerability, signatures, shock). PODs potentially offer improved survivability of the naval ship by enabling the longitudinal separation of propulsors.

Improved efficiency is achievable by using contra-rotating propellers. Since many propulsion motor designs feature two independent motors on the same shaft, dedicating each motor to its own propeller does not add significant complexity. Designing long-life bearings to support the inner shaft is an engineering challenge, but achievable. Alternately, a hull mounted shaft and propeller can be paired with a POD to provide contra-rotation without using inner and outer shafts. Ship design tradeoff studies can now be done to see what efficiencies and simplification can be done in the ship when taking full advantage of an all electric ship.

Provide General Arrangements Flexibility

The conventional ship design rules and methodology can be challenged through the use of the Integrated Power System. The basic principles of IPS offer new levels of ship survivability. The system design can result in a ship that has significant overall system reliability and power recoverability attributes. This ship design and synthesis of this system offers the ship designer new tools in the ship configuration process. Traditional ship designs have the prime movers and generators down low in the ship to support the shaft line design. An IPS configured ship offers the designer the flexibility to put the power generators in almost any location. The shaft line can be simplified with direct drive motors (AIM, PMMS or Super Conducting). Future ship designers could also challenge the conventional thinking associated with the longitudinal separation of propulsors, improve the shock and survivability design process and improved ship maintainability. The combustion air and exhaust design can also be challenged. This new electrical system in many ways can reduce the ship complexity that has been associated with naval ship design.

Improve Ship Producibility

The use of an Integrated Power System offers the ship designer and shipbuilder opportunities to improve ship producibility. For example, the elimination of long shaft-lines enables the shipbuilder to change the build sequence to simplify the erection schedule and thereby reduce the ship construction schedule. By locating PGMs higher in the ship, the in-yard need date for these items can be delayed, reducing the likelihood that the equipment will be damaged during the ship's construction. Furthermore, each module can be tested before integration into the ship, reducing the risk that equipment will fail during the ship acceptance process. Zonal distribution systems shorten cable lengths and minimize the number of spaces a cable has to penetrate.

Support Zonal Survivability

For a distributed system, zonal survivability is the ability of the distributed system, when experiencing internal faults due to damage or equipment failure confined to adjacent zones, to ensure loads in undamaged zones do not experience a service interruption. Zonal survivability assures damage does not propagate outside the adjacent zones in which damage is experienced. For many distributed system designs, zonal survivability requires that at least one longitudinal bus remains serviceable, even through damaged zones.

At the ship level, zonal survivability facilitates the ship, when experiencing internal faults in adjacent zones due to design threats, to maintain or restore the ships primary missions. Ship level zonal survivability focuses restoration efforts on the damaged zones, simplifying the efforts required of the ship's crew to maintain situational awareness and take appropriate restorative actions. Ship level zonal survivability requires sufficient damage control features to prevent the spreading of damage via fire or flooding to zones that were not initially damaged.

Because zonal survivability is an inherent feature of IPS design, the ship design process is simplified as well. While some aspects of ship survivability such as signatures are still iterative, assuring zonal survivability allows the design to converge to an acceptable survivability solution faster.

Improve Electric Power Quality of Service

Quality of Service (QOS) as defined by Doerry and Clayton (2005) is a metric of how reliable a distributed system , such as the electrical power system, provides its commodity, such as electrical power, to the standards required by the system users. It is calculated as a Mean Time Between Failures of the distributed system as viewed from the loads. A failure is defined as any interruption in service, or commodity parameters (Power Quality) outside of normal limits, that results in the load requirement not being capable of operating properly. The time is usually specified by an operating cycle, Design Reference Mission (DRM), Concept of Operations (CONOPS) or an Operational Architecture. Quality of Service is a reliability-like metric; as such the calculation of QOS metrics does not take into account survivability events such as battle damage, collisions, fires or flooding. Quality of Service does take into account equipment failures and normal system transients. A typical cause of normal system operation causing a QOS failure is the shifting of sources for the commodity such as shifting to/from shore power (without first paralleling) or manually changing the source of power using a manual bus transfer (MBT). In the design of an electrical system, the optimal configuration of a distributed system may differ for QOS considerations and for survivability considerations. An important QOS consideration is the ability to preserve power to loads when a generation element trips off line while damage to the distribution system and the ability to preserve power to vital mission systems loads is of major interest in the survivability analysis. For QOS reasons, many ships operate with their electric plant paralleled in peacetime steaming and only shift to the more survivable split plant configurations under threat conditions.

As described above, the typical implementation of QOS within IPS is done by classifying loads as un-interruptible, short-term interruptible, and long-term interruptible. By properly selected the number and ratings of PGMs (and ESMs) and implementing the QOS concepts in the control system, a high level of QOS can be designed into the power system (designing just for the maximum load is not sufficient). In the past, electric plant design practices did not take QOS into account. In some cases, the resulting electric plant did not provide reliable power continuity as expected by the operators.

Facilitate Fuel Cell Integration

Due to their inherent efficiency, fuel cells promise to play an important role in future naval power system design (Douglass and Partos 2003; Partos et al. 2003). Since fuel cells produce electrical power, their integration into IPS is natural; Fuel cells are just another type of PGM. Before fuel cells can be used however, a number of technical and ship integration issues require resolution. These issues include:

- Fuel cells require hydrogen fuel. To produce hydrogen, the Office of Naval Research (ONR) is investing in fuel reforming technology. A fuel reformer extracts hydrogen from Diesel Fuel Marine (DFM). A fuel reformer suitable for naval warship installation does not currently exist; the physical properties and cost of such a system is at best approximated.
- The quantity and type of waste products from the reformer are currently not widely known by naval architects. DFM contains a number of other elements besides hydrogen. Possible waste products include carbon monoxide, carbon dioxide, and sulfur based compounds. Gaseous waste products would likely be vented overboard. The quantity of gas produced and the allowable back pressure, currently unknown, would determine the size of the venting system. Liquid waste products would require a holding tank, the size and material of which would depend on the type and amount of waste created and the frequency in which the waste can be offloaded. Solid waste would also require a storage and disposal method. If any of the products are hazardous to personnel, system safety issues must also be addressed.
- The amount of "combustion air" required by the fuel cell is also currently not widely known by naval architects. Depending on the flow requirements, this intake air could be provided by the ship's normal ventilation system, or may require dedicated intakes. Methods for naval architects to calculate the amount of "combustion air" do not currently exist.
- What should be done with the exhaust of a fuel cell? Since some of the oxygen will have been removed from the air, can it safely be vented to the shop's atmosphere? Should it be exhausted overboard? If so, how much exhaust must be vented? What is the allowable backpressure?
- Fuel cells typically produce waste heat. Should a heat recovery system be employed? If so, what would this heat recovery system look like? With or without heat recovery, how should the heat be rejected overboard?
- Fuel cells typically behave very slowly dynamically. Should a fuel cell be integrated with energy storage to provide better transient performance? If so, how does one size and cost the requisite energy storage?
- Considering the above issues, how much space and weight should be reserved for a fuel cell and its associated systems in order to successfully integrate it into a ship design?

Provide Capability to Provide Power to the Terrestrial Power Grid

Many have observed that IPS ships can generate large amounts of power and that employing this capacity to provide power to the terrestrial power grid may be advantageous during periods of war or natural disaster. Providing this capability however, places additional requirements on the power system design that are not normally done. These include:

- A means must be provided for connecting sufficient high voltage cables to the high voltage bus to handle all of the power. Shore power connections typically are rated to carry only the maximum in port ship service load, not the total capacity of the electric plant.
- If power is to be fed directly to the terrestrial grid, the power system must be capable of synchronizing with the grid and integrating with the terrestrial power control systems. Communications will be required with the terrestrial power system command and control centers. For fear of causing terrestrial power system instabilities, the ship will not be able to vary the amount of power provided without first coordinating with the terrestrial power system command and control center.
- The shore infrastructure may have to be adapted to accept power from the electric warships. Many IPS ships will have power generation capacity that exceeds the rating of a typical terrestrial substation. Furthermore, these terrestrial substations must be located close enough to the waterfront to reduce the amount of cabling needed.
- If there is a desire to provide power overseas, the shipboard power system would likely have to be able to produce 50 Hz power. The speed governors of the PGMs must have the capability to operate at 50 Hz. Also, the total capacity would likely be significantly reduced to reflect the derating of every power system component due to operation at other than the designed frequency of 60 Hz.

IPS DESIGN WATCH ITEMS

The incorporation of IPS into a ship design offers the naval architect considerable flexibility to develop novel solutions to mission requirements. However, the naval architect must pay attention to a number of power system design issues to ensure that the power system incorporated in early stage design will in fact work as intended once the ship is in service. Following is a discussion of a number of these "details" to which a wise naval architect should pay attention.

Part Load Efficiencies

One of the advantages of IPS is the ability to improve the efficiencies of the prime movers and propulsors over the expected operating profile of the ship. This advantage can be squandered if the improved efficiencies are offset by lower efficiencies of the power conversion and electromechanical devices. Any electromagnetic device that uses ferromagnetic material will experience core losses that in part is independent of load. This means that at lower power levels, the efficiency of the electromagnetic device will decrease. Similarly, power electronics converters will typically experience lower efficiencies at part load.

For generators, the "fixed" losses are generally on the order of 1.5% of the machine rating. Additional losses on the order of 1.5% at full load are proportional to the square of the load current.

Part Load efficiency can be addressed in a number of ways. Careful design of the electromagnetic devices is one way. Another way is to modularize the devices and switch off un-needed capacity. For propulsion motors, using tandem motors in a single housing is an easy and cost effective way to improve efficiency below half power. Typically, the tandem motors are of equal rating. There is nothing to preclude one motor being sized for the endurance condition and the other rated to provide additional capacity to achieve full power. Additionally, at low power levels, one can energize only a fraction of the stator windings and/or reduce the motor flux by reducing the motor voltage. By careful design of the motor and motor drive electronics/controls, one can optimize the overall efficiency of the PMM over the requisite speed –power range. For PMMs with advanced induction motors and modern drives, one should be able to achieve above 90% efficiency operating above about 20% rated power for the combined motor and motor drive. Without optimization, the efficiency for the motor and motor drive could easily fall within the 70% to 80% range at 20% rated power.

One can also use advanced technology, such as permanent magnets and superconducting magnets to minimize or eliminate the ferromagnetic materials. In any case, the ship designer must pay attention to the assumptions used for part load efficiencies to ensure they are realistic.

Dark-Ship Start

When optimizing the electric plant for the expected operating profile, the design must still accommodate special operating conditions. One of the more critical conditions to the design is that of starting the electric plant when everything is initially turned off. It's important that the design have at least two PGMs that can start without receiving any services from other distributed systems and have sufficient capacity to start the other PGMs. The power distribution system and control system must also be designed to rapidly provide support services such as cooling water, fuel oil service, and controls once the initial prime mover starts. In many designs, small emergency diesel generators on the order of 500 KW are incorporated in the design to provide this dark-ship start capability. Special issues, such as transformer in-rush current (see below) must be accounted in the Dark-Ship starting sequence.

Shore Power

Another special operating condition that must be accommodated is shore power. In an IPS ship, it is not always obvious how to connect the ship to the terrestrial power grid. In an AC Zonal system, a high voltage (4.16 KV or 13.8 KV) shore power connection will likely be the easiest and most cost effective solution. Unfortunately, not all piers currently have the capability to provide high voltage shore power. Also, transformer in-rush current (see below) must be carefully managed to prevent the shore-power breakers from tripping. Alternatives include providing shore power connections to each zone, and providing a step-up transformer to power the port and starboard high voltage buses.

With an IFTP system, shore power can either be provided at the high voltage level or can be provided at 450 VAC and converted into DC before being fed into the port and starboard DC Buses. The latter solution requires either the incorporation of additional power conversion devices, or modification to the PCM-4s to allow an additional power input. The advantage of this solution is that if properly implemented, the acceptable range of shore power frequency (50 and 60 Hz) and voltage may allow the ship to use shore power in more foreign ports than is currently possible.

Power Generation Module Start Times

Many larger gas turbines and diesel engines can take a substantial amount of time to start and become ready to accept a load. Historically, gensets were expected to come on line within 2 minutes of being ordered. Now with larger engines, this start time can take as long as 5 minutes. The design of the power system must account for this longer start time.

Component Reliability

Understanding the reliability of power system components is key to designing a power system that delivers the requisite quality of service without providing expensive and un-needed redundancy. Unfortunately, equipment manufacturers do not consistently provide reliability data in the technical data they provide customers. During the earliest stages of design, estimates or analogy with other systems are typically used. During preliminary design, the system designer should work closely with equipment vendors of critical items to obtain valid reliability data. Otherwise, the designer must balance risk with conservatism in design.

Common Mode Failures

Common Mode Failures are those failures that result in redundant equipment both failing due to a single fault. Possible sources of common mode failures include: shared intakes and uptakes of redundant PGMS, dependence on common support systems, and poorly designed system protection that upon loss of a PGM, automatically transfer loads to remaining online PGMs without first ensuring the online PGMs have sufficient generation capacity to serve them.

Transformer In-Rush Current

When a transformer is first energized, it will experience a transient in its magnetic flux that often will result in the transformer core saturating briefly. When saturated, the transformer will draw a considerably higher than normal current to achieve the transient magnetic flux. The net result is that the transformer will experience an in-rush current on the order of two to ten times its rated current. For transformers that are rated only a small fraction of the online generation, this in-rush current does not pose a problem. If the transformer is large compared to online generation, this in-rush current can cause significant power quality problems and could result in the tripping of circuit breakers or other protective devices.

Transformer in-rush current can be dealt with in several ways. First, the transformer can be designed to minimize in-rush Current. Unfortunately this solution requires a trade-off of increasing the size/weight or accepting a decrease in efficiency. Secondly, starting resistors with their added weight and cost can be used. Thirdly, the generators can be designed to accommodate the in-rush current. Finally, the other loads and the protective systems can be designed to tolerate the transients. In any case, the PCON software must recognize this issue and prevent multiple large transformers from starting at the same time.

FUTURE WORK

Standards

The initial research and development of IPS occurred in the 1990s. IPS transitioned into the ship design process from 2002-2005 as part of the DDX surface combatant program. The use of IPS in future naval ship acquisitions requires the development of robust ship design standards. This paper has identified many technical aspects of IPS that requires coherent standards so the future ship designers can understand the complexity, system tradeoff possibilities and total ship synthesis. The authors recommend that an institutionalized design process and associated design certifications be developed and documented.

A number of design process issues exist that require attention. They include the definition of requirements including sustained speed and endurance speed. Electric load analysis is more critical but not standardized for modern warships. That includes the vital/non-vital loads, power quality (dirty/clean bus), zonal balancing of loads and electric margin policy. Power generation planning is another important area including dark ship start, inrush currents, cascade failure prevention, transient stability of paralleled large and small PGMs, margin policy, and impact of harmonic currents. Lastly, system protection including coordination of breakers, allocation of system protection and energy storage module requirements derivation.

Design Data Sheets

Design Data Sheets (DDS) have become a fundamental technical tool for defining ship design processes for ship design teams. Some examples include speed power estimates, intact stability, damage stability, structural design, etc. The first attempt to develop a DDS for IPS occurred during the IPS Full Scale Advanced Development (Lockheed Martin Corp 1995). While this document is a a good start, it does not reflect the lessons learned during the DDX IPS development. A series of updated Design Data Sheets and associated tools will be instrumental to aid the future design teams. The authors strongly support the development of updated IPS Design Data Sheets .

Tools

Naval ship design tools come in many forms. The integration of IPS to a ship design process does require a number of tools to assure success. They include establishing requirements, ship power estimation, zonal design decision aids, IPS configuration selection, development of initial ship configurations, cost estimation tools, modeling and simulation of IPS zonal architecture, etc. The use of tools will further refine the ship synthesis process. These tools and the Advanced Surface Ship Evaluation Tools (ASSET) ship design synthesis program require development of a total ship design tools architecture. ASSET along with IPS specific tools must be compatible with the Leading Edge Architecture for Prototyping Systems (LEAPS.) LEAPS is a central repository for ship design and analysis data and serves as an integrator for multiple ship design and analysis tools (Briggs et al. 2004). Power system simulations are not standardized in the community. Individual U. S. Navy shipbuilding programs use a set of tools they feel is best to meet their requirements. The Office of Naval Research has invested in the basic technology such as the Virtual Test Bed (VTB) (Broughton et. al. 2004), stability toolbox (Sudhoff et. al. 2003), and distributed heterogeneous simulation methods. (Jatskevich et. al. 2002) While these tools are currently available, the processes and procedures to apply them in the context of a ship's preliminary, contract, or detail design has not been established. The authors strongly recommend the institutionalization of electric warship design tools by integrating them into both the ship design process and the Navy's ship design tool infrastructure via LEAPS.

Education

Today's naval architects and marine engineers are aware of IPS. They have some generic knowledge. However, too few have the necessary background and exposure to state of the art tools, processes, standards, and DDS documents. The authors contend that IPS is here to stay and today's practicing naval engineers will need detailed training to understand the complexities associated with IPS in a total ship context. The ship design competency requires that IPS ship design specific education be a mainstay in future curriculums at universities and within the US Navy Naval Sea Systems Command.

CONCLUSION

New warship designs for at least the next fifty years will increasingly reflect the advantages of the Integrated Power System. This paper provides a foundational knowledge of the processes and issues for creating an effective electric warship design to meet customer requirements at lowest cost. It also highlights areas that have not yet matured and details recommendations for future work.

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