NEXT GENERATION INTEGRATED POWER SYSTEMS FOR THE FUTURE FLEET

Capt. Norbert H. Doerry[1]

ABSTRACT

The Navy recently produced a Next Generation Integrated Power System (NGIPS) Technology Development Roadmap that establishes the Navy's goal of incorporating a Medium Voltage DC (MVDC) Integrated Power System (IPS) in future surface combatants and submarines. For near term applications, NGIPS incorporates Medium Voltage AC (MVAC) and High Frequency AC (HFAC) power generation. All variants of NGIPS incorporate a Zonal Electrical Distribution System (ZEDS) that build off of the Integrated Fight Thru Power (IFTP) system developed for DDG 1000. More than a power system, NGIPS is an enterprise approach to develop and provide smaller, simpler, more affordable, and more capable power systems for all Navy ships. NGIPS is both a business and technical approach to define standards and interfaces, increase commonality among combatants (surface and subsurface), and efficiently use installed power. To promote commonality and acquisition efficiency, NGIPS implements an Open Architecture (OA) Business and Technical model. The NGIPS OA Business Model segregates the tasks of determining required capabilities, ship system engineering, architecting, module development, systems integration, and life cycle support. The NGIPS Technical Architecture includes a set of standards for ZEDS as well as power generation and distribution.

This paper reviews why Integrated Power Systems (IPS) are advantageous for naval ships, briefly describes current ship designs incorporating an IPS, presents the NGIPS business and technical model, describes future opportunities for ship design innovations, and highlights aspects of NGIPS that require close attention and further development.

INTRODUCTION

The Navy has been rapidly migrating toward ship designs with electric propulsion, weapon systems and support systems demanding substantially more electrical power than in the past. To address these increasing power demands, ship designs are using Integrated Power Systems (IPS) that provide electric power to propulsion and other electrical loads from a common set of sources. To provide direction for future IPS development, The Navy initiated the Next Generation Integrated Power Systems (NGIPS) effort.

The primary aim of the design of a shipboard electric power system is survivability and continuity (reliability) of the electrical power supply. Survivability relates to the ability of the power system, even when damaged, to support the ship's ability to continue fulfilling its missions to the degree planned for a particular threat. Quality of Service (QOS) serves as a metric of the continuity (reliability) of the electrical power supply by measuring the adequacy of distributed systems support for the normal, undamaged operation of its loads.

NGIPS implements zonal survivability with selected loads provided compartment survivability. Zonal survivability is the result of a design method where the ship is divided into multiple electrical zones aligned with damage control zones. Zonal survivability assures that loads outside two adjacent damaged zones do not see an interruption in power. Zonal survivability does assume that one of two longitudinal power buses remains intact in the damaged zones. Zonal Survivability also assumes that damage does not propagate outside the initially damaged zones. To ensure this latter condition and to enable powering non-redundant mission critical loads in damaged zones, selected loads are provided compartment level survivability. Compartment Level survivability ensures that if a load survives damage in a zone, a method for restoring power to it exists once the crew has determined it is safe to do so.

NGIPS implements two different strategies for load shedding. Initially, when the amount of load exceeds generation capacity, Quality of Service load shedding is initiated where loads that can tolerate interruptions of power for about 5 minutes or longer are shed while additional power generation capacity is brought online. If all available power generation capacity is

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

online but is still not enough to serve the load, then Mission Priority load shedding is implemented to shed the lowest priority loads to enable repowering higher-priority loads that had been shed during QOS load shedding.

Between 1992 and 2007, the U.S. Navy invested significantly in the development of the Integrated Power System. Although IPS technology development successfully focused on DDG 1000, its primary goal has, and continues to be, meeting surface ship requirements at the lowest possible cost. In addition to the IPS technical architecture implemented on DDG 1000, the Navy has also implemented more commercial IPS solutions to the T-AKE 1 class and a hybrid solution on LHD 8 and LHA 6. [Doerry and Davis 1994] [Doerry et. al. 1996] [Dalton et. al. 2002]

The need for integrated power systems will increase in the coming decades. Figure 1 shows the projected propulsion and ship service power demands for future combatants armed with advanced sensors and future weapons such as railguns and lasers. Integrated propulsion systems are also projected to benefit the signature performance of future submarine classes. For expeditionary warfare ships, combat logistics ships, Maritime Prepositioning Force – Future (MPF(Future)), and support vessels, reduced fuel costs and overall reductions in life cycle cost will continue to drive to integrated power solutions.

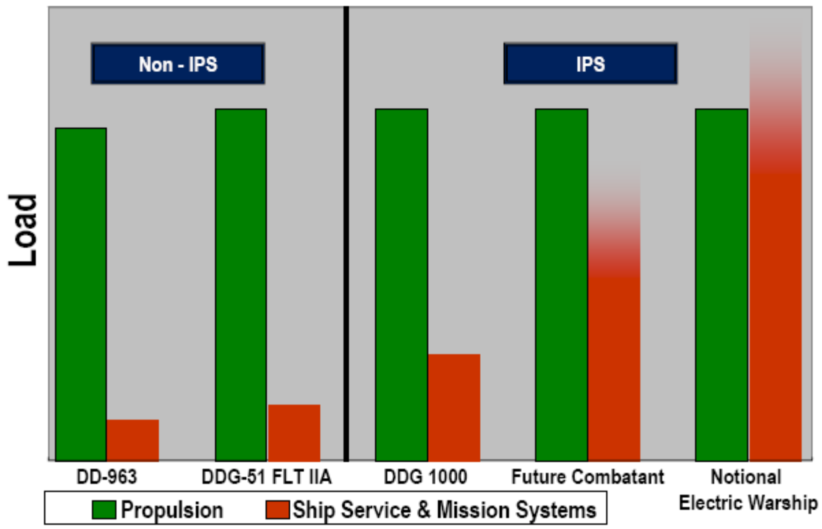

Figure 1: Future Warship Power Demand (NAVSEA 2007)

NGIPS BUSINESS AND TECHNICAL MODELS

The basic IPS architecture described by Doerry and Davis (1994) and Doerry et al (1996) has also been incorporated into NGIPS. The actual interface standards however, have evolved from these earlier works. The standard NGIPS module types as described in NAVSEA (2007) are:

- Power Generation Modules (PGM) convert fuel to electrical power
- Power Distribution Modules (PDM) consist of switchgear and cabling necessary to distribute the power
- Power Conversion Modules (PCM) convert power from one voltage /frequency to another
- Energy Storage Modules (ESM) store energy provided by and provided to the electrical power system
- Power Loads use electrical power
- Propulsion Motor Modules (PMM) convert electrical power into propulsion for the ship
- Power Control Modules (PCON) consists of software necessary to operate the power system.

These standard module types are employed in three NGIPS Power Generation Architectures and in the Zonal Electrical Distribution Architecture shown in Figures 2-4:

- Medium Voltage AC (MVAC) Power Generation exploits existing technology as used in DDG-1000 and T-AKE 1 for near term ship designs and for ships without a need for high power density. Generally, ships above 25,000 LT displacement do not benefit significantly from power dense equipment. Between 10,000 and 25,000 LT, ship designs should trade off MVAC systems with higher power dense solutions for overall ship affordability and ship suitability. Higher power dense solutions are usually superior for ships below 10,000 LT.

- Medium Voltage DC (MVDC) Power Generation is the long term goal for providing affordable power dense systems. The application of MVDC however, requires the development and standardization of new ways to manage power, assure system stability, detect faults, and isolate faults. New equipment must also be developed and qualified for ship use. Once developed, MVDC promises affordable high power dense power generation systems.
- High Frequency AC (HFAC) Power Generation As an interim solution until MVDC is developed, HFAC employs existing AC design and production technologies operating above 60 Hz., but below 400 Hz., to gain sufficient power density to enable introduction into small and medium sized surface combatants as well as submarines.
- Zonal Electrical Distribution (ZEDS) takes power produced by one of the three Power Generation Architectures, converts it to the form needed by each load, and distributes the power to the loads. ZEDS also helps ensure Quality of Service and survivability. ZEDS comes in two variants, AC-ZEDS for systems requiring standard levels of Quality of Service, and Integrated Fight Through Power (IFTP) for systems that require enhanced Quality of Service.

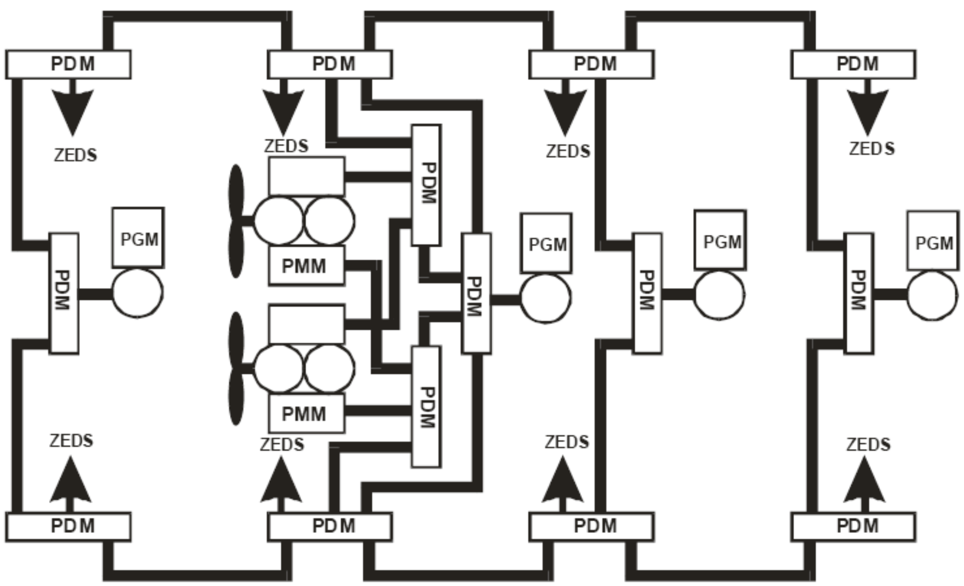

Figure 2: Power Generation Architecture (NAVSEA 2007)

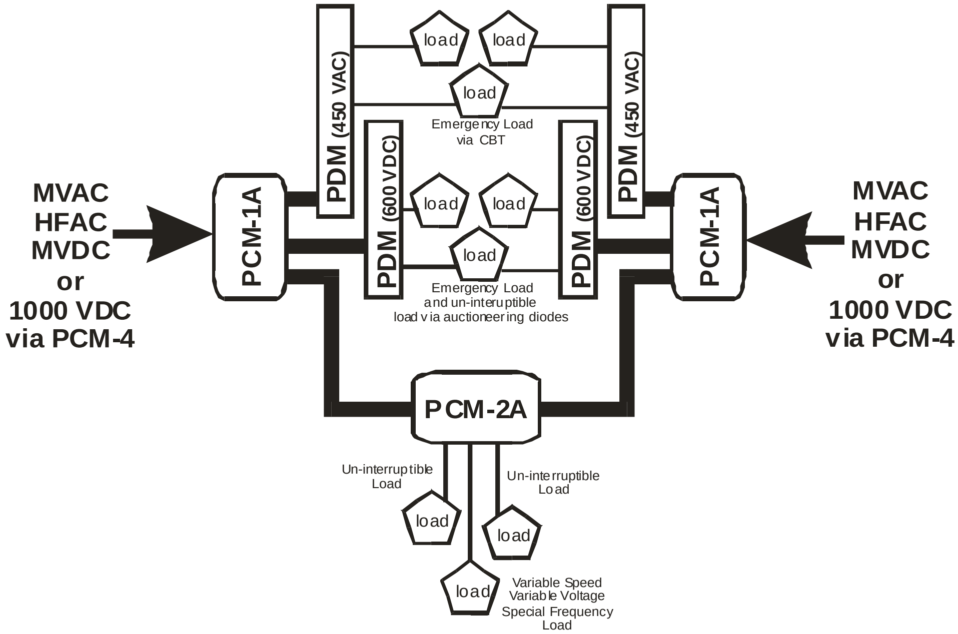

Figure 3: IFTP Zonal Electrical Distribution Architecture (NAVSEA 2007)

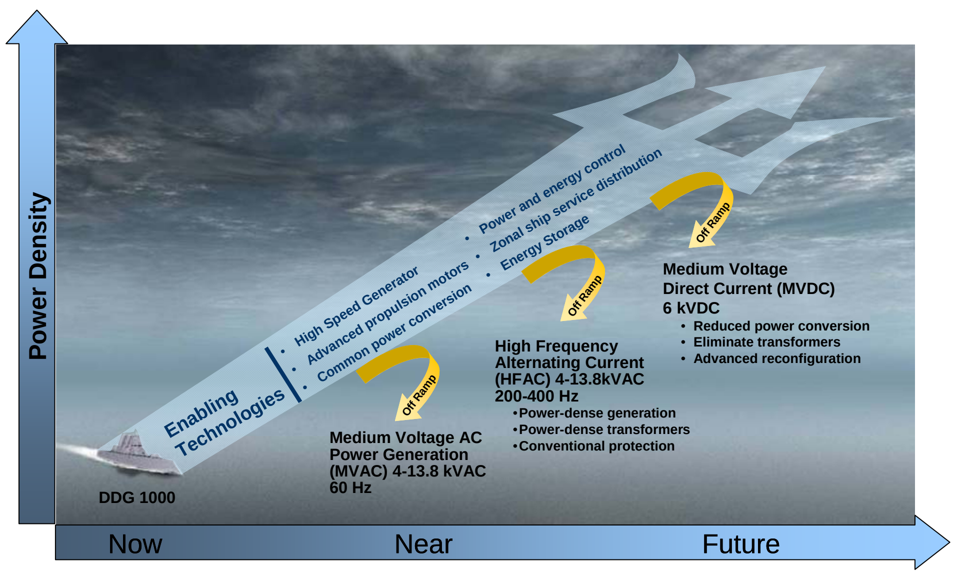

Figure 4: NGIPS Power Generation Roadmap (NAVSEA 2007)

The open architecture business approach for NGIPS is also crucial for its success. Historically, power systems have often been procured as a “turn-key” solution from a single vendor that designs, procures, delivers, and tests the complete power and propulsion system. The drawbacks to this practice include: (NAVSEA 2007)

a. The single vendor will tend to constrain component choices to its own product line and not always take advantage of potential competitor’s technologies.
b. There are many barriers to incorporating lessons learned from fielded systems.
c. The single vendor typically does not have an incentive to maximize commonality across the fleet.
d. The ability to transition Government S&T and R&D investments is limited to what the single vendor will accept.

In contrast, the NGIPS open architecture approach splits the responsibilities for an NGIPS system to enable specialization of function. The NGIPS roles currently defined are: (NAVSEA 2007)

a. Ship Requirements Developer
b. Ship Systems Engineer
c. Architect
d. Module Developer
e. Systems Integrator
f. Lifecycle Maintainer
g. Government Oversight

This approach enables the application of a common design, development, and support process for all NGIPS ships. Furthermore, it enables smooth transition of technology from S&T through R&D and into fielded systems. In this way, NGIPS offers the Navy a method for the continuous improvement in both cost and capability of its power system architectures. Details of the NGIPS Open Architecture business approach are detailed in NAVSEA (2007).

NGIPS DESIGN OPPORTUNITES

The introduction of an electric naval force will open future naval ships to fully exploit the power of electricity. Some design opportunities include: (Doerry and Fireman 2006)

Support High Power Mission Systems

If employed appropriately, NGIPS can result in a surface combatant fleet with superior mission performance, superior survivability, and reduced cost to the Navy. Since all power generated is available for ship service needs, this power could be made available to support the introduction into the fleet of many new technology weapon system elements such as high power radars, electromagnetic guns, electromagnetic launchers, and laser weapons. 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 ship reveals that significant reductions in the total number and types of prime movers in the fleet are possible in the future with the introduction NGIPS architectures 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 DDG-1000 program and in the early IPS program in the 1990s, a new design LPD could be configured with a higher power NGIPS configuration using only four prime movers and having considerable commonality with the DDG-1000 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 NGIPS 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

Integrating an NGIPS system in a ship design offers the naval architect a new tool in 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 in a ship with an NGIPS. The basic principles of NGIPS 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 NGIPS 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

Zonal survivability is the ability of a 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. (Doerry 2005)

At the ship level, zonal survivability facilitates the ship, when experiencing internal faults in adjacent zones, 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 NGIPS 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 the electrical power system provides 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 power quality outside of normal limits, that results in the load not 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 power sources 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 selecting the number and ratings of PGMs (and ESMs) and implementing the QOS concepts in the control system, an appropriate 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 NGIPS 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 NGIPS 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. For MVAC systems, 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. For MVDC and HFAC systems, appropriately rated Power Conversion Modules would be needed.

NGIPS ARCHITECTURES

Table 1 shows which NGIPS architectures are appropriate for different classes of applications. In general, submarines and small surface combatants below 10,000 LT generally benefit in cost and capability with High Power Dense power systems. Large ships above 25,000 LT generally do not benefit in cost and capability from High Power Dense power systems. The preferred solution between 10,000 and 25,000 LT can not be generalized and depends on the specific requirements of the ship under design. Appendix A of NAVSEA (2007) provides the analysis supporting this guidance. Enhanced Quality of Service is appropriate for ships that have mission systems requiring high operational availability such as surface combatants and submarines. Standard Quality of Service is appropriate for many auxiliary ships.

	Enhanced Quality of Service Requirements	**Standard Quality of Service Requirements**
High Power Density Requirements	Power Generation: Goal: Medium Voltage DC (MVDC) Interim: High Frequency AC (HFAC) Enhanced QOS features incorporated into Zonal Electrical Distribution	Power Generation: Goal: Medium Voltage DC (MVDC) Interim: High Frequency AC (HFAC) Standard QOS features incorporated into Zonal Electrical Distribution
Standard Power Density Requirements	Power Generation: Medium Voltage AC (MVAC) Enhanced QOS features incorporated into Zonal Electrical Distribution	Power Generation: Medium Voltage AC (MVAC) Standard QOS features incorporated into Zonal Electrical Distribution

Table 1: Power Architectures for different classes of applications (NAVSEA 2007)

Medium Voltage AC Power Generation

Ship designs where high power density is not required should use the Medium Voltage AC Power (MVAC) Architecture. A MVAC system is compatible with both an IFTP and an AC-ZEDS ship service power distribution system. In an MVAC system, power is generated as 3 phase 60 Hz. power at one of three standard voltages: 4.16 kV, 6.9 kV, or 13.8 kV using a high-impedance ground. 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 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 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 of the breakers by 20% and a 16% generator subtransient reactance) 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. Assuming PGMs are selected to provide equal capacity on two split buses, Figure 5 shows the range of Total Power System Power that each voltage level can support (450 VAC is shown only for comparison). Note that the overlap in power ranges allows the system designer some flexibility in selecting a power generation voltage for a given application. Staying within the specified power ranges for a given bus voltage enables the use of Commercial off the Shelf (COTS) derivative generators, switchgear, cabling, and other distribution system equipment. With current technology, systems employing 4.16 kV can employ motor drives without a large, heavy and expensive propulsion transformer. Anticipated improvements in commercial motor drive technology and insulation systems will enable the use of transformerless propulsion motor drives at 6.9 kV in the near future. (NAVSEA 2007)

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 2: MVAC Largest Generator or Load vs. Voltage Based on Circuit Breaker Limits (NAVSEA 2007)

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

Table 3: MVAC Maximum Bus Power Based on Fault Current Interruption Capability (NAVSEA 2007)

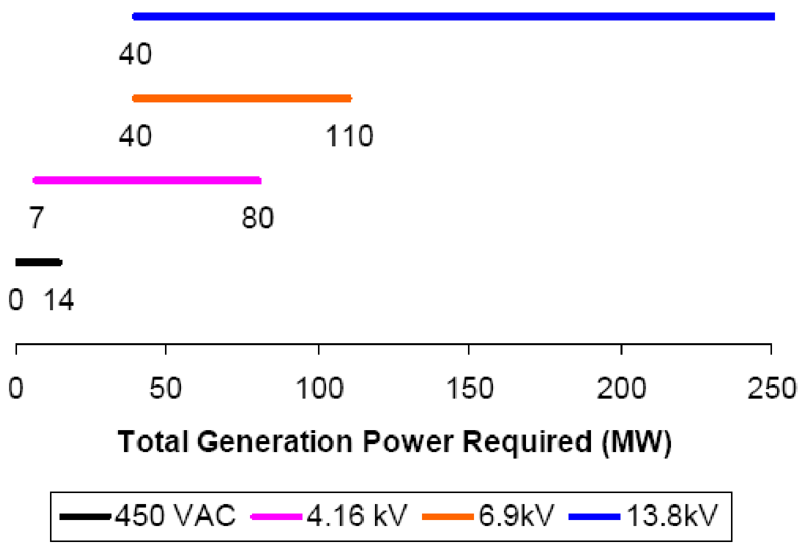

Figure 5: PDM Bus Voltage for MVAC Distribution (NAVSEA 2007)

High Frequency AC Power Generation

In a High Frequency AC (HFAC) system, power is generated at a fixed frequency greater than 60 Hz. and less than 400 Hz. Most likely, the distribution voltage will be either 4.16 or 13.8 kV using a high-impedance ground. The advantages of a HFAC power system include: (NAVSEA 2007)

a. Magnetics smaller & lighter than 60 HZ. The cross sectional area of a magnetic core of a transformer is approximately inversely proportional to the frequency of operation. Thus the weight of the transformer core (not including the windings) of a 240 Hz. transformer would be expected to be about ¼ the weight of a 60 Hz. transformer that uses the same core material.
b. Harmonic filters minimized or eliminated. Because the propulsion motors would be employing 3 phase to multi-phase transformers, the current harmonics injected on the power bus would be substantially reduced, perhaps even to the level that would not require a harmonic filter. If a filter were necessary, the higher frequency operation would enable a much smaller filter than that required for 60 Hz. operation.
c. Galvanic isolation between subsystems. A HFAC system would employ power dense transformers to isolate all loads from the HFAC high power bus. The transformers would minimize common mode currents from the power converters, limit the impact of ground faults, and limit transient over voltages. Additionally, transformers limits available short circuit current to power converters
d. Improved acoustic performance over 60 Hz. Operation. By operating at a higher frequency than 60 Hz. the acoustic absorption of noise from equipment (such as transformers) vibrating at the power system fundamental frequency is greater in seawater. The average acoustical absorption <a> in seawater is given approximately by

$$< a > \cong 0.04\, f^{\,1.35}\, dB \,/\, km \; (f \; in \; kHz)$$

At 240 Hz., the acoustical absorption is about 6.5 times that at 60 Hz which reduces the ship's detection range. Additionally, sound isolation of equipment is lighter and easier at higher frequencies.
e. Minimal technology development required vs MVDC

The challenges with implementing a HFAC system include: (NAVSEA 2007)

a. High number of poles required for generators interfaced with "slower" prime movers. For the range of prime movers of interest to shipboard applications, a frequency within the range of 240 to 360 Hz is likely optimal, but further study is needed. One implication for operating in this frequency range is that due to the large number of required generator pole pairs needed for 1800 rpm operation, medium speed diesel engines would require either the use of a speed increasing gear, or some type of advanced technology generator. Permanent Magnet generators can support high numbers of pole pairs, but do not have the requisite ability to regulate voltage needed to directly interact with a power system (Some type of developmental in-line voltage regulator would be needed). Gas turbines that operate at 3600 rpm would also likely need increasing gears or advanced technology generators to operate above 240 Hz. High speed (7200 - 14400 RPM) gas turbines and steam turbines could use conventional round rotor synchronous machine technology.

b. Because generator frequency is a multiple of generator speed, prime movers are restricted to specific operating speeds. This may result in sub-optimal fuel efficiency or dynamic responsiveness.

c. Because all of the loads on a HFAC bus will likely behave as constant power loads with negative incremental impedances, careful design is required to ensure system stability. While much progress has been made in developing generalized methods for assuring system stability within the science and technology realm, translating these methods into robust specifications, standards and integration techniques is still required.

d. Higher frequency operation above 60 Hz. requires derating of cable and switchgear designed for 60 Hz. The derating factors for cable and switchgear and guidance for bus voltage require further study. Preliminary analysis indicates the derating factor for operating COTS circuit breakers at 240 Hz. will be on the order of 0.70. [Brick, et. al. 2007] Additionally, the impact of higher frequency operation on sensors, protective relays, switchboard controls, voltage regulators, and speed governors is not known.

e. Ground Fault current is a function of the line to ground parasitic capacitance. The impedance of a capacitor is inversely proportional to frequency, which means that as the system frequency increases with a constant capacitance, the line to ground impedance decreases, resulting in higher ground fault currents. In fact, because cables must be derated, the number of cables and the line to ground capacitance will increase above that of a 60 Hz. system, further increasing the ground fault current. Use of additional components may be required to sectionalize the electrical distribution system, or otherwise reduce ground fault currents to allow continued system operations.

f. Increased cable installation concerns (EMI, EMC, Inductive Heating). Additional losses and EMI generated in the cables may adversely impact other systems and equipment located near the cable ways. Inductive heating may impact cable raceways and penetrations. This may require larger equipment standoffs, or new designs for non-magnetic cable supports and penetrations. Component cable entry may need to be increased.

g. A method for connecting to shore power must be established. Either the ship must convert the available 60 Hz. power into the HFAC required by the ship, or the shore power connection must provide the HFAC power.

h. Limited higher frequency power test capability/infrastructure. Manufacturers are not likely to have test equipment or facilities to test their equipment at frequencies other than 60 Hz. Test equipment will either have to be made available to manufacturers, or the equipment will have to be tested at a dedicated test facility. Alternate test methods may also be developed to qualify equipment without using power sources at the design frequency.

i. Paralleling of Generators at higher frequencies. Operation at higher frequencies reduces the window of time that a generator breaker can close to parallel a generator. The ability of existing breakers and paralleling controllers to operate within this narrower time window is not known.

j. Lack of design standards, practices, guides, design tools, and supporting data. A design infrastructure is needed to ensure successful integration of HFAC systems in all stages of ship design.

k. Higher frequency operation will result in a lower power factor as compared to MVAC systems. Low power factor translates into somewhat larger cabling and generators.

Medium Voltage DC Power Generation

The primary architectural difference between an HFAC and a MVDC system is that instead of distributing High Frequency AC power through out the ship, the system distributes Medium Voltage DC power. This change though, impacts most of the power generation modules and requires S&T and R&D investment. The distributed power will likely employ balanced voltages around ground at one of 2 or 3 standard voltages in the range of ±3,000 VDC to ±10,000 VDC using a high-impedance ground. The primary reasons for employing an MVDC system include: (NAVSEA 2007)

a. Decouples prime mover speed from the frequency of the bus. Enables optimization of the generator for each type of prime mover without having to incorporate reduction gears or speed increasing gears. Generators are not restricted to a given number of poles. The speed can even vary across the power operating range of the prime mover to optimize on efficiency and /or responsiveness.
b. Enables operation of power conversion equipment at frequencies an order of magnitude higher than with the HFAC system, resulting in even smaller transformers. If galvanic isolation is proven not necessary, additional size reductions are possible. This is offset somewhat by the need for additional power conversion equipment to produce high frequency power.
c. Reduces engineering concerns with respect to EMI and EMC present with HFAC systems.
d. Potential reduction in cable weight (depending on voltage selection) due to lack of skin effect and reactive power resulting from phase shifts between current and voltage waveforms in ac systems. (DC systems can have reactive power due to voltage and current ripple)
e. With power electronics closely connected with each electromagnetic device, increased ability to control fault currents to levels considerably lower than with ac systems.
f. Improved acoustic performance over MVAC and HFAC systems. Since there is not a common frequency of vibrating equipment, the acoustic signature has a broader signature with fewer tonals that can be observed in the acoustic signature of the ship.
g. The paralleling of generators only requires voltage matching and does not require time critical phase and frequency matching.
h. Enables future high power demanding electric Mission Loads in a much more compact and power dense architecture.

The challenges with implementing a MVDC preclude a near term implementation of a shipboard MVDC system and include (NAVSEA 2007) (Doerry and Amy 2008):

a. Traditional fault detection and isolation techniques employed by conventional AC circuit breakers and based on fault current are not desirable for MVDC systems due to the difficulty in extinguishing DC arcs in the absence of a voltage or current zero crossing. Instead, MVDC is anticipated to use power electronics and advanced controls to quickly identify and isolate faults before large fault currents are generated. In the design of the power electronics, consideration must be made to ensure transient stability and limit potential over-voltages during transients. The details, methods, and standards for implementing power electronics and advanced controls based fault detection and isolation require research and development in addition to implementation engineering. Additionally, new fault detection and isolation components may require development.
b. Because all of the loads on a MVDC bus will likely behave as constant power loads with negative incremental impedances, careful design is required to ensure system stability. While methods have been demonstrated on fielded systems for assuring system stability, translating these methods into robust specifications, standards and integration techniques is still needed.
c. Standardized methods for controlling prime mover power and sharing loads between power generation modules must be established. In AC systems, real power is regulated and shared through the speed governors on the prime movers, while reactive power is regulated and shared through the voltage regulator. In DC systems without reactive power (not counting voltage and current ripple) power is controlled through the voltage regulator. Developing standardized methods for linking voltage regulation to the speed governor of the prime mover, and communicating load sharing data with other power generation modules require development.
d. A grounding strategy for MVDC system must be established. The strategy must address the size and cost associated with providing galvanic isolation within power conversion modules with the risk for high, potentially dangerous, ground fault currents.
e. Power Quality standards for MVDC require development. The standards have an impact on the size, weight, and cost for both rectifiers and the loads. Establishing standards that optimize the total system performance and cost across the range of ship applications is required.
f. Lack of an established Industrial Base. The DC Switchgear as well as the power electronic fault detection and control systems needed to make shipboard MVDC systems viable have an insignificant commercial market. Consequently, the Navy will rely on a small industrial base of vendors with MVDC experience and will have to actively address risks associated with the loss of a key vendor

through such methods as large number of contingency spares and establishing a large in-house engineering capability.

g. Lack of design standards, practices, guides, design tools, and supporting data. A design infrastructure is needed to ensure successful integration of MVDC systems in all stages of ship design.

h. A method for connecting to shore power must be established. Either the ship must convert the available 60 Hz. power into the MVDC required by the ship, or the shore power connection must provide the MVDC power.

Zonal Electrical Distribution System

All of the power generation architectures within NGIPS interface with a zonal electrical distribution system (ZEDS). For ships requiring a standard level of Quality of Service, an AC-ZEDS approach as shown in Figure 6 would be appropriate. ACZEDS as implemented on LHD 8 incorporates existing technologies for transformers, switchgear, cables and controls and will not be discussed further.

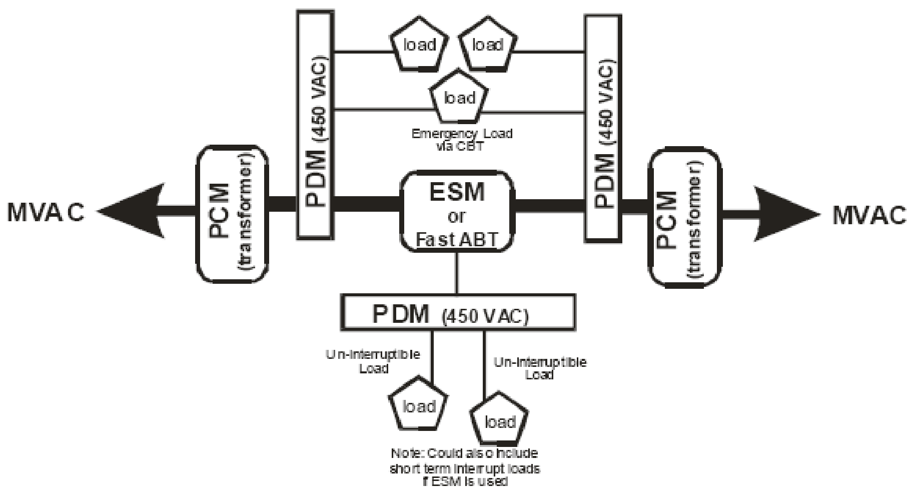

Figure 6: AC-ZEDS interfacing with MVAC

Figure 3 presented the IFTP architecture for ships requiring a high level of QOS. As presented in NAVSEA (2007), IFTP is a refinement of the power distribution system developed for DDG-1000. This architecture consists of the following elements

PCM-1A:	Power Conversion Module for interfacing with Power Generation Architectures
PCM-2A:	Power Conversion Module for providing loads with the type of power required
PDM with CBT	Power Distribution Module including Controllable Bus Transfers for distributing power
PCON	Power Control Module consisting of software for Power Management and Fault Response
ESM	Energy Storage Modules

PCM-1A

The primary purpose of PCM-1A is to protect the longitudinal Medium Voltage Power Generation bus from in-zone faults (such as from battle damage) and to convert the power from the longitudinal bus to a voltage and frequency that PCM-2A can use. PCM-1A may also provide power directly to loads. There are two general strategies for PCM-1A to protect the longitudinal buses from in-zone faults: current limiting and opening faulted circuits in considerably less than a cycle (typically less than 0.5 ms.). The fast clearing time is needed to prevent mis-coordination of breakers due to multiple near-simultaneous faults from weapons induced damage. One example of a current limiting approach is given in Figure 7. The input power convert to 1000VDC protects the longitudinal bus from voltage collapse by limiting the current it draws from the power system. Likewise, the SSCM power converters also limit current to the loads to prevent voltage collapse of the internal 1000VDC Bus.

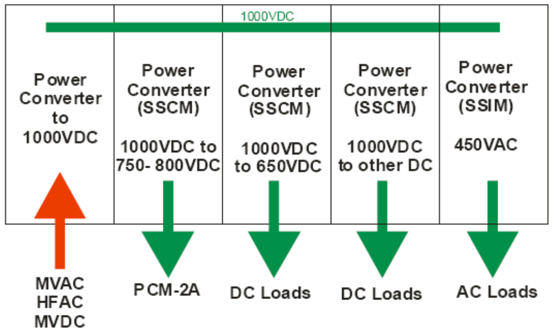

Figure 7: Notional NGIPS PCM-1A Architecture

Figure 8 and Figure 9 show an alternative PCM-1A architecture based on fast (< 0.5 ms) hybrid circuit breakers. There are currently several ongoing development efforts to produce these fast hybrid breakers. (Ykema et al. 2008) (Bowles et al. 2008) Note that in Figure 7 Figure 8, and Figure 9, the lack of energy storage implies that interruptions of power on the longitudinal bus will also be experienced by downstream loads. It may be possible to use a conventional medium voltage breaker on the input of the PCM-1A if analysis demonstrates that the risk of taking down the longitudinal bus is low.

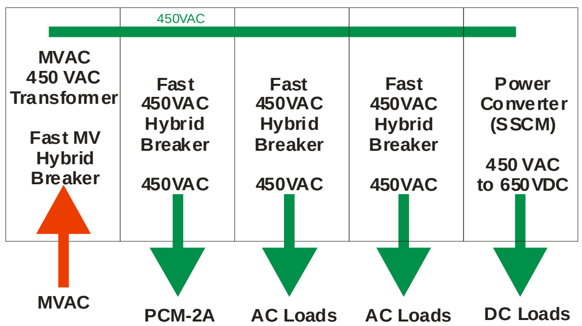

Figure 8: Notional NGIPS PCM-1A Architecture with Hybrid Breakers

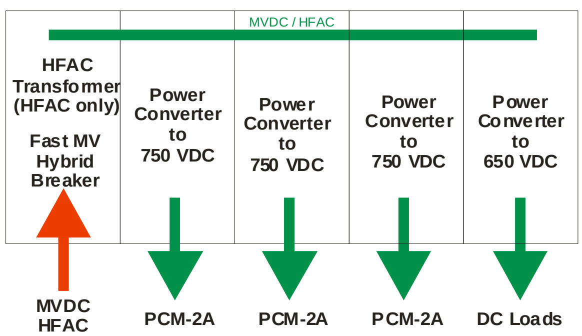

Figure 9: Alternate Notional Architecture for PCM-1A for MVDC / HFAC

If integrated with energy storage of sufficient power rating, response time and energy capacity, PCM-1A could also provide power to un-interruptible loads.

PCM-1A should be modular and scalable to enable supplying an arbitrary number of loads requiring one of several different voltage levels. Where possible, power conversion submodules should be interchangeable with PCM-2A and specified with open standards such that power conversion submodules from multiple vendors are interchangeable. (Doerry 2008)

PCM-2A.

The primary purpose of PCM-2A is to provide loads with the type of power they need with the requisite survivability and quality of service. One model of the PCM-2A is the Integrated Power Node Center (IPNC) described in MIL-PRF-32272.

The IPNC can accept either 440VAC 60 Hz. or 750 VDC power as input and can provide multiple types of power as output (see Table 4) However, to fully implement the PCM-2A functionality within the NGIPS architecture, MIL-PRF-32272 does require some modification. These are described by Doerry (2008)

Power Modules	Ratings (Ratings are based on maximum continuous current. Overload ratings are not required.)
Input Power Modules:	
1. 440 V, 60 Hz, 3-phase	15 A, 30 A, 50 A, 100 A, 200 A, 400 A
2. 750 V, DC	50 A
Output Power Modules:	
1. 440 V, 60 Hz, 3-phase (Adjustable for higher frequency – de-rating may be necessary)	5 A, 15 A, 30 A, 50 A, 100 A, 200 A, 400 A
2. 115 V, 60 Hz, 3-phase, 3-wire – MFPM (Adjustable for higher frequency – de-rating may be necessary)	35 A, 60 A
3. 115/200 V, 60 Hz, 3-phase, 4-wire – MFPM (Adjustable for higher frequency – de-rating may be necessary)	25 A, 35 A, 50 A
4. 115 V, 3-phase fast switch modules	10 A
5. 375 V, DC	15 A, 30 A
6. 120 V, DC	10 A, 20 A, 40 A, 60 A
NOTE: Output power is equivalent to input power minus losses (see 3.5.14 for efficiency).	

Table 4: IPNC Power Modules (MIL-PRF-32272)

In configuring an IPNC, multiple input power modules from different sources can provide uninterruptible power (assuming the different sources are independent and not likely to lose power at the same time). Each of the output power modules can be turned on or off through the machinery control system. In this manner, loads can be shed adaptively based on quality of service or mission priority.

Dedicated power modules that are programmed to provide a soft start should be provided to loads having large starting or in-rush currents.

Ideally, a zone would have multiple PCM-2As that have dual power feeds from PCM-1As from the port and starboard longitudinal bus. The PCM-2As would be physically close to the loads they serve such that if the PCM-2A is damaged from weapons effects, then the loads served by the PCM-2A are also damaged. However, affordability will likely drive the total number of PCM-2As within a zone downward. Hence affordability and survivability must be traded off as part of the total ship systems engineering process.

PDM

Within the in-zone power distribution system PDM consists of the cabling, power panels, light switches, junction boxes, small transformers, etc. that connect the PCM-1A and PCM-2A to each other and the loads. The PDM also contains the Controllable Bus Transfer (CBT) which is described below.

The weight and cost of cabling is directly impacted by the size of the conductors required. Traditionally, conductor size is determined by the maximum value determined from one of three calculations:

a. Maximum allowable sustained current to prevent overheating of the cables and damage to the insulation system. This current level is called the ampacity of the cable and is a function of the diameter of the conductor.
b. Maximum allowable voltage drop to prevent loads from being provided power outside of the range specified in MIL-STD-1399 300B. This is a function of the diameter of the conductor as well as the length of the cable.
c. Ability to sustain fault currents without overheating and damaging the insulation while the power system detects and isolates a fault. This is a function of the available fault current, the time it takes for circuit protection to clear the fault current, and the diameter of the conductor..

Because PCM-1A limits fault currents; and zonal design methodologies will ensure that most, if not all 440V cable runs will be less than 180 ft where voltage drop is not a concern, then cables of length less than 180 ft for 440V applications can be sized only for ampacity.

Where possible, cables providing power to 115 v loads should not exceed 50 ft to prevent excessive voltage drop. If longer cables are needed, consider employing local 440v to 115v distribution transformers or conductors larger than that required based on ampacity.

Traditional power panels can be used if all the loads served by the power panel can be treated as a single load in terms of Quality of Service and Mission Priority Load shedding. Individual circuit breakers in traditional power panels can typically be tripped from a machinery control system, but generally require manual reclosing. Should industry introduce new circuit breakers that can quickly be opened and closed based on control system command signals, then this restriction on power panels can be lifted.

Controllable Bus Transfer (CBT)

A controllable bus transfer (CBT) provides two paths of power to loads that require compartment level survivability and are not physically close to the PCM-1A or PCM-2A that directly provides it power. A CBT must be able to switch the source of power to the load based on command from the control system or through a local control operator interface. Since a CBT's main role is to enable recovering equipment following damage to a zone, operation of a CBT differs from an Automatic Bus Transfer (ABT) in that power is not reapplied to a load until the operator is assured doing so is safe. A CBT does not have a requirement to switch quickly.

Ideally a CBT would be described in a Performance Specification that includes physical, electrical, and control interfaces. A CBT should either be bulkhead mountable or be able to be incorporated within load equipment it serves.

PCON

The Power Control Module (PCON) consists of the software necessary to control the behavior and report the status of other NGIPS modules and controlled loads. Where the PCON software resides has not been determined. Options include hardware controllers physically located in either the PCM or PDM modules, as well as possibly installed in an external machinery control system.

Within the zonal power distribution system, PCON implements the following functions:

a. Remote monitoring and control of NGIPS modules and controllable loads.
b. Resource Planning
c. System Configuration
d. Mission Priority Load Shedding
e. Quality of Service Load Shedding
f. Fault Detection and Isolation
g. Maintenance Support
h. Training

The PCON software should be developed for robustness in anticipation of requiring change over the life of the ship as well as enabling software re-use across multiple ship designs. Open architecture approaches as described by Amy et al. (1997) should be considered in developing PCON.

Energy Storage Module (ESM)

An in-zone power distribution system may or may not need an Energy Storage Module (ESM) to meet Quality of Service Requirements. If one is needed, an ESM can use a host of technologies depending on the power and energy requirements. Examples include batteries (Jones and Edwards 2008), capacitors (TPL 2006), rotating machines / flywheels (Toliyat et al. 2005) (Hockney and Polimeno 2005), and superconducting magnetic energy storage (SMES) (James and Stejic 2008).

Where to integrate energy storage within the in-zone power distribution system is still an open question. One option is to create a new bi-directional power module for the IPNC (PCM-2A) that would connect to an adjacent energy storage module, or incorporate the energy storage within the bi-directional power module. Another option is to integrate energy storage in or with the PCM-1A. One could also integrate the ESM with the port and starboard longitudinal bus.

NGIPS DESIGN WATCH ITEMS

The incorporation of NGIPS 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. (Doerry and Fireman 2006)

Part Load Efficiencies

One of the advantages of NGIPS 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. The role that Energy Storage Modules can play in preventing the need for a Dark-Ship Start in addition to enabling a Dark_ship Start should be explored.

Shore Power

Another special operating condition that must be accommodated is shore power. In an NGIPS ship, it is not always obvious how to connect the ship to the terrestrial power grid. In an MVAC system, a medium 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 medium 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 HFAC or MVDC Power Generation, a shore-power PCM is needed to convert to match the shore power with what the ship needs. One advantage to this is that the PCM could be configured to accept a variety of voltages and frequencies as input.

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, generator sets 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 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 conventional laminated steel 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

Medium Voltage DC

Achieving the goal of an affordable power dense IPS using Medium Voltage DC, Doerry and Amy (2008) highlight a number of areas requiring additional work. These are:

a. Developing power management methods for normal conditions
b. Developing power management methods to ensure Quality of Service
c. Developing power management methods to ensure survivability
d. Ensuring system stability
e. Developing a fault response strategy
f. Ensuring power quality
g. Enabling effective maintenance support
h. Establishing system grounding practices

Zonal Electrical Distribution

A number of tasks remain to be accomplished to establish the technical basis and documentation for implementing an NGIPS IFTP zonal electrical distribution system. As described by Doerry (2008) these tasks are:

i. Update MIL-PRF-32272 to fully define the functionality and interfaces required by PCM-2A. Incorporate "switching modules"

j. Develop a Performance Specification for PCM-1A.

k. Produce an in-zone electrical distribution system design and criteria handbook.

l. Develop a control system interface between the power system and loads.

m. Determine the viability of producing affordable militarized hybrid breakers capable of detecting and isolating faults as well as coordinating with other breakers in less than .5 ms.

n. Conduct tests to determine if ANSI/EIA 709.2-A-2000 Control Network Powerline (PL) Channel Specification is suitable for shipboard applications. Produce an application guide for applying ANSI/EIA 709.2-A-2000 to shipboard applications.

o. Develop an open interface in PCM-1A and PCM-2A for integrating control system hardware such as Programmable Logic Controllers, Control Network Switches and Routers, and control system processors.

p. Conduct a study to determine the best approach to implementing the PCON software. Produce an application guide for producing the PCON software for a given ship application.

q. Determine if upon a deficiency of power generation capacity, loads can be shed fast enough to ensure stable operation. If not, propose design rules for sizing and integrating energy storage to ensure stability.

r. Develop and document a method for aggregating loads for sizing power distribution equipment. Explore probabilistic methods described by Amy (2005).

s. Develop and document a method for characterizing and estimating loads during early stage design to support distribution equipment sizing, design for QOS, and design for Survivability.

t. Conduct a business case analysis to determine if using high-impedance grounding on the in-zone distribution systems is cost-effective.

u. Determine the reliability achievable with the Input and Output Power Modules of the IPNC. If not substantially greater than 30,000 hours, identify opportunities to improve the reliability.

v. Improve the efficiency of the input and output power modules of the IPNC.

w. Coordinate with the HVAC community to ensure future advancements in HVAC technology are consistent with NGIPS design implementations.

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. In the past few years, IEEE has initiated several panels to update or develop recommended practices in support of the electric warship. A big success has been the establishment of IEEE 1662-2008 "Guide for the Design and Application of Power Electronics in Electrical Power Systems on Ships." Other IEEE standards developments include P1709 "Recommended Practice for Medium Voltage DC Distribution on Shipboard", P1713 "Recommended Practice for Shore to Ship Power", and P45 "Recommended Practice for Electrical Installations on Shipboard." The use of NGIPS in future naval ship acquisitions requires the development of these and many other robust ship design standards. This paper has identified many technical aspects of NGIPS that requires coherent standards so the future ship designers can understand the complexity, system tradeoff possibilities and total ship synthesis. An institutionalized design process and associated design certifications is needed.

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 good start, it does not reflect the lessons learned during the DDX IPS development. A series of updated DDSs and associated tools will be instrumental to aid the future design teams. .

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.

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. Electric Warships are now a fact of life and today's practicing naval engineers will need detailed training to understand the complexities associated with NGIPS in a total ship context. The ship design competency requires that electric warship design specific education be a mainstay in future curriculums at universities and within NAVSEA.

CONCLUSION

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

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