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Open Architecture Approach for the Next Generation Integrated Power System

ABSTRACT

Between 1992 and 2006, the U.S. Navy developed the Integrated Power System (IPS) which integrates the electrical power generation and ship propulsion systems. A militarized IPS has been implemented on DDG 1000 in addition to more commercial IPS solutions for the T-AKE 1 class and LHD 8. The Next Generation Integrated Power System (NGIPS) will incorporate the lessons learned from the IPS efforts to date to develop an open architecture (OA) technical and business approach to procuring power systems.

While OA has historically been applied to computer hardware and software systems, this paper describes a method for applying OA concepts to a traditional HM&E system. This paper also discusses opportunities and challenges in establishing a NGIPS business model and technical architecture.

INTRODUCTION

A recent Open Architecture Task Force (OATF) defined Naval OA as …

"Naval OA is a combination of collaborative-competition business and technical practices; including Peer Reviews for cost-effective innovation, with rapid Technology Insertion processes fostering third-party developed modules (hardware and/or software), for continuous, incre mental increases in warfighting capability, while reducing cost."

“Developers” can include Science and Technology (S&T) centers of excellence, Labs, Small Business Innovative Research (SBIR) institutions, non-traditional defense vendors, and other sources. By opening the business model and using a designated System Integrator, rather than a single Prime developer, innovation and competition are leveraged across the entire commercial base.

The OATF concentrated on applying the OA Technical and Business Model to combat systems. This paper adapts these concepts to the NGIPS and describes the issues associated with implementing an open technical architecture and business model.

Between 1992 and 2006, the U.S. Navy invested significantly in the development of the IPS. IPS integrates the electrical power generation and ship propulsion systems. 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 through eight affordability initiatives:

• Extend Architectural Advantage

• Promote Commonality

• Exploit Producibility

• Reduce Infrastructure

• Reduce Component Costs

• Reduce Manning

• Reduce Energy Costs

• Reduce Combat System Costs

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)(Doerry and Fireman 2006)

The NGIPS will incorporate the lessons learned from the IPS efforts to date to develop an OA technical and business approach to procuring power systems. Since OA is traditionally applied to combat systems and other computer hardware and software intensive systems, one must consider the differing characteristics of Hull, Mechanical and Electrical (HM&E) systems:

- Hardware and Software technical innovation occurs at a slower pace in HM&E systems. Moore’s law is not a major factor.

- The continuous, incremental increases in capability are generally applied to classes of ships, or flights within a class, not necessarily to the same ship over its lifetime. In some cases, such as Machinery Control Systems and Power Converters, hardware and/or software refresh may occur one or more times over the life of the ship. Of more importance, is the ability to affordably add to the capacity of a distributed system over the ship's life, rather than installing considerable Service Life Allowance during ship construction.

NGIPS OPEN ARCHITECTURE BUSINESS MODEL

The OA Business Model is based on successful programs that rapidly delivered significant operational capability upgrades at lower costs and successful commercial market examples. Both sets of examples had the following key principles:

• The use of Performance Specifications that define "what" is needed not "how" it is designed (Note: Performance Specifications are also characterized by their extensive use of well-defined and detailed interface specifications in addition to well defined validation methods);

• Subdivision of labor or specialization at the module or component level;

• Defined and segregated roles and responsibilities for component delivery, system integration and life cycle support;

• A defined feedback process to create a "spiral" process to provide feedback from the evaluation of fielded systems to update architecture documentation and module designs.

The OA Business model depicted in Figure 1 describes the basic business model for military acquisition programs that fully embrace advantages and opportunities available with Commercial off-the-shelf (COTS) technologies.

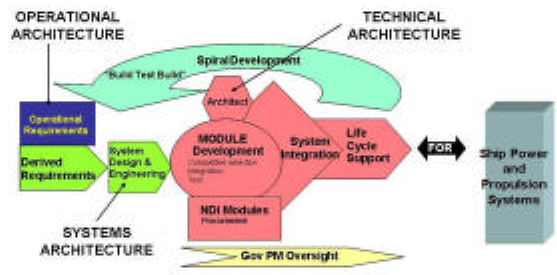

FIGURE 1. NGIPS Business Model

Required Capabilities

Required capabilities developed by staff of the Chief of Naval Operations (OPNAV) as part of Joint Capabilities Integration and Development System (JCIDS) process. (CJSF 2005) The required capabilities are form the basis of the Department of Defense Architectural Framework (DODAF) "Operational View" or "Operational Architecture" (DOD 2003).

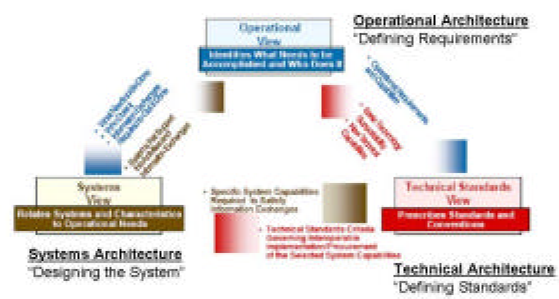

FIGURE 2: DOD Architectural Framework (DOD 2003)

Derived Requirements and System Design and Engineering

Derived Requirements for the Power and Propulsion system for a given ship acquisition program are developed by the ship design team. This ship design team could be either Government or Industry led. Normally there will be a Power and Propulsion Systems Engineering Manager (SEM) assigned to the design team that will lead the engineering efforts of the power and propulsion system.

The Derived Requirements are used to determine the DODAF "systems view" or "systems architecture" and to select and tailor modules for the power and propulsion system.

Architect

The architect function is led by the Technical Warrant Holder (TWH) for NGIPS and is generally concerned with the maintenance of the DODAF "technical architecture" for NGIPS. The government TWH is supported by a government / industry peer review team. The architect function is concerned with cross-platform issues and only becomes involved with specific ship issues when deviations or waivers to the standard processes are needed.

Responsibilities include:

- Custodianship of the NGIPS architecture to include:

a. Development and maintenance of standards and specifications such as Naval Vessel Rules (NVR), military specifications and standards as well as participation in industry standards bodies such as IEEE.

b. Development and maintenance of interface specifications and validation / testing standards for NGIPS module types.

c. Development and maintenance of standard performance specifications for NGIPS module types.

d. Development and maintenance of design data sheets and associated design and analysis tools.

- Development and maintenance of Module Characterization Sheets for capturing data on qualified and developmental modules for use with design and analysis tools.

- In collaboration with a Peer Review process and ship concept analysis, develop and maintain a technology roadmap / priority list for desired technology improvements.

Module Development

Government Program Management, based on the technology roadmap, prepares specifications and Statements of Work (SOW) for development contracts in conformance with the NGIPS Technical Architecture.

The Module Developer is responsible for maturing the technology and "qualifying" the module through the module validation and testing standards.

Non Developmental Item (NDI) Modules

Vendors of qualified modules work with the Architect to ensure Module Characterization Sheets are kept up-to-date and to re-qualify modules following design changes.

System Integration

The Systems Integrator uses the derived requirements from the systems engineering process, the technical architecture, and results from analysis, modeling and simulation to produce module procurement specifications. To preclude conflicts of interest, the Systems Integrator must be independent of the source selection of vendors for the module procurements.

Once the procurement is made (by either the government or the ship integrator / ship builder) the Systems Integrator assists the government in ensuring the vendor is meeting the procurement specifications, continues to validate that the Power and Propulsion system will work (and if not, what Engineering Changes are needed to make it work), and participates in component and system testing.

Life Cycle Support

Following fleet introduction of an IPS warship, an organization, either Government or industry led, manages the IPS configuration of in-service ships. This life cycle support activity would perform reliability analysis, equipment condition trending analysis, and maintenance analysis as well as addressing modernization, safety, environmental, reliability, diminishing sources, and obsolescence issues. The life cycle support organization, in concert with appropriate technical warrant holders, would develop and promulgate safe operating procedures and safe operating envelopes. This activity would also develop maintenance requirements, procedures, and plans. When needed, the life-cycle support organization would provide assistance in adjudicating Departure from Specifications (DFS) and other critical fleet issues. The life cycle support organization would also assist in maintaining educational skill requirements of the work-force, and when needed, assist in evaluating the actual skill level of the work-force. The life cycle support organization provides feedback to the architect on suggested improvements to the Technical Architecture documents.

Government Oversight

An OA approach is very different from the "turn-key" systems that have often been specified in previous ship acquisition programs. In an OA approach, the Government plays an important role in the design, procurement, and integration of systems and system modules. A skilled, knowledgeable, and empowered Government workforce is vital to ensuring that the standards, specifications and other documentation comprising the technical architecture are kept up to date and reflect advances in technology to achieve desired levels of performance at lowest cost. Without continuous vigilance, OA technical practices and business practices can quickly devolve into application specific interfaces and solutions that negate the benefits of OA. On the other hand, an OA must not become bureaucratic or so dogmatic that technical architecture can not support the development of affordable and effective systems architectures. Strong government technical leadership, supported by a capable team of Government and contractor engineers and acquisition specialists is needed to ensure the successful implementation of an OA approach.

NGIPS OPEN ARCHITECTURE TECHNICAL MODEL

Integrated Power Architecture

The Integrated Power Architecture (IPA) provides the framework for partitioning the equipment and software of IPS and NGIPS into modules. IPA defines six functional elements and the power, control and information relationships between them. Every IPS module corresponds to one of the IPA functional elements. A power relationship is one involving the transfer of electrical power between two functional elements. A control relationship refers to the transmission of commands from one functional element to another while an information relationship refers to the transmission of data from one functional element to another. The six functional elements are Power Generation, Power Distribution, Power Conversion, Power Load, Energy Storage and System Control. (Doerry and Davis 1994)

POWER GENERATION

A Power Generation Functional Element converts fuel into electrical power. The electrical power is transferred to one or more Power Distribution Functional Elements. A Power Generation Functional Element exchanges control and information signals only with System Control Functional Elements.

An associated Power Generation Module might typically consist of either a gas turbine or diesel engine, a generator, a rectifier, auxiliary support submodules and module controls. Other possible technologies include solar cells, fuel cells, or other direct energy conversion concepts.

POWER DISTRIBUTION

A Power Distribution Functional Element transfers electrical power between other Functional Elements. Whenever possible, control and information signals should only be exchanged with System Control Functional Elements. Power Distribution elements should only communicate directly with other functional elements (other than System Control) only in limited cases where latency and network speed of the Machinery Control System is not sufficient for system protection. Fault protection systems should be designed, if possible, to not require the power distribution modules to communicate control signals with any functional element other than system control. An associated Power Distribution Module might typically consist of bus duct, cables, switchgear and fault protection equipment.

POWER CONVERSION

A Power Conversion Functional Element converts electrical power from the form of one Power Distribution Functional Element to the form of another Power Distribution Functional Element. Power may be transferred only to and from Power Distribution Functional Elements. Control and Information signals can be exchanged only with System Control Functional Elements. An associated Power Conversion Module would typically consist of a solid state power converter. Another possibility is a transformer. The power conversion equipment associated with generators and motors are, however, part of the Power Generation and Power Load Functional Elements respectively. They are not considered part of a Power Conversion Functional Element.

POWER LOAD

A Power Load Functional Element is a user of electrical power received from one or more Power Distribution Functional Elements. A Power Load may optionally deliver power to one or more Power Distribution Functional Elements under transient conditions (regenerative braking for example). A Power Load may exchange control and information signals with System Control Functional Elements, external (non-IPS) systems, and in limited cases Power Distribution Functional Elements (See Power Distribution). Associated Power Load Modules include Propulsion Motors and ship service loads.

ENERGY STORAGE

An Energy Storage Functional Element stores energy. Power is transmitted to and from one or more Power Distribution Functional Elements via electric power. An Energy Storage Functional Element exchanges control and information signals with only System Control Functional Elements.

SYSTEM CONTROL

A System Control Functional Element consists of the software necessary to coordinate multiple other Functional Elements. A System Control Functional Element receives information from other functional elements and possibly external (non-IPS) systems. Similarly, a System Control Functional Element may receive control commands from or negotiate control actions with external systems and other functional elements. A System Control Functional Element resides on an external distributed computer system and therefore does not have a power interface.

Inter-zonal Power Generation, Distribution, and Propulsion Architecture

NGIPS offers the opportunity to evolve the IPS interfaces that comprise the current Technical Architecture. At the present time however, there are no obvious alternatives that can reduce ship design impact and ship cost without developmental risk.

Figure 3 shows the traditional three Propulsion Distribution Module (PDM) IPS architecture model. PDM-A is generally a high-voltage (4.16 to 13.8 kV 3 phase at 60 Hz) bus. All power generation modules (PGM), propulsion motor modules (PMM), and other high power loads connect to this PDM-A. Using traditional 60 Hz. a.c. power at a sufficient voltage to limit rated current and fault current enables PDM-A to use commercially based vacuum circuit breakers. PDM-A is generally confined to the major engineering spaces. PDM-B on the other hand, is generally composed of port and starboard buses that run most of the length of the ship. In the Integrated Fight Through Power (IFTP) system, PDM-B is a 1000 VDC bus. The Power Conversion Module PCM-A is a transformer rectifier. From a zonal survivability perspective, the port and starboard PDM-B buses must be protected such that the chance of damage to both buses due to weapons effect is low. (Doerry 2006) The PCM-B also protects the port and starboard PDM-B buses by preventing faults within a zone from impacting the voltage of either bus. To provide un-interruptible loads with high Quality of Service (QOS), the port and starboard buses must be protected from common mode disturbances on PDM-A. (Doerry and Clayton 2005) This can be accomplished by always operating PDM-A in split plant mode, or by incorporating Energy Storage into PCM-A or PCM-B, by attaching an ESM to PDM-B, or adding energy storage within the In-Zone Distribution.

Power density in the Figure 3 model can be improved by making PDM-A a high voltage (10 kV) DC bus. A DC bus is attractive because it decouples the speed of the prime mover from the frequency of PDM-A. Each prime mover can operate at its most economical speed using a high frequency generator to generate power that is then rectified. Furthermore, conductors in PDM-A can be sized purely for real power, since there is no reactive power at DC[1]. High speed generators are generally smaller and lighter than 60 Hz. generators. From a system viewpoint, the additional rectifiers on the generators are mostly offset by the elimination of the rectifiers on the motor drives for the propulsion motor modules. PCM-A would become more complex because it would likely become a high frequency converter driving a high frequency transformer that is then rectified. PCM-A would likely be more power dense (but more expensive) than a simple 60 Hz. transformer rectifier.

One drawback of making PDM-A a high voltage DC bus is that a new fault protection scheme (that can be implemented within an Open Technical Architecture) would require development and validation. Furthermore, ensuring stability of a DC bus fed by controlled rectifiers with power conversion devices as loads that appear as negative incremental impedances, is challenging. Developing a method for specifying the dynamic characteristics / impedance of the interface in such a manner to assure system stability for an arbitrary power system design is challenging.

Power density in the Figure 3 model can also be improved by making PDM-A high frequency AC (application specific within the range of 100 to 400 Hz.). While the generators would be smaller than 60 Hz. generators, choosing a common frequency for different prime movers may require compromises. Traditional vacuum breakers are likely to provide adequate fault protection within the target frequency range. The impact of operating a power system with fundamental voltage and current waveforms other than 60 Hz. on Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) is a risk area. Paralleling higher frequency generators may also prove challenging due to shorter available time to close the paralleling breaker before the two generators are significantly out of phase.

Figure 4 provides a variation of the Traditional three-PDM IPS architecture by eliminating PDM-B. In this model, Port and Starboard buses operating at the PDM-A voltage connect all the power generation modules, propulsion motor modules, high power loads, and in-zone distribution through PCM-Bs. The obvious advantage is the elimination of the PCM-As. The downsides are the increased demands on PCM-Bs to filter harmonics caused by the Propulsion Motor Modules, and the likely large difference in voltages between PDM-A and the in-zone distribution. Additionally, PCM-Bs may require the use of galvanic isolation (usually in the form of a high frequency transformer) to establish safe ground levels in the in-zone distribution during faulted conditions of PDM-A. Because the size of the PCM-Bs will likely grow, it is not clear whether this architecture is more power-denser or cheaper than the Figure 3 architecture. As with Figure 3, QOS requirements for un-interruptible loads requires operating PDM-A in a split plant mode or by incorporating energy storage on PDM-A, within PCM-B, or within the in-zone distribution.

For the Figure 4 architecture, a high frequency AC PDM-A would eliminate the need for the inverter front end of PCM-B, which could reduce its size and weight somewhat. Figure 4 could also be implemented with a medium voltage DC PDM-A (~1000 to ~3000 Volts DC).

[1] The impact of non-DC currents must be accounted for. One could claim that since non-DC currents in a DC distribution system do not contribute to the average power consumed, but do increase the RMS current, that non-DC currents are the source of reactive power in a DC system.

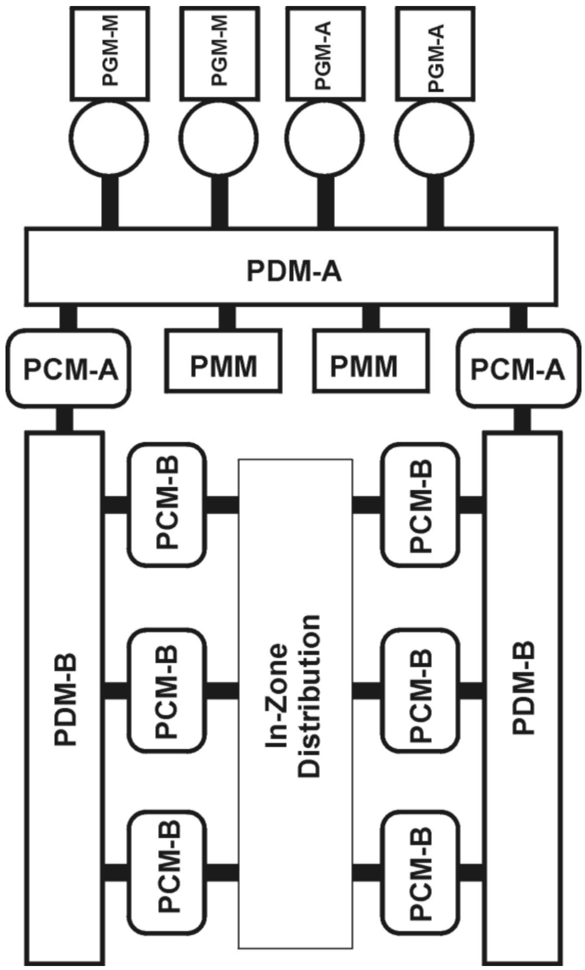

FIGURE 3. Traditional three-PDM IPS architecture

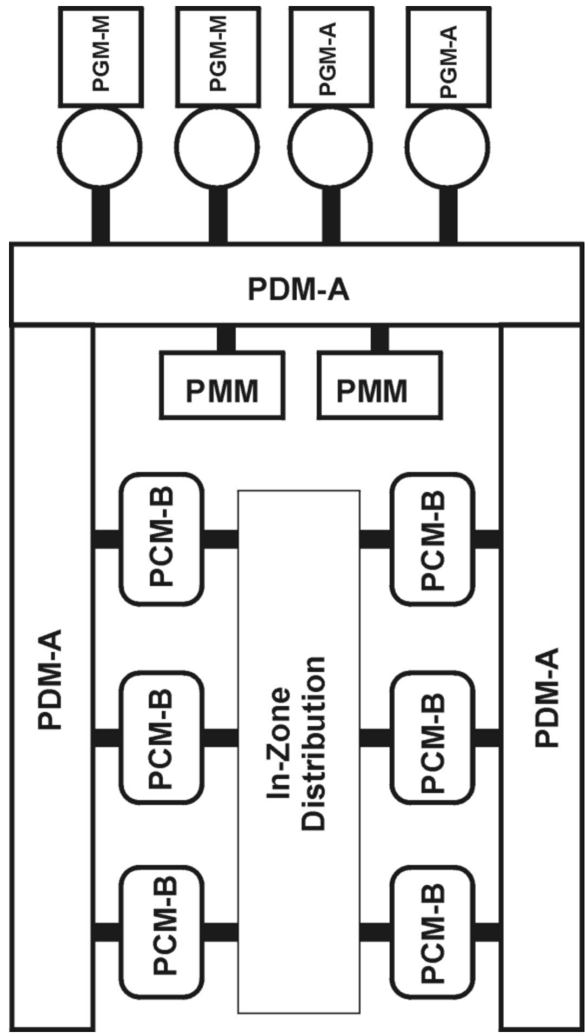

FIGURE 4. Two-PDM IPS Architecture

The architectures depicted in Figures 3 and 4 required the PGMs to only provide power to PDM-A. Figure 5 shows an alternate architecture that allows PGMs to connect to either PDM-A or PDM-B. It may be cheaper for certain PGMs, such as fuel cells, to provide power at the PDM-B interface rather than the PDM-A interface. The Figure 5 architecture may also be advantageous because one could limit PDM-A to the main machinery space(s). If PCM-A were bi-directional, the PGM-As could provide propulsion power, otherwise they would be restricted to powering ship service loads. Providing PCM-A with bi-directional capability would likely add cost, size and weight to the module.

For all of these architectures, the best means for connecting to shore power is an open question.

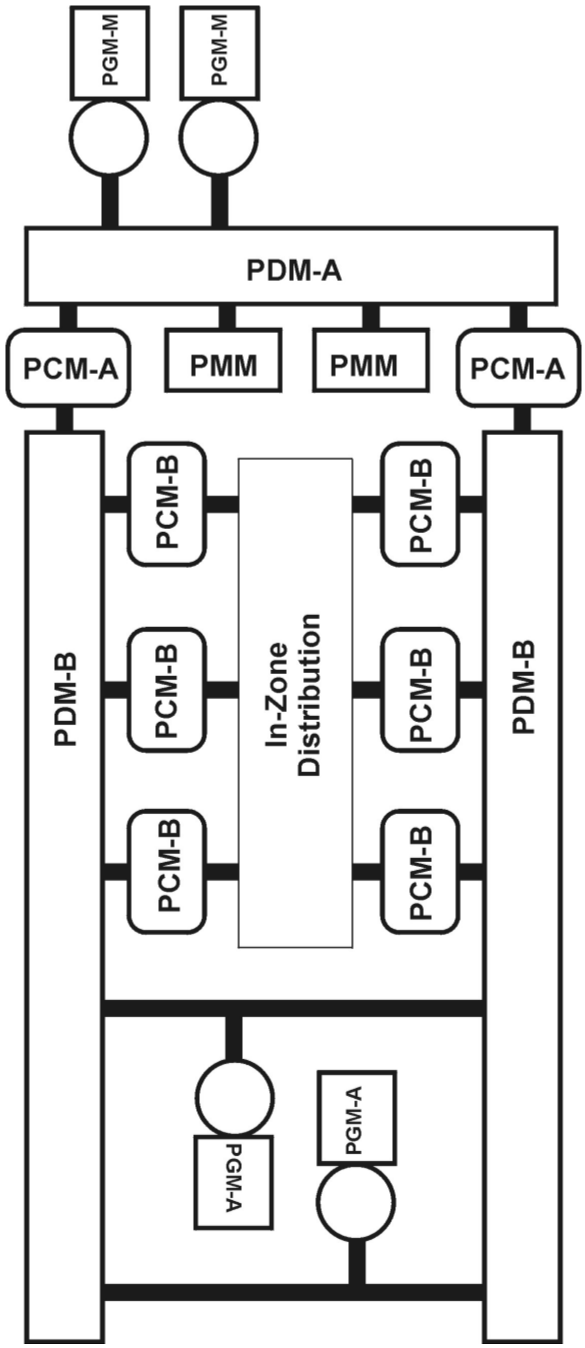

FIGURE 5. PGMs on multiple PDMs

In-zone Architecture

Figure 6 shows a typical DC Zonal in-zone distribution similar to IFTP. As with the previous inter-zone architectures, PCM-B serves to protect the port and starboard buses from faults with the zone. PCM-B provides DC power directly to loads via PDM-D, or AC power via PDM-C, PCM-C. and PDM-E. PCM-C must be reliable enough to provide adequate QOS. If PCM-B is not reliable enough for QOS considerations, every load should be treated as an un-interruptible load. Un-interruptible DC loads are provided power through auctioneering diodes fed from independent PCM-Bs. AC loads are provided uninterruptible power because PCM-E is served by two independent sources. However, if PCM-E is not close to an emergency load, then an alternate source of power from a different PCM-E is needed to provide compartment level survivability. This alternate source of power may be in a different zone.

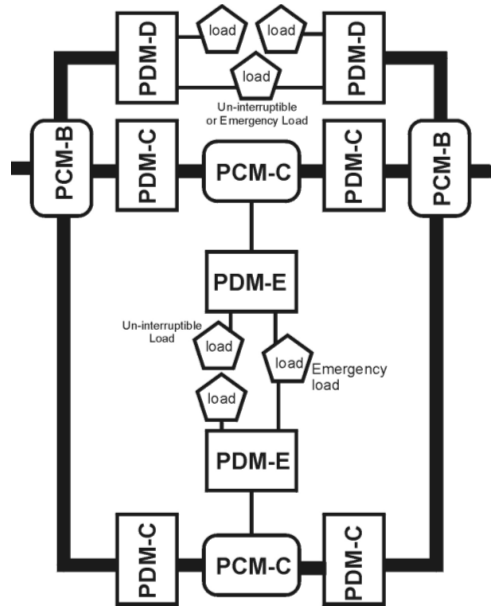

FIGURE 6. DC Zonal In-Zone Distribution

Figure 7 shows a typical AC Zonal implementation which would likely only be used if the power fed to PCM-B were 60 Hz. AC. PCM-B typically is a transformer. For un-interruptible loads, an Energy Storage Module is likely needed. Alternately, an extremely fast acting electronic automatic bus transfer could be used. Short term and long term interrupt emergency loads that require compartment level survivability would be provided power via traditional automatic bus transfer devices, or perhaps by controllable bus transfer devices that are commanded by the System Control software. The PCM-Bs in this example do not have to be in the same zone. If both PCM-Bs are outside the zone of a load, one PCM-B should be a zone forward of the load's zone, and the other aft.

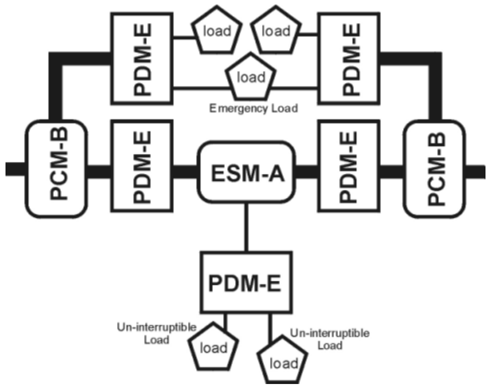

FIGURE 7. AC Zonal In-Zone Distribution

Figure 8 shows an alternate in-zone distribution system where PCM-C converts power to the form needed by loads nearby to the PCM-C. Because each PCM-C is provided with two independent sources of power, and a PCM-C is located near (within a threat weapon damage envelope) every load requiring compartment survivability, ABTs or auctioneering diodes are not needed. For this architecture to work however, the PCM-C must have a sufficient level of reliability to provide the requisite QOS. Because a zone could have many PCM-Cs, the cost of these modules must be kept low. An air-cooled PCM-C would be desirable to ease shipboard integration. The efficiency of PCM-C should also be as high as practical to reduce the cooling load within the zone.

Determining the best way to size the capacity of the different elements of the in-zone distribution system to minimize cost, yet still provide the requisite QOS and survivability, is still an open issue. The three methods that have been proposed to date: Demand Factors, Load Factors, and Stochastic methods, all have their strengths and weaknesses as detailed by Doerry and Fireman (2006).

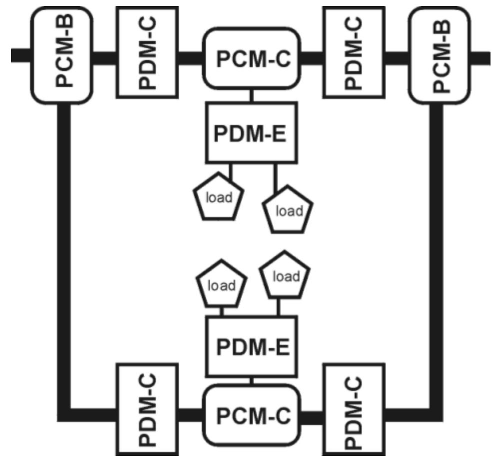

FIGURE 8. In-Zone Distribution with local power conversion

Module Implementation

POWER DISTRIBUTION MODULES

Power Distribution Modules consist of the switchboards, load centers, power panels and cabling necessary to connect the other modules and loads of an Integrated Power System. Additional functions of a power distribution module include fault detection and isolation, routing of power, automatic paralleling of generators, power quality monitoring, equipment isolation, and load shedding of loads that do not communicate with the Power Control Modules.

AC Distribution Systems

AC distribution systems typically use conventional circuit breakers for fault detection and isolation. Circuit breakers "trip" based on the time-current profile that the circuit breaker experiences, under voltage or frequency conditions, or by an external signal. Circuit breakers closer to a source are programmed to trip later for a given current level than circuit breakers closer to a load. This is done to "coordinate" the circuit breakers so that the breaker closest to a fault will trip and isolate the fewest number of loads. Fault isolation on a bus fed from multiple sources is more difficult. Special devices, called Multi-Function Monitors (MFM) are currently used to detect faults on a bus with multiple sources, identify the best breakers to isolate the fault, and send the appropriate external signals to quickly trip the identified breakers.

Conventional circuit breakers are generally limited by the amount of current that they can carry under steady-state conditions and the amount of current that they can interrupt under a faulted condition. Circuit breakers for 450 Volts AC (VAC) systems are generally limited to 4000 amps for steady-state conditions resulting in the largest source or load generating or using 3.1 Mega-Volt-Amp (MVA). Breakers for 4.16 Kilovolts (kV) to 13.8 kV are generally limited to 3500 amps, resulting in the largest electrical source or load generating or using 25 MVA for 4.16 kV systems and 84 MVA for 13.8 kV systems.

For prime movers with a power rating exceeding the limit of a breaker at the chosen distribution system voltage, one alternative is installing two generators on the same shaft, each with a rating below the maximum allowed by the available breakers. Paralleling generator sets with multiple generators on the same shaft requires special non-standard control methods because of the lack of independent phase control for each generator.

The fault current interrupting capacity of the breakers in conjunction with the sub-transient reactances of the generators determines the maximum amount of power that can be provided to a single power bus. For "normal" generator design, one can approximate the fault current it will produce as about eight times the generator current rating. With this approximation, a maximum of 8 MVA from all paralleled generators can be supplied to a 450 VAC bus, 42 MV for a 4.16 kV bus, and 203 MV for a 13.8 kV bus. 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 (4.16 kV to 13.8 kV) 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 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.

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 QOS.

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). The use of higher technology rectifiers, such as Pulse Width Modulated (PWM) rectifiers, could reduce the amount of harmonics induced on the high voltage bus.

DC Distribution Systems

DC circuit breakers are generally not available for the voltage levels, current levels, and fault current levels required for a traditional breaker "coordination" method for fault detection and isolation of a power system for a typical warship. Instead, a DC Distribution system would rely on all sources limiting fault current through power electronics. New methods are required to detect and isolate faults in a DC distribution system using contactors and power electronics instead of circuit breakers. The allocation of system protection functions among the various IPS modules is still an open issue.

With silicon technology, acceptable performance can be achieved with a 3000 VDC bus voltage. Typically, the ground point would be centered within the range (i.e. ±1500 VDC). Future advances in silicon carbide power devices are anticipated to enable 10 kV DC buses.

Due to reactive power flow and the skin effect for AC conductors, DC conductors of a given diameter and voltage can carry more power than an equivalent AC conductor (Both must still account for non-fundamental frequency currents). DC conductors should be designed to cancel external magnetic fields to reduce the ship's magnetic signature.

Additional advantages of DC include the simplicity of auctioneering diodes for providing alternate sources of power, the elimination of rectifier front ends for motor drives, and the ability to easily integrate prime movers and generators of different and variable speeds.

POWER CONVERSION MODULES

Power conversion modules typically consist of transformers and/or power electronics. Transformers are a good means of providing electrical isolation between the input and output of the power conversion module. Transformers can convert power from one voltage to another over a very broad but fixed range. Power electronics add the ability to regulate the output and decouple load current and voltage harmonics from the input current and voltage harmonics.

In general, higher switching speeds for power electronics are desirable to reduce the size of filters and other magnetic devices in the converter. Silicon devices are commercially available that can directly switch DC voltages at relatively high frequencies (>15 KHZ) up to 1000 VDC in operational converters. As the voltage increases, complexity of the converters increase and the switching frequency in silicon decreases. Considerable research is being invested into Silicon Carbide power devices that promise to considerably raise the voltage capability of the devices while retaining high frequency operation.

Power conversion modules often include common modular power conversion components that can provide tailored power to sets of loads as either single components, or as sets of parallel components. High reliability can be achieved if the single component is very reliable, or if an N+1 rule is applied to paralleled components that are hot-swappable. Providing the extra 1 in the application of the N+1 rule can be expensive. Ensuring high reliability of single components is currently difficult because methods for predicting power component reliability are immature. Furthermore, a methodology is needed for translating QOS requirements into power conversion component redundancy requirements.

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, are 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.

AC to AC

The most straight-forward AC to AC power conversion module for a single frequency is a transformer. It's generally more economical to have fewer large transformers rather than more smaller transformers. Unfortunately, the startup transient of a large transformer can cause system problems.

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 Power Control software must recognize this issue and prevent multiple large transformers from starting at the same time.

Another option for AC to AC conversion is the use of power electronics. Power electronics can be used to convert AC of one frequency to another. Power electronics when coupled with high frequency power transformers can also provide galvanic isolation. The use of power electronics can largely eliminate transformer in-rush issues, provide high quality output power despite harmonic rich input voltage waveforms, and provide fault current limiting. It is also possible to provide multiple independent outputs, thereby incorporating many functions of a load center (normally part of a distribution module) directly into the PCM.

AC to DC

The simplest and easiest way to create DC from AC is through the use of a 6 pulse rectifier. A six pulse rectifier however, inserts high harmonic currents into the AC supply, which interacts with line and generator impedances to cause high voltage harmonics. Harmonic currents can be reduced by inserting filters into the power system. Harmonic currents can also be reduced by inserting a phase shifting transformer before the rectifier to create 6 or more phases for rectification. This transformer however, has the traditional in-rush current issues as well as adding significant size and weight to the rectifier.

Active rectifiers use active power electronics to rectify the AC voltage into DC voltage while drawing current low in harmonics. There are many different power electronics topologies that can be implemented for an active rectifier; each has its own advantages and disadvantages.

DC to AC and DC to DC

Inverters convert DC power into AC power of the frequency and voltage needed by the load. Converters convert DC power into DC power at another voltage. A number of different topologies exist for implementing inverters and converters. Many production inverters / converters use “hard switching” where the power semi-conductor devices shut off when the voltage across it and the current through the device are both non-zero. Hard switching stresses the semi-conductor devices, increases switching losses, and can reduce inverter/converter reliability. “Soft switching” inverters/converters switch only when the voltage across the power electronic devices is zero or the current through them is zero. Soft Switching is usually implemented with resonant inverters/converters which improve efficiency, but are more complex than hard switched inverters/converters.

POWER GENERATION MODULES

Power Generation Modules currently use prime movers with rotating shafts driving AC generators. The prime movers can be steam turbines, gas turbines, or diesel engines. In the future, fuel cells may directly provide DC power. To directly generate 60 Hz power, the fastest shaft speed possible is 3600 RPM using a 2 pole generator. Increasing the number of poles in the generator decreases the shaft speed (i.e. 1800 RPM uses a 4 pole generator and 1200 RPM uses a 6 pole generator) to maintain the same frequency. Many steam and gas turbines are more power dense and operate more efficiently at speeds higher than 3600 and would require a reduction gear to produce 60 Hz.

Power. Generating power at a higher frequency for a High Frequency AC bus, or for rectification into HVDC could reduce the size and improve efficiency of gas turbines and steam turbines.

Gas turbines and diesel engines typically experience unplanned shutdowns after considerably less than 10,000 hours of operation. For this reason, the power system should have sufficient capacity with at least one PGM out of service to supply the worst case ship service load operating condition plus enough propulsion power to achieve a tactically useful speed.

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. 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. Employing a "tent rating curve" may prove advantageous in the ability to take advantage of the higher gas turbine rating at low temperatures.

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, 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 design techniques including modeling and simulation are necessary to ensure the power system behaves as desired.

Fuel cells typically are very slow in dynamic response to changing load. For this reason, fuel cell implementations on a ship will likely require integration with Energy Storage. Whether the Energy Storage Module is provided as a distinct module (ESM) or integrated into the Fuel Cell PGM is an open question.

ENERGY STORAGE MODULES

An Energy Storage Module (ESM) 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 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. Could also be used to improve transient response of fuel cells.

Although the advantages of an ESM are known and batteries are a standard feature of submarine power systems, a shipboard qualified ESM for surface ship use has not yet been developed. Ideally, a single ESM architecture employing common and scalable hardware and software elements could be employed to meet all of the above categories.

POWER LOAD AND PROPULSION MOTOR MODULES

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 Expanded Ship Work Breakdown Structure (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 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 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.

In hybrid drives, a Propulsion Motor Module may provide power to a reduction gear that is also connected mechanically to a prime mover such as a gas turbine or diesel engine. In a hybrid configuration, the propulsion motor is sized to propel the ship over a speed range that encompasses a large fraction of the ship's operational profile. The mechanical drive prime mover is used as a "boast" plant to enable the ship to attain the sustained speed requirement at lowest cost. The LHD 8 propulsion plant is a good example of a hybrid drive.

For near term ship designs, Advanced Induction Motors (AIM) and Permanent Magnet Motor Systems (PMMS) are the preferred technologies that provide the best cost versus 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.

One drawback of large motors and motor drives is the drop off in efficiency at low power levels. 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.

Future combat systems such as high power radars, high power lasers, and railguns will also prove challenging to integrate into an integrated power system. Establishing interface requirements for high power pulse loads that are not too stressing of either the power system or the combat system design is critical. For stable system operation, these loads will likely have to communicate via information or control interfaces to the power control modules before drawing a pulse of power. Because of the immaturity of the high power combat system designs, establishing good interface standards for these loads will be difficult if not impossible in the near term. Determining how to anticipate without over-constraining these future loads in the interface standards in the near term will be a challenge for the next years.

POWER CONTROL MODULES

The Power CONtrol module (PCON) 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.

While the Power Control Modules are software, survivability and Quality of Service requirements will impact the design of the hardware network the Power Control Modules will reside on. Survivability and QOS will also influence the partitioning and redundancy of the software implementation of the Power Control Modules.

The Power Control Module should facilitate maintenance of the various IPS Modules. Ideally electrical isolation and tagouts would be implemented or at least facilitated by features in the Power Control Module. Special operating modes of IPS Modules may be required for conducting condition monitoring tests, preventative maintenance, and corrective maintenance.

The Power Control Modules should be developed in a manner to easily maintain over its lifecycle. Additionally, commonality of software across the fleet through Open Architecture tenets should be implemented. Ideally, the software should be self-configuring, or require a minimum of configuring when installed onboard any one ship.

CONCLUSIONS

An OA Business Model for NGIPS is based on the following tenets:

• The use of Performance Specifications that define “what” is needed not “how” it is designed;

• Subdivision of labor or specialization at the module or component level;

• Defined and segregated roles and responsibilities for component delivery, system integration and life cycle support;

• A defined feedback process to create a "spiral" process to provide feedback from the evaluation of fielded systems to update architecture documentation and module designs.

The implementation of an OA fits very well within the DOD Architectural Framework. A technical architecture (technical view) that establishes standards, tools, and processes is maintained independently from the systems architecture (systems view) for a given application that is developed to implement an operational architecture (operational view) established by the end user.

The Integrated Power Architecture describes the functional decomposition of IPS and NGIPS. While the implementation of various modules was been established for IPS and implemented in ongoing designs, updating the interface standards and implementations for NGIPS to reflect advanced in technologies for future designs requires additional study and trade-offs.

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