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In-Zone Power Distribution for the Next Generation Integrated Power System

ABSTRACT

The Navy recently produced a Next Generation Integrated Power System (NGIPS) Technology Development Roadmap that reaffirmed the Navy's use of Zonal Electrical Distribution Systems (ZEDS) within an Integrated Power System (IPS) architecture for future surface combatants and submarines. The Navy is currently implementing ZEDS on DDG-1000 in the form of the Integrated Fight Through Power (IFTP). As described in the NGIPS Technology Development Roadmap, investments in the in-zone distribution system are needed to ensure applicability to a wide range of ships and to improve the affordability of the system. This paper will explore different options available for meeting survivability and quality of service requirements while decreasing cost. These options include different design strategies as well as component development. Examples include integrating Ship Service Inverter Modules into a new design PCM-1A and integrating load center functionality into a new design PCM-2A. The paper will also make recommendations for future work.

The views expressed in this paper are those of the author and are not necessarily official policy of the U.S. Navy or any other organization. The intent of this paper is to foster dialogue to gain a better understanding of NGIPS in-zone Power Distribution.

INTRODUCTION

Figure 1 illustrates the NGIPS Technology Development Roadmap. Starting with the today's technology as embodied in DDG 1000 which features Medium Voltage AC (MVAC) Power Generation and an Integrated Fight Through Power (IFTP) implementation of Zonal Electrical Distribution, the roadmap increases power density and affordability by transitioning to High Frequency AC (HFAC) power in the near term and eventually to Medium Voltage DC (MVDC) power. Common to all of the Power Generation architectures, the NGIPS Technology Development Roadmap projects the current IFTP zonal electrical distribution system will evolve to improve affordability while meeting survivability and quality of service (QOS) requirements (NAVSEA 2007).

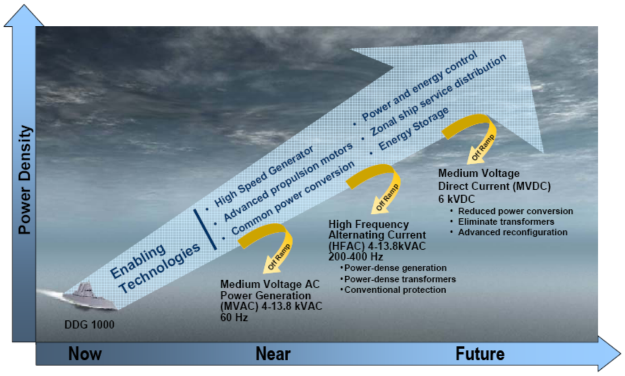


Figure 1: NGIPS Technology Development Roadmap (NAVSEA 2007)

NGIPS continues the use of the seven basic IPS module types described by Doerry and Davis (1994):

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

Figure 2 illustrates a notional IPS architecture based on MVAC with an interface to IFTP. Figure 3 shows a notional IFTP architecture that could be integrated with an IPS MVAC architecture. While the current MVAC IPS / IFTP architecture meets DDG 1000 requirements, future ship survivability and Quality of Service (QOS) requirements may be more cost effectively met by alternative architectures.

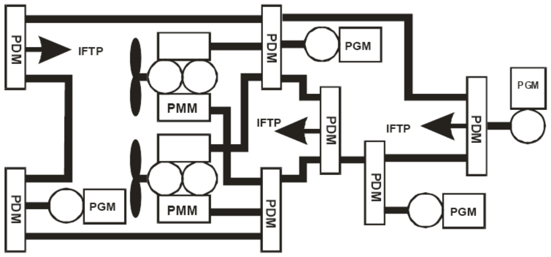


Figure 2: Notional MVAC with IFTP Power System Architecture

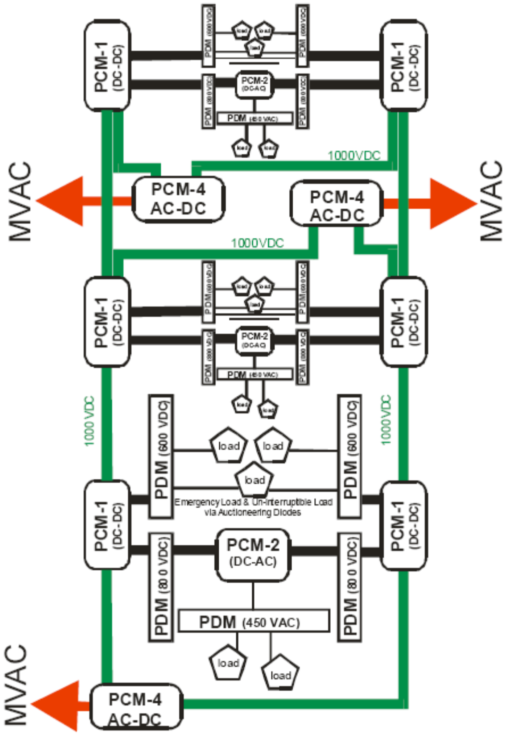


Figure 3: Notional IFTP In-Zone Power System Architecture

As shown in Figure 4 and Figure 5, the NGIPS technology proposes simplifying the architecture by eliminating the 1000 VDC longitudinal bus and distributing the medium voltage power longitudinally. A new PCM-1A replaces PCM-1, but adds functionality in that it incorporates the interface to the medium voltage power distribution system and can provide either ac or dc power directly to loads that do not require un-interruptible power. A new PCM-2a, modeled after the Integrated Power Node Center (IPNC) described in MIL-PRF-32272 is used to provide power to un-interruptible loads while emergency loads are provided alternate sources of power via PCM 2a or a controllable bus transfer in the case of ac loads, and auctioneering diodes in the case of dc loads.

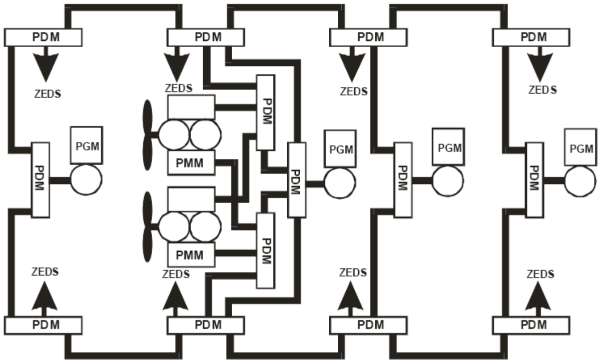


Figure 4: Notional NGIPS MVAC/HFAC/MVDC Power System Architecture

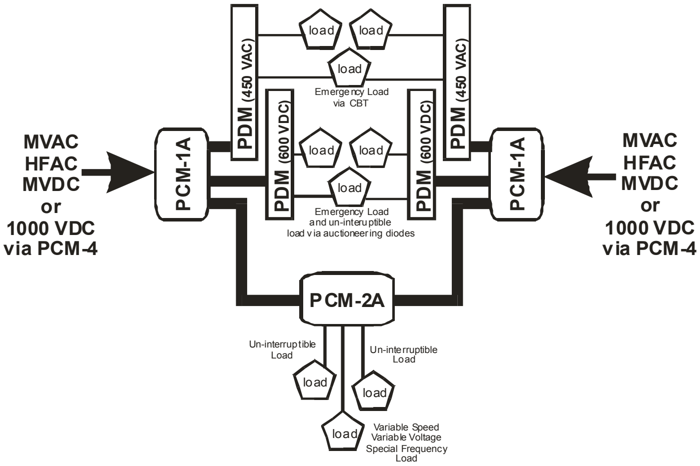


Figure 5: Notional NGIPS In-Zone Power System Architecture

IN-ZONE POWER DISTRIBUTION SYSTEM ARCHITECTURE

PCM-1A

The primary purpose of PCM-1A is to protect the longitudinal 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 6. 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.

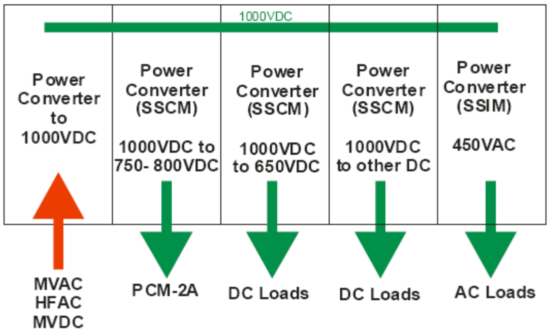


Figure 6: Notional NGIPS PCM-1A Architecture

Figure 7 and Figure 8 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 6 Figure 7, and Figure 8, 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.

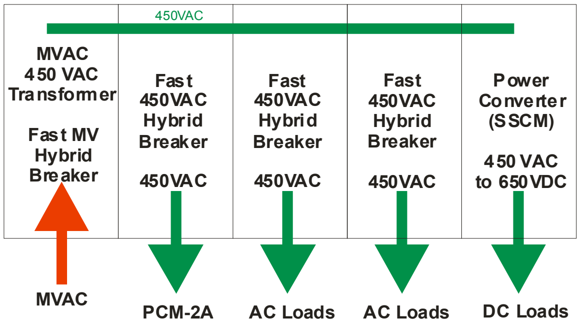


Figure 7: Notional NGIPS PCM-1A Architecture with Hybrid Breakers

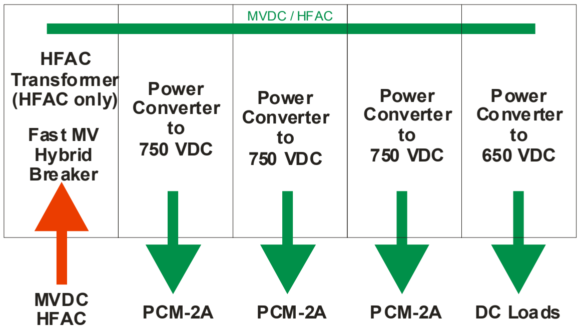


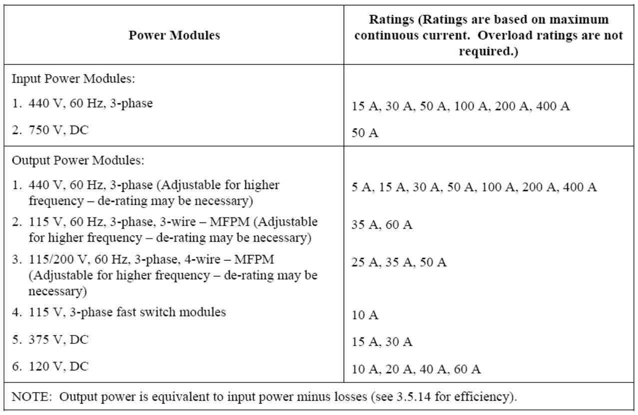
Figure 8: Alternate Notional Architecture for PCM-1A for MVDC / HFAC

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.

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 1)



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 1: 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.

Consideration should be given to providing loads having large starting or in-rush currents with dedicated power modules that are programmed to provide a soft start.

To fully implement the PCM-2A functionality within the NGIPS architecture, MIL-PRF-32272 requires amplification in the following areas:

- The control interfaces are not well defined.
- The physical interfaces of the Power Modules are not defined.
- The physical interfaces of the IPNC are not defined.
- Air cooling of the IPNC is not explicitly defined.
- The control of motor speed to enable power modules to serve as variable speed drives is not well defined.
- Support for "switching modules" to enable the output of a single output module to be shared among multiple (up to about 10) loads. The switching modules would act as circuit breakers, but would also be able to be turned on and off quickly upon command from the control system.
- Reliability of the power modules should exceed 30,000 hours MTBF.
- Consideration should be given to making Power Modules hot-swappable.

Additionally, there are a number of other internal inconsistencies in the standard that require correction in the next revision.

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. See Table 2.
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. See Table 2.
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. See Figure 9.

Because PCM-1A limits fault currents to values significantly below the limits shown in Figure 9; 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.

TSGA	Diameter (in)	Ampacity 40C	Resistance / 1000 ft	Voltage loss per 100 ft at ampacity	% Voltage loss per 100 ft ref 440 Volts	Length for 4% loss at 440 V (ft)
3	0.41	11	4.7	8.95	2.04%	196.5
4	0.45	18	2.9	9.04	2.05%	194.7
9	0.58	39	1.4	9.46	2.15%	186.1
14	0.72	51	0.88	7.77	1.77%	226.4
50	0.97	110	0.26	4.95	1.13%	355.3
150	1.52	235	0.081	3.30	0.75%	533.8
300	1.96	348	0.043	2.59	0.59%	679.1
400	2.2	435	0.031	2.34	0.53%	753.5

DDS-304-2 of 15 May 1984 DDS-304-1 of 1 Nov 1963

Table 2: Ampacity and voltage loss for TSGA Cable

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.

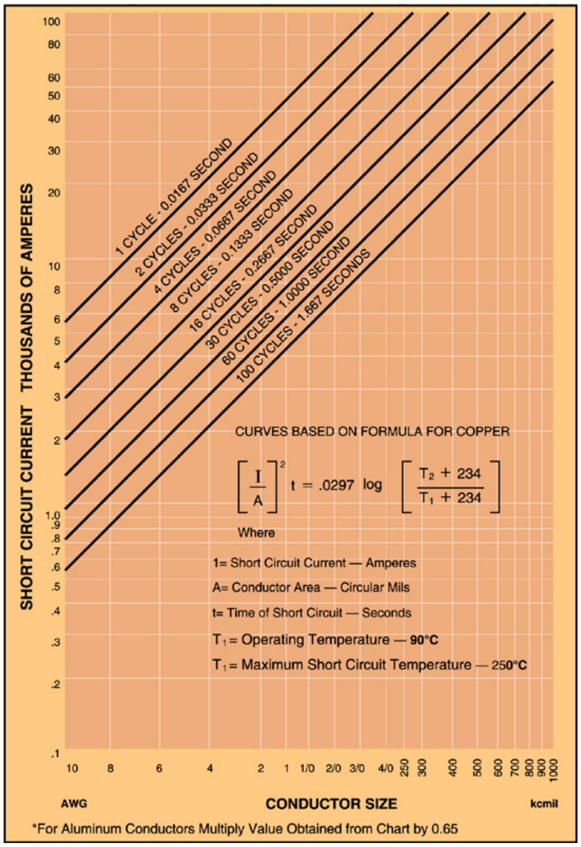


Figure 9: Maximum Short Circuit current vs Conductor size (www.okonite.com)

Controllable Bus Transfer (CBT)

A controllable bus transfer (CBT) provides two paths of power to loads that require compartment level survivability (see the survivability section below) 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.

QUALITY OF SERVICE

Quality of Service is a metric of how reliably the power system provides power to the loads. It is calculated as a Mean-Time-Between-Service-Interruption (MTBSI). Quality of Service is a reliability 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 operation transients.

A service interruption is any interruption in service, or power quality degradation outside of acceptable parameters for a period of time, which result in the parent system of the load not being capable of meeting its requirements. The duration of service interruption is measured relative to two times: *t1* and *t2*.

t1 is defined as the maximum time to clear faults and reconfigure the distribution system without bringing on additional generation capacity. For system employing conventional circuit breakers, *t1* is on the order of 2 seconds.

t2 is defined as the maximum time to bring the slowest power generation module online. *t2* is typically on the order of 1 to 5 minutes.

Different operating conditions of the ship may have different requirements for the Mean Time between Service Interruption (MTBSI). These different operating conditions are generally defined and the MTBSI calculated over an operating cycle or alternately a Design Reference Mission. Associated with each operating condition is a machinery concept of operation that details the expected policies for redundancy, rolling reserve, etc. needed to achieve the ship requirements specified MTBSI.

As described by Doerry and Clayton (2005) and Doerry (2007), loads can be categorized into four QOS categories: Un-Interruptible, Short Term Interrupt, Long Term Interrupt, and Exempt.

Loads classified as Un-interruptible can tolerate service interruptions from a minimum value on the order of 4 ms up to time t1. The power system is designed to provide the minimum achievable service interruption to un-interruptible loads, typically less than 4 ms with a reliability in excess of the customer specified MTBSI.

Loads classified as Short-term Interrupt can tolerate service interruptions greater than *t1* and less than *t2*. The power system is designed to provide service interruptions to short-term interrupt loads less than *t1* in duration with a reliability in excess of the customer specified MTBSI.

Loads classified as Long-term interrupt can tolerate service interruptions in excess of *t2*. The power system is designed to provide to long-term interrupt loads service interruptions less than *t2* in duration with a reliability in excess of the customer specified MTBSI.

For Integrated Power System (IPS) configurations, sufficient redundancy in generation is not provided to enable the ship to achieve its maximum speed with any one generator out of service. Propulsion power for IPS ships may thus be split into three categories: Short Term Interrupt, Long Term Interrupt, and Exempt. The installed generation capacity of the ship must be capable of supporting all categories of load for all loads for every operating condition with all generators online, and must support all loads except the Exempt Load with one power generation module out of service. Unless otherwise specified by the ship requirements, that portion of propulsion load needed to exceed the minimum tactical speed is Exempt Load.

The concept of the Exempt Load is only used in sizing the installed generation capacity of the ship. In operation of the power system, exempt load is treated as long-term interrupt load unless otherwise specified by the ship requirements.

SURVIVABILITY

NGIPS assumes a zonal design methodology. The basic concepts of zonal design and its relationship to survivability (and Quality of Service) are described in detail in Doerry (2005, 2007) and summarized here. Once a ship concept of operation has been defined and the survivability requirements articulated in the form of Design Threats and Design Threat Outcomes, zonal design is implemented through:

a. Identifying zone boundaries. Zones should be large enough such that weapons induced damage for non-overmatching threats will not span more than two adjacent zones. Zones should align with watertight bulkheads. There should be enough zones such that sufficient mission capability will survive the loss of any two adjacent zones. For most surface combatants, 5 to 7 longitudinal zones typically provides sufficient arrangement flexibility while preserving survivability performance.

b. Defining a notional architecture and concept of operation for each distributed system. Where possible, align distributed system generation elements with loads to minimize the need to interconnect zones.

c. Identifying and allocating Mission System elements to zones. For Mission Systems that are expected to operate as part of a Design Threat Outcome to a challenging Design Threat, the mission system should include sufficient redundancy and spatial separation such that the mission system capability is preserved with the loss of all mission equipment in any two adjacent zones. The capability of equipment to continue operating without interruption in undamaged zones is called Zonal Survivability. Zonal Survivability addresses the vulnerability portion of survivability.

d. Identifying non-redundant mission systems and emergency loads that require compartment level survivability. Compartment level survivability implies that two sources of power are provided to the load such that the physical location where the two sources come together are within the damage envelope of the equipment. If the load survives damage to the zone, there should be a high level of probability that power can be restored to it. The restoration of power in general should not occur until the operator is assured that it is safe to do so. While Zonal Survivability addresses vulnerability, Compartment level survivability addresses recoverability.

e. Incorporating the notional distributed system architecture and mission systems into the appropriate ship synthesis model. Ensure the distributed system components have sufficient capacity to meet margined load and service life requirements.

f. Analyzing the synthesized ship in terms of Quality of Service and Survivability to verify requirements are met. Identify cost and performance drivers to identify potential changes to the ship configuration to better meet ship concept requirements at the lowest cost.

DESIGN IMPLEMENTATION ISSUES

Load Aggregation for sizing distribution system equipment

A standard method is needed for determining the required rating of the in-zone power distribution equipment. Doerry and Fireman (2006) identified three general approaches, each with possible variations:

- <u>Load Factors</u>: Load factors are multipliers to all the loads served by a power system device. The power system device must have a rating greater than the sum of the product of each connected load multiplied by its load factor. Establishing realistic non-conservative load factors and adjusting the analysis to account for special operating conditions are challenges for using this method. Historically, load factors as applied within the Electric Plant Load Analysis (EPLA) have been used to size generator sets.
- <u>Demand Factors</u>: A demand factor is obtained from a graph in MS18299 (NAVSEA 1987) based on the total connected load (measured in amps) for 450 VAC loads. The Demand Factor is applied directly to the total connected load to determine the rating. Historically, Demand Factors have been applied to the sizing of feeder cables, feeder breakers, and load centers. Perhaps coincidently, Load Factor analysis and Demand Factor analysis have historically returned similar results. The original physics based rationale for Demand Factors is currently not known.
- <u>Stochastic Methods</u>: Amy (2005) proposes another method based on representing electric loads as probability density functions and determining both an expected value for electric load and a standard deviation. With this method, one can establish required component ratings to achieve any level of risk for meeting the electrical power demand. As a design progresses and more is known about the loads, the standard deviation of the probability density functions can be expected to decrease, resulting in greater confidence in meeting the electrical power demand.

Control System Interface with Loads

One of the enablers of selective load shedding for Quality of Service and Mission Priority Load shedding is establishing standard control system interfaces with electrical loads. The Open Systems Interconnection Basic Reference Model or "OSI Model" (Figure 10) defines 7 layers (sets of related functions) for enabling data communication. To help ensure successful control system integration, standards and protocols must be defined for each of these layers. For NGIPS applications, many standards and protocols exist and are used for 6 of the 7 layers. Selecting and adopting physical, data link, network, transport, session, and presentation layer protocols and standards for NGIPS modules should be straight forward. At the application layer however, standards suitable for implementing NGIPS power management functions to include quality of service and mission priority load shedding do not exist. One standard that comes close to meeting NGIPS needs is the ANSI/EIA 709.1 Control Networking Standard otherwise known as the *Lonworks Protocol*.

At the application layer, the Lonworks Protocol defines a member of a control system in terms of Network Variables, Configuration Properties, and Manufacturer-defined properties (Figure 11). The Lonworks Protocol includes a large number of Standard Network Variable Types (SNVTs) that standardize the application layer for many commercial and industrial control applications. The Lonworks object model does allow for User-defined Configuration Property Types (UCPTs) and a manufacturer-defined section that can be employed by a NGIPS standard to provide the necessary capability to exchange data to implement NGIPS power management and load shedding algorithms.

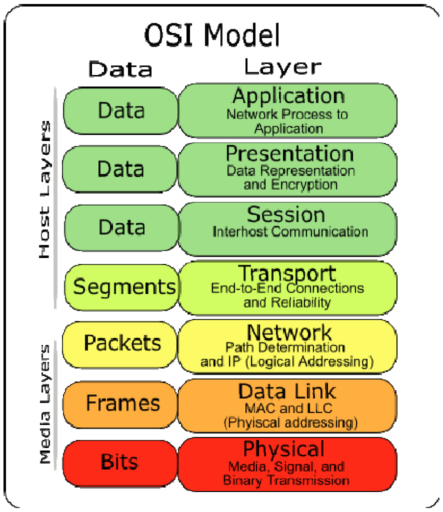


Figure 10: OSI Model (http://www.3mfuture.com/network_security/arp-guard-arp-spoofing.htm)

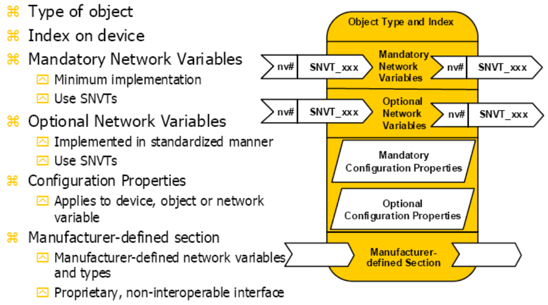


Figure 11: LONWORKS Object Model (Echelon 1999)

For the purposes of NGIPS power management, PCON must be able to command loads to enter a Load Electrical Power System Mode as well as a Maintenance mode. To implement this, standardized commands at the application layer are needed for the following:

Load Electrical Power System Modes

- Hard Shutdown (unit is off, no communications, power typically turned off within PDM)
- Normal Shutdown (unit is off, communications are on, power available at the load)
- Standby Power Mode (unit is drawing the minimum power to respond to commands)
- Low Power Mode (unit is responding to commands in a limited way, restricting the use of power)
- Full Power Mode (unit is fully functional)

Load Maintenance Modes

- Tagged Out (With the exception of an "emergency stop", the Electrical Power System Mode can not be changed until the unit is tagged in)
- Tagged In (Electrical Power System Mode can be changed)

Load Information Interactions

- System Condition and Status
- Configuration Management Data
- Maintenance History
- Operational Log
- Condition Assessment Data
- Consumable Usage rates and replacement time predictions
- Operator and Technical manuals

In addition to these modes, the other systems that the load is part of may also have requirements for control interfaces. Therefore, the NGIPS approach to defining the application layer must be consistent with other machinery control standardization efforts.

While there are many possible solutions for implementing the "Media Layers" of Figure 10, using the power cables to communicate control signals for low-bandwidth has the potential to save material costs, engineering labor, and production labor by not requiring the design, acquisition, and installation of copper or fiber optic control cabling. An existing standard, "ANSI/EIA 709.2-A-2000 Control Network Powerline (PL) Channel Specification" could possibly meet shipboard needs. An alternate standard currently under development is "IEEE P1901 Draft Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications."

Implementation of QOS and Mission Priority Load Shedding

Quality of Service (QOS) load shedding is different in philosophy from Mission Priority Load Shedding. In QOS load shedding, loads are allowed to have interruptions in power for a period of time that they can tolerate (minimum achievable for un-interruptible, *t1* for short term interrupt, and *t2* for long term interrupt). The importance of the load to achieving the current mission is not a factor in QOS load shedding. In general the power system is designed such that for single failures in the power system, sufficient capacity can be restored within the QOS time limits.

In Mission Priority Load shedding, loads are prioritized according to their importance to fulfilling the current mission of the ship. Mission Priority Load shedding is only implemented if sufficient capacity can not be restored during the period of QOS load shedding.

The general concept of operation for implementing QOS and Mission Priority Load Shedding in an NGIPS system is as follows:

a. During normal operation, PCON ensures that upon loss of any one arbitrary power source (PGM/ESM/PCM), there is remaining capacity in the remaining online power sources to power all online uninterruptible and short-term interrupt loads.

b. When PCON detects that the amount of load exceeds the available power generation / energy storage capacity (or PCM capacity within a zone), then QOS load shedding is initiated. If the power capacity shortage is at the total generation level, then long term interrupt loads through-out the ship are shed to the degree necessary to restore balance. If the power capacity shortage is at the zonal level, then long-term interrupt loads are shed only in the impacted zone.

c. PCON initiates bringing on additional power generation capacity. Once online, all shed loads are restored.

d. PCON initiates reconfiguration of the power system to restore power (if necessary) to short term interrupt loads within time *t1*. Uninterruptible loads should not experience a loss of power.

e. If PCON determines that bringing adequate power generation capacity is not possible within time *t2*, then PCON initiates Mission Priority Load shedding. Some un-interruptible and short-term interrupt loads of lower mission priority are shed to enable bringing online higher mission priority long-term interrupt loads.

f. Should additional power generation capacity become available, shed loads are brought back online.

g. If the mission of the ship changes, then mission prioritization can also change, resulting in shedding of some online loads to enable powering other previously shed loads.

Key to implementing QOS and Mission Priority load shedding is having the capability to shed and restore power to individual loads (or groups of loads that will always have the same QOS category and Mission Priority). This selective shedding of loads is enabled by implementing one of the following methods:

a. Implementing the control system – load interface described above directly in the load equipment. (This is the preferred approach where possible)

b. Implementing the control system – load interface described above using a local controller near the load equipment to translate the load's proprietary control interface to the standard control interface. This local controller could include a power switch for securing power to the load. If the local controller requires less than 12.94 watts, then power can be provided to the controller via the control cable using the IEEE 802.3 clause 33 Power over Ethernet (PoE) specification.

c. Providing power to loads without a control interface from a "switching module" within PCM-2A. The "switching module" provides the selective shedding capability.

d. Providing the load from a dedicated output module from PCM-2A. This is likely the preferred approach for uninterruptible loads or high power loads.

PCM Efficiency and Thermal Management

Improving the efficiency of the input and output modules of PCM 2A and PCM 1A is important to reducing demands on the ships Heating Ventilation and Air Conditioning (HVAC) System and equipment cooling systems. Thermal management must be addressed both during steady-state operation, and during system startup. From a total system efficiency viewpoint, chill water or intermediate temperature water as proposed by Frank and Helmick (2007, 2008) is more efficient than air cooling. However, during the start up of the power system or following battle damage, the cooling water systems may not be available. For these cases, a cooling method with sufficient thermal inertia, (such as air cooling) is preferred. Perhaps a compromise is using air cooling in a space that is provided with energy saving Variable Air Volume (VAV) control to manage air temperature and air replenishment. Frank and Helmick predict significant savings in using advanced HVAC controls such as VAV over conventional HVAC design.

The IPNC currently only requires an efficiency of 85%. This implies that up to an additional 17.6% of the electrical load served by the IPNC must be removed from the IPNC as heat. Improving the efficiency of the power modules is therefore a worthy goal.

For power systems employing MVAC power generation, the PCM 1A architecture of Figure 7 can provide power to short-term and long-term interrupt loads without the use of power modules. The resulting improvement in efficiency may prove advantageous.

In any case, the thermal management strategies employed by the In-zone power distribution system should align with the technology of future HVAC systems as described by Frank and Helmick.

Component Reliability

Affordably achieving Quality of Service depends on reliability of the in-zone power systems equipment. Because the output modules of PCM 2A and potentially PCM 1A can directly provide power to loads, their reliability should be very high with a Mean Time Between Failure (MTBF) much greater than 30,000 hours. Components that have a reliability much less than 30,000 hours MTBF should be provided with N+1 redundancy (i.e. one more component provided than required to meet capacity needs). N+1 redundancy is likely not needed for components with a MTBF of about 30,000 hours and a short Mean Time to Repair (MTTR) and a short Mean Logistics Delay Time. For these components, the ability to hot swap modules should be considered to minimize MTTR. For additional discussion of component reliability, see Doerry (2007).

Maintainability

Maintainability must be designed into the power system equipment. Issues that should be considered include:

- Integration of equipment tag-out procedures into PCON, PDM, PCM-1A and PCM-2A. Details of the Navy's tagout procedures are provided in the "Tag-Out Users Manual" (NAVSEA 2007).
- Hot-swappable input and output modules in PCM-2A to minimize the number of loads impacted by maintenance action on the PCM-2A.
- Minimize scheduled maintenance on NGIPS modules – especially those that are non-redundant in the power system.

- Integration of Condition Based Maintenance into PCON and the control interface requirements for NGIPS modules as well as the Control System – Load control interface.

Galvanic Isolation and System Grounding

In general, all power systems are grounded either intentionally through a grounding system, or unintentionally through parasitic capacitances and EMI filters. As detailed by Jacobson and Walker (2007), the benefits of a grounding system include:

- In a fault-free condition, a grounding system establishes a predictable system grounding point and minimizes voltage stress seen by the system elements
- Under transient fault conditions, a grounding system may limit transient voltages applied to insulation systems and equipment.
- Under steady-state fault conditions, a grounding system can facilitate the localization of fault, thereby enabling system reconfiguration to isolate the fault.

If a grounding system is used, accepted practice is grounding each galvanically isolated power system at exactly one point to minimize ground circulating currents.

Within the In-Zone Power Distribution System, one of the key questions will be whether to require galvanic isolation between the MV system and the in-zone power distribution. Galvanic isolation generally comes with increased weight and cost of the PCM-1A, but significantly reduces the risk of having high line to ground voltages on distribution equipment and user equipment due to ground faults on the medium voltage bus. These high line to ground voltages within the in-zone power distribution system during the medium voltage bus ground faults can lead to insulation failure and subsequent equipment and electrical system failures. A thorough risk analysis should be conducted before implementing a system design not requiring galvanic isolation.

Traditionally, naval warships have used ungrounded systems at the 450VAC level. Transient over voltages that can weaken insulation systems can be reduced however, by employing a high-impedance ground on the 450 VAC systems. A high impedance ground system has the same operational benefits of an ungrounded system (continued operation with one line-to-ground fault). On the other hand, high impedance grounding requires additional hardware at increased cost. A business case analysis is needed to determine if reduced maintenance on user equipment will offset the increased cost of the high-impedance grounding system.

Energy Storage

The amount of energy storage needed, if any, in the in-zone distribution system depends greatly on design decisions made at the Medium Voltage level. If the Medium Voltage system is designed to ensure that either the port or the starboard longitudinal bus is always powered and has enough power capacity to serve all un-interruptible and short-term interrupt loads (see following section), then in-zone energy storage is generally not needed.

In the case where there is not sufficient power generation upon loss of a power generation module to power all un-interruptible and short-term interrupt load, then energy storage can be employed to provide the missing capacity for the minutes needed to bring another power generation module on line. In this case the energy storage module / submodule should have a power rating sufficient to provide the missing capacity and an energy rating sufficient to power the loads for about 10 minutes (to account for successive faults). In the limiting case where the power system is designed to enable single engine operation, then Energy Storage is required and must have sufficient capacity to power all short-term interrupt and un-interruptible loads.

The switches in PCM-1A and PCM-2A are assumed to be capable of switching fast enough upon a deficiency of power generation capacity to shed sufficient load before the system becomes unstable. If this is not the case, then energy storage of high power capability but relatively low energy capacity is needed to hold up the power system while loads are shed.

Energy storage in the range of 250KW for 15 to 30 minutes may also be needed to provide emergency starting power for large PGMs.

For certain combat systems with large pulse loads, energy storage can reduce the need for significant rolling reserve (thereby reducing fuel consumption). In this case, the combat system energy and power demands for the minutes needed to bring additional power generation modules online would dictate the requirements for the ESM.

Energy Storage can also be used to provide level loading with large pulse loads to reduce the maximum installed power generation capacity.

FUTURE WORK

This paper has highlighted a number of areas that need more work to fully define the NGIPS in-zone power distribution system. While many of these items are also listed in the NGIPS Technology Development Roadmap, some are new and should be incorporated in the next revision of the Roadmap. Future work required includes:

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

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

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

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

e. 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.

f. 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.

g. 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.

h. 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.

i. 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.

j. Develop and document a method for aggregating loads for sizing power distribution equipment

k. 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.

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

m. 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.

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

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

CONCLUSIONS

This paper explores evolutions of the NGIPS in-zone power distribution system to meet survivability and quality of service requirements while decreasing cost. These options include different design strategies as well as component development. A number of technical issues are highlighted and require resolution before a standardized in-zone power distribution system can be developed. To address these technical issues, a number of tasks are proposed for accomplishment in the future.

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