Dr. Norbert H. Doerry and Dr. John V. Amy Jr.
Naval Sea Systems Command

# The Road to MVDC

## ABSTRACT

Electric weapons such as the Electromagnetic Railgun and the Laser Weapon System, advanced high power sensors and Electronic Warfare systems will be ready for advanced surface combatant designs in the coming decades. To affordably supply these high power electric loads will likely require an integrated power system. If a surface combatant of less than 10,000 mt is desired, high power density of the electrical generation, distribution, and propulsion equipment will be needed. To achieve these power densities, Medium Voltage DC (MVDC) will likely be required. This paper details the state of MVDC technology and the work necessary to mature MVDC technology sufficiently to support a surface combatant design.

## NOMENCLATURE

| | |
|---|---|
| AC | Alternating Current |
| ADM | Advanced Development Model |
| CRP | Controllable Reversible Pitch |
| DC | Direct Current |
| EDM | Engineering Development Model |
| ESM | Energy Storage Module |
| EMALS | Electromagnetic Aircraft Launch System |
| EMRG | Electromagnetic Railgun |
| ESS | Energy Storage Subsystem |
| HED | Hybrid Electric Drive |
| IEEE | Institute of Electrical and Electronics Engineers |
| IPNC | Integrated Power Node Center |
| LC | Load Center |
| MFM | Multi-Function Monitor |
| MVAC | Medium Voltage AC |
| MVDC | Medium Voltage Direct Current |
| PCM | Power Conversion Module |
| PFN | Pulse Forming Network |
| PGM | Power Generation Module |
| PMM | Propulsion Motor Module |
| QOS | Quality of Service |
| VAC | Volts AC |
| VDC | Volts DC |

## INTRODUCTION

To remain militarily relevant, the warships of tomorrow will require ever evolving weapons and sensors. Many of these weapons and sensors will present large, nonlinear, stochastic, and potentially pulse loads to the power system. With an AC distribution system, these loads would be required to adhere to MIL-STD-1399-300 (low voltage) and MIL-STD-1399-680 (high voltage) interface requirements and would consequently be required to incorporate considerable dedicated power conditioning and energy storage. These dedicated power conditioning and energy storage solutions will present affordability and reliability challenges.

Distributed systems exist on ships to provide a common source for a commodity when economic analysis demonstrates that it is more affordable to centrally generate and distribute the commodity to a given reliability and quality standard than it is to locally generate the commodity for each load. In the past, energy storage was required for only a few loads; local energy storage was more economical. As the need for energy storage continues to increase for many loads throughout the ship, incorporating energy storage into the distributed electric power system will likely prove cost effective.

Migrating the electrical generation and primary distribution system from the traditional 60 Hz systems whose interfaces are described in MIL-STD-1399-300 and MIL-STD-1399-680 to MVDC will enable the use of a power system - load interface standard that will provide the reliability and quality needed by the emerging electric weapons and sensors and reduce the need for local dedicated power conditioning and energy storage. A number of recent accomplishments and ongoing trends indicate that MVDC is the most practical means to support high power electric weapons and sensors from both a power system perspective and a total ship perspective.

This paper provides an overview of an MVDC shipboard architecture based on IEEE 1709, IEEE 1826 and previous efforts documented in Doerry (2008), Doerry and Amy (2008, 2011), NAVSEA (2007) and PMS 320 (2013). This MVDC architecture is used to discuss design factors common to both AC and DC systems as well as those unique to only DC systems. Recent advances in MVDC technologies are detailed followed by a discussion of remaining challenges and future work.

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the Department of the Navy, the Department of Defense, or the U.S. Government.

## MVDC ARCHITECTURE OVERVIEW

IEEE 1826 describes a zonal architecture as depicted in Figure 1. Zonal architectures have been shown to reduce cost and facilitate survivability; zonal architectures have been incorporated in many recent warship designs. A shipboard MVDC representation of the zonal architecture is depicted in Figure 2. In mapping Figure 2 into the IEEE 1826 architecture (Figure 1), the following interpretations are made:

- The MVDC Bus (Thick Blue Line in Figure 2) including segmentation disconnects (In the Bus Nodes of Figure 2) is an External System. The bus nodes in the forward and aft most zones are normally configured to isolate the port and starboard busses from each other.
- Generator sets, otherwise known as Power Generation Modules (PGMs) and MVDC loads (such as Propulsion Motor Modules (PMM) and Electromagnetic Railguns (EMRG)) are “overlay zones” over the zonal ship-service distribution system. Zones are segregable sets of loads and power system components, not necessarily a geographic boundary.
- Ship-Service zones are defined by geographic boundaries based on survivability considerations.
- Not every ship-service zone will have a PGM “overlay zone” within its boundaries.
- Alternate sources for in-zone Integrated Power Node Centers (IPNCs) and Load Centers (LCs) are inter-zone connections. The number of inter-zone connections should be minimized.
- The number of ship-service zones will be determined by ship design considerations. Minimizing cost while maximizing survivability are often the major design objectives in establishing the number of zones.

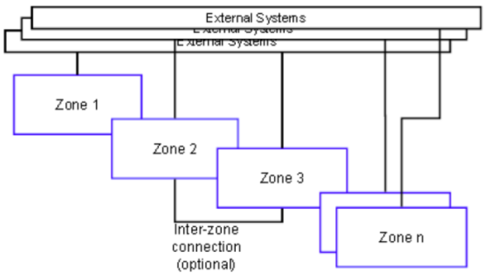


**Figure 1: IEEE 1826 Zonal Architecture**

The Medium Voltage Bus is recommended to operate at 6,000, 12,000 or 18,000 VDC with power quality standards based notionally on IEEE 1709.

.

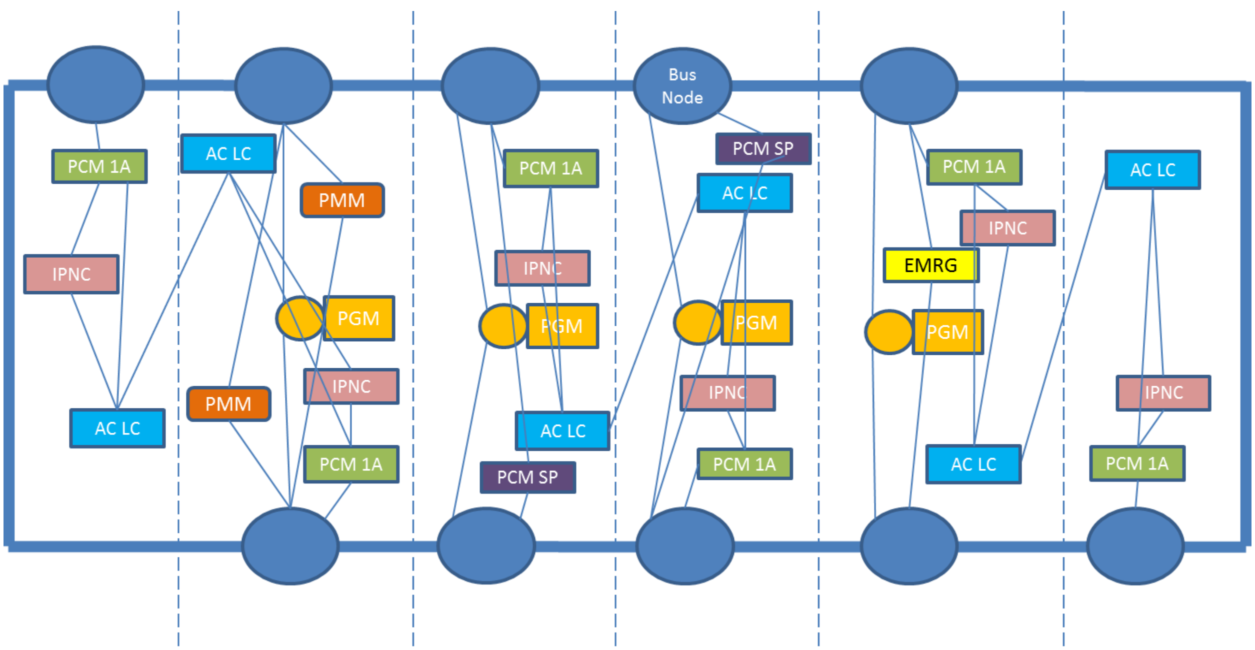


**Figure 2 : MVDC Zonal Architecture**

Figure 3 depicts a notional bus node. A bus node enables segmenting the MVDC Bus to allow multiple bus configurations and to isolate damaged portions of the bus (via the disconnect switches to the “Next Zone” in Figure 3). It can also isolate zones from the MVDC bus. If circuit breaker functionality is provided in the power sources (PGM or Power Conversion Module PCM-1As containing Energy Storage), then the bus node may contain only no-load disconnects. Otherwise circuit breakers capable of interrupting fault current may be required for PGMs and PCM-1As. The bus node may also include functionality for the detection and localization of bus faults; functions currently provided for AC systems by the Multi-Function Monitor (MFM) (Greene 2005). A device to establish the ground reference of the MVDC bus may also be incorporated into the Bus Node.

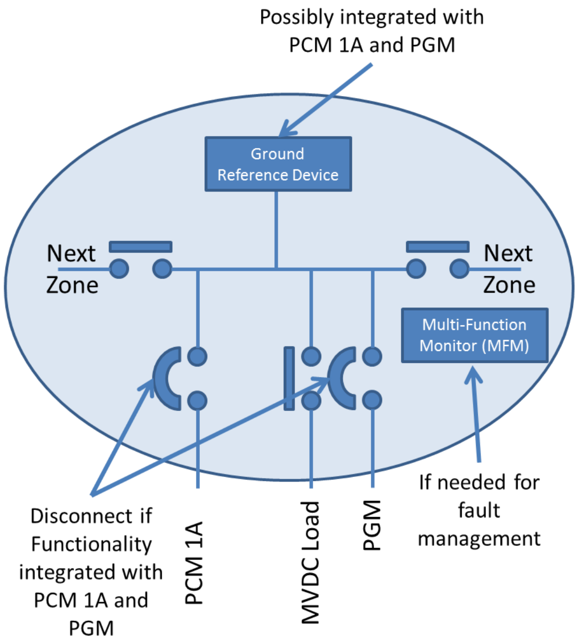


**Figure 3: Bus Node**

Figure 4 depicts the IEEE 1826 in-zone architecture. Many of these elements map to the notional PCM-1A depicted in Figure 5. The mapping includes the following interpretations:

External-to-bus Conversion

The input modules of PCM-1A serve as the external-to-bus conversion. The number of input modules provided is anticipated to be based on the following:

- N-1 modules satisfy max in-zone loads. The additional redundancy ensures power reliability to loads in the event one module becomes in-operative.
- N modules satisfy all vital in-zone and vital adjacent zone loads. In the case that the adjacent zone's PCM-1A becomes inoperative, a single PCM-1A in one zone is able to supply power to vital loads in both zones.

Bi-directional power flow to the MVDC bus enables the Energy Storage Module (ESM) to power the MVDC Bus (Alternately, the ESM may have its own connection to the MVDC bus and the input module may be unidirectional from the bus to the In-Zone Distribution Bus)

Bus-to-internal conversion

The bus-to-internal conversion is implemented via output modules in PCM-1A or solid state Circuit Breaker in PCM-1A. To satisfy 450 VAC loads powered via load centers / power panels, the number of 450 VAC output modules provided is anticipated to be dependent on:

- N-1 modules satisfy all in-zone loads.
- N modules satisfy all vital in-zone and vital adjacent zone loads

In addition to 450 VAC loads, the PCM-1A can power one or more IPNCs and other DC loads (end-user devices).

In-Zone Energy Storage

In-zone energy storage is considered part of the PCM-1A. Physically, the in-zone energy storage may be in a separate cabinet from the remainder of the power electronics. The in-zone ESM is anticipated to interface to internal PCM-1A bus (although it may prove beneficial to have the capability to provide power directly to the MVDC bus). The in-zone ESM should be modular to satisfy both zonal and total ship energy storage requirements.

In-Zone Generation

If present, in-zone generation will likely be low power and intended primarily for emergency use internal to the zone. In-zone power generation interfaces to the internal PCM-1A bus via circuit breaker.

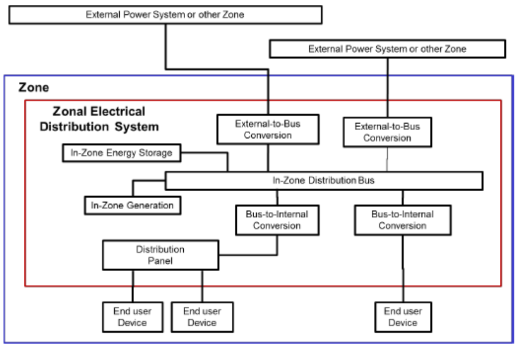


**Figure 4: IEEE 1826 In-Zone Distribution**

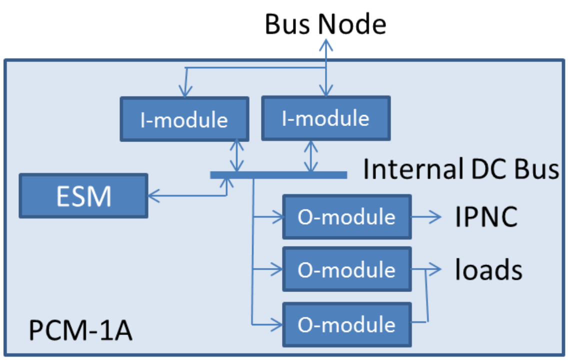


**Figure 5: PCM-1A Notional Architecture**

Figure 6 depicts one implementation of an INPC based on MIL-PRF-32272. The IPNC incorporates power conversion Input and Output Modules to provide dedicated high quality power to specific loads or sets of loads. For the MVDC architecture MIL-PRF-32272 should be modified to incorporate:

- 1000 VDC input modules
- Provision for energy storage for ~1 second

Zones may have multiple IPNCs to supply un-interruptible loads, loads with special power needs, and 400 Hz loads.

The 1000 VDC input module of the IPNC provides the power system designer a choice of using a 1000 VDC or a 450 VAC as the primary interface between the PCM-1A and the IPNC; the choice likely will be based on cost. A second power interface (notionally a 450 VAC interface) would normally be included to enable powering from the the adjacent zone in the event the in-zone PCM-1A becomes inoperative. Using 450 VAC from an adjacent zone may result in the lowest cost solution to provide power to vital loads in both zones should one PCM-1A become inoperative; a dedicated output module in the adjacent zone may not be required.

The energy storage in the IPNC allows 450 VAC Load Centers in zone and in adjacent zone to reconfigure within ~1 second without impacting un-interruptible loads.

**Figure 6: IPNC Example**

The load centers (Figure 7) can employ traditional AC circuit breakers, but must be configured to coordinate properly with a reduced fault current. The 450 VAC output inverters of the PCM-1A will likely current limit at the rated current.

Survivability analysis may indicate that multiple load centers within a zone are required. In this case, "Daisy-chaining" the load centers as shown in Figure 8 may be required to provide power to undamaged loads within a zone that has experienced battle damage (compartment level survivability). Careful routing of feeder cables is required to maximize the probability that the alternate source of power from the adjacent zone survives.

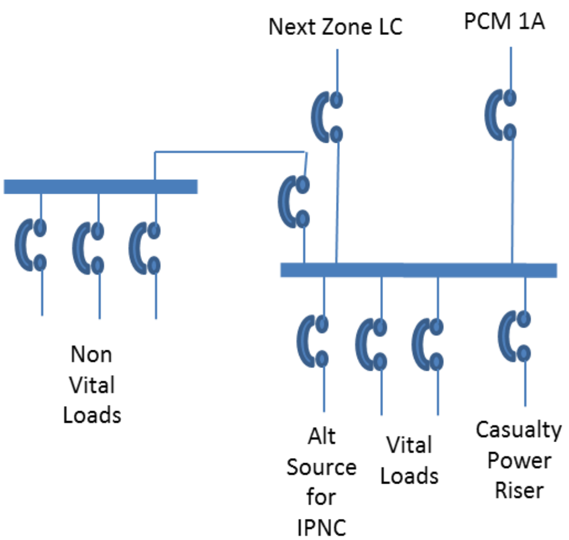


**Figure 7: Notional Load Center Architecture**

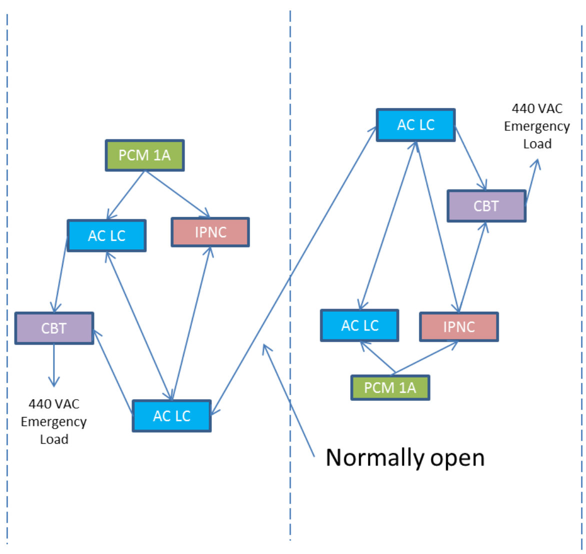


**Figure 8: Compartment Survivability**

Figure 9 depicts a notional architecture for a Power Generation Module (PGM). From an IEEE 1826 perspective, a PGM is its own zone that interacts with the external systems (MVDC buses) via bus nodes. Using a split winding generator and two independent rectifiers enables each PGM to supply power to both busses. This configuration should provide better transient performance during bus faults, and simplifies system integration for power systems incorporating an odd number of PGMs with high power ratings. A cross connect, normally left open, would enable a PGM in the case of a faulted MVDC bus to provide full rated output to a single bus, subject to load-flow limitations.

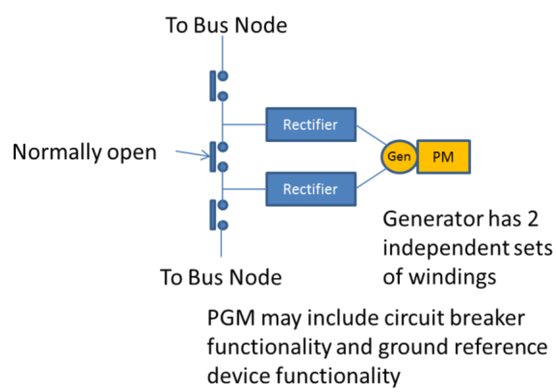


**Figure 9: PGM Notional Architecture**

Figure 10 depicts a notional architecture for a Propulsion Motor Module (PMM). As with the PGM, the PMM is considered its own zone that interacts with the external system (MVDC) via bus nodes. The PMM is anticipated to consist of two independent motors and drives, each normally fed from independent busses. The motors, while independent electrically, may be manufactured as a single unit. A cross connect, normally left open, would enable a PMM in the case of a faulted MVDC bus to be powered from a single bus, subject to load-flow limitations.

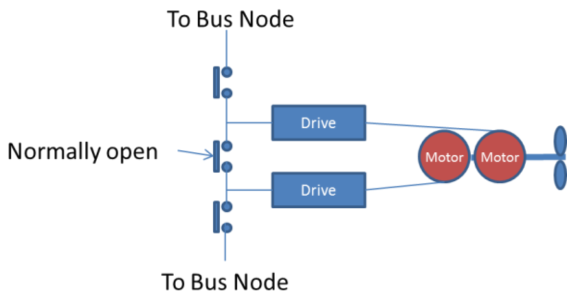


**Figure 10: PMM Notional Architecture**

Figure 11 depicts a notional architecture for an electromagnetic railgun. The PCM-1B is anticipated to have the same general architecture as the PCM-1A, but be capable of power levels greater than 10 MW. Each PCM-1B is normally powered by an independent bus. The PCM-1B includes power conversion to drive the mount (train and elevation motors, loading system, etc.) and the Pulse Forming Networks (PFN). The PCM-1A may also include Energy Storage to provide the capability to power the PFN until sufficient PGMs are brought online to provide the power. The energy storage may also be used to buffer the pulse loading of the MVDC bus during a multiple shot engagement.

Note that this same notional architecture can be applied to existing mechanical ships if 450 VAC or MVAC input modules are incorporated into the PCM-1B. The amount of energy storage provided will likely be higher for a mechanical drive ship because the electrical power capacity is significantly less than for an integrated power system.

To minimize cost, commonality should be promoted for the PCM-1A and the PCM-1B designs.

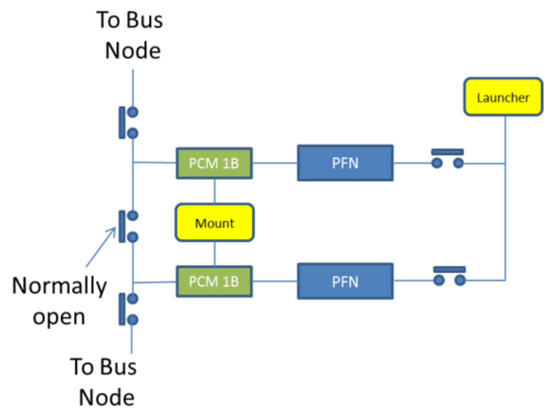


**Figure 11: EMRG Notional Architecture**

## WHY MVDC?

As described in (NAVSEA 2007) the primary reasons for employing an MVDC system include:

a. Prime mover speed is largely decoupled from the power quality of the bus. The generator can be optimized for each type of prime mover without having to incorporate reduction gears or speed increasing gears; generators are not restricted to a given number of poles. The speed can even vary across the power operating range of the prime mover to optimize on efficiency and /or responsiveness.

b. Power conversion equipment can operate at high frequencies resulting in relatively smaller transformers and other electromagnetic devices.

c. Without the skin effect experienced in AC power transmission, the full cross section of a DC conductor is effective in transmission of power. Additionally, power factor does not apply to DC systems. Depending on the voltage selection, cable weights may decrease for a given power level.

d. Power electronics can control fault currents to levels considerably lower than with ac systems employing conventional circuit-breakers. Lower fault currents reduce damage during faults.

e. Since there is not a common frequency of vibrating equipment, the acoustic signature has a broader signature with fewer tonals that can be observed in the acoustic signature of the ship as compared to a ship operating at a constant AC frequency.

f. The paralleling of power sources only requires voltage matching and does not require time critical phase matching. This should enable power generation modules to come on line after starting faster, thereby reducing the aggregate amount of energy storage needed within the PCM 1As to provide power while another Power Generation Module is brought online.

g. Gas turbine engines with a high speed power turbine mated with a high speed generator that produce higher than 60 Hz frequency power are easily accommodated. A combination of high speed power turbines and generators enables a shorter generator set. Shorter generator sets enable shorter machinery space lengths which assist ship designs in meeting floodable length requirements for damaged stability. Enabling the integration of higher speed gas turbines into power systems also provides additional opportunities for competition and potential cost savings. Note that the impact of skin effect on conductor size can be mitigated with minimizing the distance between the generator and rectifier.

h. High power, highly dynamic, demanding electric mission loads (such as EMRG, Lasers, high power radars, and electronic warfare systems) are more easily accommodated with MVDC. Because the speed of the prime mover does not directly affect power quality at the MVDC bus (as is the case with AC systems) the rotational inertia of the generator and power turbine (for multi-spool gas turbines) can be employed as energy storage, minimizing total ship impact of additional energy storage.

## DESIGN IMPLICATIONS FOR ALL POWER SYSTEMS

At present, mission systems installed on U.S. Navy combatant ships are required to conform to the load constraints of MIL-STD 1399 Sections 300 and 680. Here, the discussion focuses on load application / removal rates and pulse loading. If energy storage is required for a mission system to comply with these load constraints, then that energy storage equipment must be included within the mission system’s scope of supply.—Energy storage equipment must count against the mission system’s weight, volume, cost, reliability, maintainability and so on. Today, each mission system brings its own energy storage.

An objective here is for a naval combatant less than 10,000 mt to affordably host advanced sensors, warfare systems and energy weapons. These advanced mission systems possess electric load dynamics which cannot be directly supplied from classic AC power systems. Rather, energy storage is required between the advanced mission systems’ electric load dynamics and a classic AC power system. An example of a system which does such ‘buffering’ is found within the ElectroMagnetic Aircraft Launch System (EMALS) which is presently being tested on CVN 78. The Energy Storage Subsystem (ESS) of EMALS provides maximum launch energies of over 100MJ delivered during a launch lasting several seconds with a peak power on the order of 150MW. Designed to meet demanding mission performance, safety of flight and service life requirements, the ESS does so without exceeding the maximum permitted power per Energy Storage Group of the ESS of ~5MW while meeting MIL-STD 1399 Section 680 load constraints. The ESS weighs on the order of 440LT and occupies on the order of 40,000ft$^3$. The energy stored in the ESS is only available within EMALS; no other system on CVN 78 can access this energy. Accommodating multiple advanced mission systems' load dynamics in a modest-sized surface combatant necessitates a different approach.

There are multiple actions which can be taken with regards to power system design to reduce the weight and volume needed to accommodate multiple advanced mission systems:

- The first action is to use controls (software implementation) to obtain required power system design performance from less hardware capacity than would be needed otherwise.
- The second action is to develop energy storage resources which can be shared by the multiple advanced mission systems (and the ships' power systems) instead of each bringing their own.
- The third action is to develop a power system capable of providing greater energy dynamics than classic AC power systems, a MVDC power system in this case.
- The fourth action is to employ power system components which can fulfill more than one power system function simultaneously, e.g. power converters which also current limit and isolate faults obviating the need for distinct circuit breakers.

***Power Management***

In classic AC power systems, very little is required of power management. In fact, response to changes in load occurs passively. The role of power management is to ensure sufficient online generating capacity, usually a task assigned to Engineering Department watchstanders. What control does exist is focused on sharing load between paralleled generators, adjusting real power output through speed regulation and providing reactive power through voltage regulation. The advantages of the passive load response are that it's simple, does not require an elaborate control system nor even communications with a machinery control system. The chief disadvantages are:

- Speed and voltage regulation and machine inertia limit the load dynamics that can be supplied.
- Operators must maintain the online capacity which they deem prudent.
- Insufficient online capacity is remediated via brute force load shedding.

Doerry and Amy (2008) detail how the role of power management varies situationally. 'Normal' power management functions, as before, to ensure sufficient online capacity, perhaps autonomously. 'Quality of Service' (QOS) power management serves to continue providing power, in accordance with loads' tolerance to interruptions during response to a power system fault or failure. 'Survivability' or 'Mission priority' power management is triggered when power and energy resources, for whatever reason, are insufficient to supply load and meet QOS objectives.

The actions discussed above can be implemented in a phased approach by evolving power management and controls design. Once fully implemented, required performance will likely be achievable with less installed capacity than would be otherwise needed.

In classic U.S. Navy power systems, the loads do not have an interface with power management. This has begun to change. EMALS has an interface with the machinery control system which provides a commanded power limit to EMALS. On DDG 1000 and DDG 51 Hybrid Electric Drive (HED), power for propulsion is subject to power management.

The addition of a power management interface between the power system and larger loads provides another means to match online capacity in the near term with load demand. By being able to command limits to larger loads, the online capacity can be more completely exploited. This addition to the power system design capability does require communications and an additional level of controls for power management. (A reversionary behavior must be invoked by the power system and loads upon loss of communications with power management.) Adding a power management interface for the larger loads is the next step in the phased approach for implementing the first action. Advanced mission systems must be designed to have and to act upon this interface.

A follow-on step in the phased approach is the development of an interface with combat systems controls and, specifically, mission resource planning and, ultimately, mission system cueing. Taking advantage of mission system load elasticity and energy storage/energy management, the objective of Science and Technology and Research and Development would be to develop a real-time forecast and prioritization of mission loads based upon the combat system scheduler. This load forecast, ideally, would expand the operating area for 'Normal' power management while more completely utilizing installed capacities, enabling modest sized generating and energy storage capacities.

### *Energy Storage/Energy Management*

The second action which can be taken with regards to power system design to reduce the weight and volume needed to accommodate multiple advanced mission systems is to develop shared energy storage. Implementing shared power generation (ship service and propulsion share generator sets) on DDG 1000, via the Integrated Power System, resulted in a very modest sized machinery plant for a ~14,500LT ship, ~80MW installed. Compared with the machinery plant of LCS, a ~3500LT ship with ~73MW installed, it's not much larger (although LCS has much higher sustained speed). An "Integrated Energy Storage System" can be similarly pursued.

Doerry and Amy (2011) define the different functions which energy storage can fulfill for a power system. The power system functions assigned to energy storage, energy storage media charge/discharge rates, power capacity, energy capacity, survivability and locations relative to energy storage users, all will determine the weight and volume required for energy storage. These concerns are a strong function of ships' missions and the installed mission equipment.

Different forms of energy storage generate different voltages and currents. It is anticipated that each different form of energy storage will require some form of converter to interface with standard power system interfaces. These converters offer means for control of the energy storage media, fulfilling power system functions and coordination of dynamics with power generation, contributing to the third and fourth actions discussed above.

Implementing shared energy storage brings the necessity for energy management. While some of the functions of energy storage argue to maintain a fully charged state, 'buffering' load dynamics argues for maintaining the ability for energy storage to accept energy. Transitioning from providing to accepting energy can be driven by load/power system dynamics or by commands intended to maintain a nominal state of charge. Here, energy management must be integrated with power management. It must be included in the phased approach towards long-term power management capability. This has not yet been accomplished.

### *System Stability*

With an increasing population of controlled load equipment, steps to develop an actively controlled (vice passive) power system justifiably raise the concern of power system stability. Pursuing the third action, develop a power system capable of providing greater energy dynamics, necessitates tight, high-bandwidth control loops. Affordability argues for adopting a 'direct' approach for designing a stable power system, especially but not exclusively for MVDC power systems. An 'indirect' approach would be to design the power system, then to analyze its stability, redesigning if it's found not to be. A 'direct' approach would be to design the system to be stable in the first place. Stabilizing controls are satisfactory during nominal operation; in reversionary modes, e.g. loss of controls communications, power system behavior must be inherently stable albeit perhaps at reduced performance and / or capacity. A 'direct' power system stability design approach will likely have power system equipment design implications and mission system equipment design implications. These implications could involve assignment of poles and zeros, control loop time scales and bandwidth, specified impedances and/or exchange of system models.

### *Propulsion options*

As detailed by Doerry et al. (2010) mechanical drive naval warships typically employ gas turbine and/or diesel engines mechanically connected to propellers via reduction gears. Gas turbines and some diesels cannot reverse their direction of rotation and have a minimum operating speed. For these prime movers, Controllable Reversible Pitch (CRP) propellers are typically employed to enable slow speed and reverse operation. Twin shafts provide reliability, maneuverability, and some survivability improvements over single shaft designs. In some cases a forward bow thruster is provided to assist in coming alongside a pier and possibly as an auxiliary propulsion system. To improve survivability, the propulsion equipment is separated longitudinally; the shafting can extend over half the length of the ship.

Integrated powers systems (independent of the choice for MVDC or MVAC) expand propulsion options for naval warships. Electric propulsion enables the use of fixed pitch propellers, contra-rotating propellers, and podded propellers. Each of these options improves the propulsor efficiency over traditional twin-screw CRP solutions.

CRP propellers require a larger hub to house the mechanism for adjusting the pitch of the propeller blades. This increased hub size can decrease the efficiency of the propeller by 5 to 10% as compared to a Fixed Pitch Propeller. Propulsion motors are reversible and can operate over their full speed range and can therefore take advantage of the improved fuel efficiency of the Fixed Pitch Propeller.

Contra-rotating propellers improve propeller efficiency by recovering the rotational energy of the forward propeller with the aft propeller. For some ships, contra-rotating propellers have improved efficiency by 5 to 12%. Mechanical drive ships have traditionally not employed contra-rotating propellers because of gear and shafting complexity. Electric propulsion implementation of contra-rotation is much simpler. Since many propulsion motor designs feature two independent motors on the same shaft, dedicating each motor to its own propeller does not add significant complexity. Shaft bearing design and acoustic performance are areas that require engineering attention in designing a contra-rotating system.

Podded propulsion has proven economically advantageous in a number of commercial ship applications. For naval ships a NATO study (2001) concluded that the behavior of a pod in a combat environment (vulnerability, signatures, shock) was not fully known. Podded propulsion enables longitudinally separating propulsors to improve the vulnerability performance.

Podded propellers can improve the flow of water into the propeller and thereby improve fuel efficiency. Additional fuel efficiency is achievable by using a hull mounted shaft and propeller paired with a pod to provide contra-rotation without contra-rotating shafting. Model tests for a high-speed sealift ship showed a hybrid contra-rotating shaft-pod configuration (Figure 12) had the highest propulsion efficiency at the speeds of interest (36 and 39 knots). This configuration showed a reduction of 13.3% required power as compared to a 4 propeller shaft baseline. (Cusanelli and Wilson 2009)

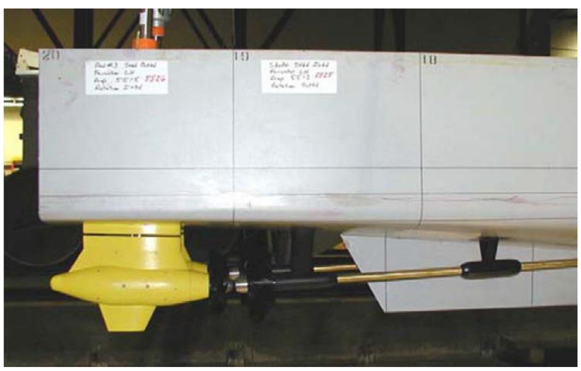

**Figure 12: High Speed Sealift Ship Model (Cusanelli and Wilson 2009)**

# SPECIAL CONSIDERATIONS FOR MVDC SYSTEMS

## *Bus Regulation & Prime Mover Regulation*

In classic AC power systems, real power is regulated through prime mover governor control of speed (frequency regulation). Reactive power is regulated through generators' voltage regulation. DC power systems have no associated frequency to regulate. Paralleling prime mover driven energy sources on a DC bus does not require synchronization and can be accomplished more quickly than in AC systems. Supplying electric power to users can be via a voltage source scheme or a current source scheme. How the Navy procures the power user equipment in ships is more compatible with a power system based upon a voltage source scheme. Hence, until it can be shown that adopting a current source scheme provides financial benefit sufficient to justify changing how power user equipment is procured, a voltage source scheme will be attributed to MVDC power systems. Therefore, bus voltage regulation would be the basis for the control of power. In fact, an important objective along the road to MVDC is to demonstrate, at full-scale, a regulated MVDC bus supplied by at least two dynamically different sources.

In taking the third action to reduce the weight and volume needed to accommodate multiple advanced mission systems, develop a power system capable of providing greater energy dynamics, using an integrated dynamic control to respond to load changes offers an approach for increasing the amount of energy delivered in a short amount of time. Such an 'integrated dynamic' could be powering the regulated MVDC bus using:

1) a gas turbine or diesel driven DC (rectified) generator and

2) 'fast' energy storage.

By supplying a MVDC bus with no frequency regulation requirement, the power control of the prime mover, gas turbine or diesel, is provided with an additional degree of freedom, which can be used to increase dynamic response. Other prime mover developments under consideration could provide additional improvements to the dynamic response of the prime mover itself.

A number of approaches to regulating the MVDC bus are available. One simple approach would be to employ a ‘droop’ response wherein the bus voltage would reflect its per-unit load. An ‘integrated dynamic’ would have the prime mover source respond to longer time scale, ‘average’, load changes and the ‘fast’ energy storage respond to rapid ‘pulse’ load changes. Criteria for assessing the different approaches for regulating the MVDC bus are necessary before selecting one. A ‘droop’ response may be an appropriate reversionary mode when controls communications are not present to provided commanded regulation set points.

### *System Grounding*

Grounding considerations in a MVDC system are analogous to those in MVAC systems. The location of the system ground point is one difference. In a MVAC system, grounding (high impedance or otherwise) associated with the neutral of the generator, or related point, is a logical choice. A corresponding approach for a MVDC system would be to install a resistive mid-point between the two poles. The mid-point could then be grounded (high-impedance or otherwise). Other alternatives with respect to the ground point are to be considered. EMALS has implemented MVDC distribution between the ESS and the inverters which power the launch motors; this MVDC distribution subsystem is ungrounded.

Distributed system capacitance is familiar to shipboard LVAC and MVAC power systems, having been measured; the effect of distributed system capacitance on MVDC power systems is less studied. Guidance for specifying maximum component and system capacitance is still an open research question.

### *Fault Detection, Localization and Isolation*

Baragona et al (2014) provided an excellent example of how power converters within a MVDC power system can fulfill power system functions that had typically been assigned to single function pieces of equipment in the past. This paper argues for the benefit of the fourth action, to employ power system components which can fulfill more than one power system function simultaneously. The different functions that the power converters, which must be present for the system to function at all, are capable of performing are enabled by the available, sensed data which is collected and acted upon by the converters. Fault detection, localization and isolation depends upon sensed data. Power converters at the input/output of energy storage modules and prime mover driven sources, at the input of PCM-1A, at the output of PCM-1A and throughout the mission systems all have available their local data. Additional data can be developed for the power system, if needed, through adaptation of Multi-Function Monitors to MVDC. Reliable methods of fault detection must be developed.

### *Magnetic Signature*

A DC current creates a constant magnetic field which can leave a residual magnetic field in ferrous materials. This residual magnetic field contributes to the overall ship magnetic signature and susceptibility to mines and magnetic influence sensors. The creation of residual magnetic fields can be minimized by physically locating conductors carrying current in opposite directions very close to one another; the magnetic field from one conductor can cancel out the field from the other. Ideally a coaxial power cable would completely eliminate the magnetic field.

One concern will be in the design of terminations and the routing of conductors within power system and load equipment. Creepage and clearance requirements to prevent arc faults will require separation of conductors and locally result in increased magnetic fields. The signature of these fields may be mitigated through magnetic shielding, but with possibly increased weight and cost.

The potential for these residual magnetic fields should be considered in the design of the ship's degaussing system. As an alternative (or in addition) to magnetic shielding, developing and implementing a method for deperming these localized residual magnetic fields should be investigated.

# PROGRESS

Since the dissemination of the 2007 NGIPS Technology Development Roadmap, much work has been focused upon the development of MVDC system technology. The Navy's shipbuilding partners conducted an analysis of MVDC power systems identifying the technical risks of implementation. This analysis informed multiple ONR efforts, including but not limited to research performed by ESRDC. The analysis also provided input to PMS 320 for their efforts.

### *Silicon Carbide Power Electronics*

Development of commercially available, affordable silicon carbide power electronic switching modules greatly enhances the ability of a MVDC power system to meet the challenging dynamic performance requirements and weight and size constraints. The qualities of silicon carbide modules most valuable to this effort are:

1) high switching speeds which increase frequencies internal to converters (from 10s of Hz to 10s of kHz) thereby greatly reducing the size and weight of magnetic and capacitive components

2) lower losses (higher converter efficiencies) which reduce thermal footprints, and

3) higher voltage capability which reduce switching modules required in series for MVDC applications. See McCoy et al. (2007).

ONR projects have successfully demonstrated, at relevant scale, the three qualities described above. Ongoing efforts are pursuing affordability of silicon carbide modules useful to the Navy's power systems needs but also leveraging the commercial market for such modules.

### *Stability Methods*

As discussed in the section above, "SPECIAL CONSIDERATIONS FOR MVDC SYSTEMS", stability and stabilizing controls are going to be a first order consideration in the development and design of MVDC power systems. The work by Sudhoff et al. (2003) is germane. Application of stability techniques applied in the DDG 1000 design represent the starting point; however, the process for 'direct' stability design remains to be developed. Belkhayat et al (2014) describe techniques which will be useful in implementing 'direct' stability design. The impedance measuring equipment also represents a successful application of silicon carbide modules.

### *Specifications and Standards*

The following standards germane to MVDC have been developed:

- IEEE 1662-2008, "IEEE Guide for the Design and Application of Power Electronics in Electrical Power Systems," Approved 10 November 2008.
- IEEE 1709-2010, "IEEE Recommended Practice for 1 to 35 kV Medium Voltage DC Power Systems on Ships," Approved June 2010.
- IEEE 1826-2012, "IEEE Standard for Power Electronics Open System

Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW," Approved 22 June 2012.

The following specification and standard activities related to MVDC are ongoing:

- NAVSEA T9300-AF-PRO-020 Design Practices and Criteria Manual, Electrical Systems for Surface Ships Chapter 300 is being updated to better reflect zonal electrical distribution and integrated power systems. This update is also planned to include power quality requirements for DC distribution systems.
- IEEE P45.1 and P45.3 are under development as part of the overall process to update IEEE 45, "Recommended Practice for Electrical Installations on Shipboard."
- MIL-PRF-32272 IPNC, is being updated and is planned to include input modules for a 1000 VDC interface.
- A new military detail specification for Power Electronic Conversion Equipment, Naval Shipboard.

# REMAINING CHALLENGES

## *Special Studies*

To refine the MVDC system concept and provide the technology basis for establishing specifications and standards, several studies are needed:

- MVDC Systems Architecture: The MVDC Architecture Overview section above described many of the features that an MVDC system is expected to have. A number of issues remain and need to be studied to include: How best to integrate energy storage, standard MVDC voltages and associated power quality, grounding locations, and functional allocation of fault detection, localization and isolation.
- MVDC Fault Detection, Localization and Isolation. While there has been much work done in this area, a clear path to defining the preferred method for allocating functionality for fault detection, localization and isolation to the different MVDC power system components has not been accomplished. This study should recommended requirements for incorporation into specifications and standards.
- MVDC System Stability. A study is needed to define the process for analyzing and specifying design parameter to ensure stable system operation. The study should partition system stability functionality to different MVDC power systems components. This study should recommended requirements for incorporation into specifications and standards.
- MVDC Voltage Regulation and Power Sharing: A study is needed to define the method for regulating the MVDC bus voltage and sharing power among PGMs and PCM-1As (acting as ESM) to keep the bus voltage within power quality requirements, even when subjected to pulse loads. This study should recommended requirements for incorporation into specifications and standards.
- MVDC QOS and Component Reliability: Need research in predicting component reliability for the purpose of calculating QOS mean-time-between-service-interruption. These prediction methods should be validated with experimentation. The results of this analysis should be incorporated into component specifications as part of verification methods.

- MVDC System Grounding: Need a study to determine the best system grounding strategy to employ on naval MVDC systems. The study should partition system grounding functionality to different MVDC power systems components. This study should recommended requirements for incorporation into specifications and standards.
- MVDC Power Management Approach: Need a study to determine the best power management approach to employ on naval MVDC systems. The study should partition power management functionality to different MVDC power systems components. This study should recommended requirements for incorporation into specifications and standards.
- MVDC System Control Strategy: Need a study to determine the MVDC system control strategy. This study should describe the algorithms needed for the system control software, and the general controls concept of operation. It should include Ground Rules & Assumptions, and provide a high level control architecture. The study should be detailed enough to specify a Control System Advanced Development Model.
- MVDC Shore Power Approach: Need a study to determine the best shore power approach(es) to employ on naval MVDC systems. The study should partition shore power functionality to different MVDC power systems components. This study should recommended requirements for incorporation into specifications and standards.
- MVDC Casualty Power Approach: Need a study to determine the best casualty power approach to employ on naval MVDC systems. The study should partition casualty power functionality to different MVDC power systems components. This study should recommended requirements for incorporation into specifications and standards.
- MVDC Maintainability and Reliability Design Approach

### *Specifications and Standards*

Much work remains to codify MVDC design and procurement. In particular, the following specifications and standards work is recommended.

- Update "NAVSEA T9300-AF-PRO-020 Design Practices and Criteria Manual, Electrical Systems for Surface Ships Chapter 300" to reflect MVDC
- Develop MVDC Power Generation Module performance specification
- Develop PCM-1A / PCM-1B performance specification
- Update MIL-PRF-32272 to reflect potentially new DC input module requirements and Energy Storage requirements.
- Develop MVDC cable / bus pipe specifications
- Develop MIL-STD-1399 section(s) for DC interfaces
- Develop interface specification for "Intelligent Load"
- Develop MVDC Propulsion Motor Module performance specification
- Develop MVDC forward propulsor performance specification
- Develop MVDC switchgear performance specifications
- Update the Power Electronic Conversion Equipment, Naval Shipboard detail specification to address MVDC issues.

- Develop a standard, handbook, or incorporate into another standards document, standard methods for fault detection, localization, and isolation in MVDC systems.
- If needed, develop an MVDC ground reference device specification
- If needed, develop a MVDC Multi-Function Monitor specification
- If needed, develop a Controllable Bus Transfer specification
- If needed, develop a MVDC Energy Storage Module specification

### *Development of PCM 1A / 1B*

An Advanced Development Model (ADM) of a reconfigurable PCM-1A / 1B is recommended to identify and solve design and engineering problems. This ADM should be employed to validate / update draft PCM-1A / 1B specifications and reduce the technical risk for an Engineering Development Model (EDM) for the first shipboard application. The ADM does not have to be production representative, but must address known risks. For example, if shock mitigation efforts are considered low risk, then the ADM need not be designed for shock if the design modifications for shock hardening do not impact the other aspects of the design. The ADM should be fully tested to characterize its performance.

### *Development of MVDC PGM*

ADMs of a diesel engine based MVDC PGM and a gas turbine based MVDC PGM are recommended to identify and solve design and engineering problems. These ADMs should be employed to validate / update the draft MVDC PGM specification and reduce the technical risk for an Engineering Development Model (EDM) for the first shipboard application. The ADMs do not have to be production representative, but must address known risks. Maximum re-use of existing test assets is highly recommended. The ADMs should be fully tested to characterize their performance.

### *Development of MVDC Switchgear*

Switchgear suitable for naval MVDC systems are not readily available from industry. Designs for a family of disconnect switches suitable for 6000, 12000, or 18000 VDC with current ratings ranging up to at least 4000 amps (8000 amps would be desirable). Note that since each longitudinal bus can support half the total load, two 6000 VDC, 4000 amp busses can support 48 MW of power transmission; two 6000 VDC, 8000 amp busses or two 12000 VDC, 4000 amp busses, can support 96 MW of power transmission. If fault interruption functionality is not incorporated into PCM-1A / 1B and PGMs, then a family of circuit breakers are also needed. The development must properly balance volume, weight, and cost.

### *Development of MVDC cable / bus pipe*

Insulated bus pipe and superconducting cables offer the opportunity to significantly reduce the volume and weight of the MVDC bus as compared to more traditional cabling. Both alternatives require development to ensure they can be successfully and affordably integrated into a naval power system and perform well in a naval environment. If traditional cables are employed, new cable types suitable for naval MVDC applications must be designed, fabricated and tested.

### *Development of Control Systems*

A good design and implementation of the control software for a MVDC power system is key to success. This software should be designed in a scalable and modular manner using the tenets of open architecture where possible. The control software should at a minimum implement the following functions:

- Voltage regulation and power management (including load management)
- Electric Plant configuration
- Quality of Service Load Shedding
- Mission Priority Load Shedding
- Fault Detection, Localization, and Isolation
- Prevention of cascading faults
- Cybersecurity
- Equipment configuration
- Equipment monitoring
- Condition Based Maintenance
- Tagouts and Maintenance
- Training

The software development process should also include developing realistic use cases for software testing. The software should be designed to minimize required testing, both during initial development and during lifecycle maintenance and development.

### *Development of Design Synthesis and Analysis Tools (including cost)*

MVDC will only be incorporated in future ship design if analysis tools show that it is cost effective to do so. Unfortunately, many of the existing design tools are not sensitive to the potential benefits of MVDC; hence there is a risk that MVDC will not be accurately evaluated for both cost and performance in future ship concept studies and preliminary designs. Hence improving these tools in parallel with maturing the MVDC technology is vital to ensuring a successful transition to a future ship design.

### *MVDC FSAD System Demonstration*

Mitigating a number of technical risks for implementing MVDC on a naval ship will likely require a Full Scale Advanced Development system demonstration. The FSAD system demonstration should be used to validate the design and integration methods for a shipboard system. The equipment employed in the FSAD system demonstration do not have to be production representative, but must address known risks. Following the FSAD systems demonstration, the Navy should have confidence in being able to successfully integrate a MVDC system onboard a naval ship. The MVDC FSAD system demonstration should occur prior to the Analysis of Alternatives for the first ship opportunity.

## CONCLUSION

This paper has shown why MVDC power distribution systems are important to future naval warships which will be equipped with electric weapons and high power sensors. Properly managing both energy and power will be key to affordable power systems with the density required for warships under 10,000 mt. The paper details the anticipated characteristics of a naval MVDC system, highlights the work that has been accomplished to develop such a system, and lists the remaining required work. Only by steadily applying resources to the remaining tasks, will the U.S. Navy be able to affordably integrate MVDC, electric weapons, and high power sensors affordably in a future surface combatant.

## REFERENCES

Baragona, Thomas A., Paul E. Jordan, P.E., Bruce A. Shiffler, "A Breaker-Less, Medium Voltage DC Architecture," presented at ASNE Electric Machines Technology Symposium (EMTS) 2014, May 28-29 Villanova University, Villanova, PA.

Belkhayat, M., B. A. Smith, D. L. Vrtachnik, D. W. Mintz, and J. L. Verhulst, “Validation of a Direct–Quadrature (D-Q) Impedance Measurement Device Through Comparison of Impedance Models with Impedance Measurements”, Presented at ASNE EMTS 2014, Villinova, PA.

Cusanelli, Dominic S., and Michael B. Wilson, "Comparisons between Hullform and Propulsor Combinations for a High-Speed Sealift Ship," presented at the SNAME Annual Meeting, Providence, RI, October 21-23, 2009.

Doerry, CAPT Norbert, USN, "In-Zone Power Distribution for the Next Generation Integrated Power System," Presented at ASNE Advanced Naval Propulsion Symposium 2008, Arlington, VA, Dec 15-16, 2008

Doerry, CAPT Norbert USN and Dr. John Amy, "Functional Decomposition of a Medium Voltage DC Integrated Power System," Presented at the ASNE Shipbuilding in Support of the Global War on Terrorism Conference, Biloxi, MS, April 14-17, 2008

Doerry, Dr. Norbert H. and Dr. John V. Amy Jr., "Implementing Quality of Service in Shipboard Power System Design," Presented at IEEE ESTS 2011, April 11-13, 2011, Alexandria, VA

Doerry, Norbert H., Timothy J. McCoy, and Thomas W. Martin, "Energy and the affordable future fleet," Presented at the 10th International Naval Engineering Conference and Exhibition (INEC 2010), Portsmouth, UK, May 11-13, 2010.

Greene, William C., "Evaluation of Non-Intrusive Monitoring for Condition Based Maintenance Applications on US Navy Propulsion Plants," SMNAME and SMME Thesis, MIT, June 2005.

IEEE 1709-2010, "IEEE Recommended Practice for 1 to 35 kV Medium Voltage DC Power Systems on Ships," Approved June 2010.

IEEE 1826-2012, "IEEE Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW," Approved 22 June 2012.

McCoy, T.J., C.H. Brown, J.V. Amy Jr. and C.F. Krolick. "Implications of silicon-carbide (SiC) technology on all electric ships." AES 2007, Conference Proceedings. London, England. 25-26 September 2007.

NATO NIAG NG6-SG/4,(2001) "Electric Warship Technology, NIAG/SG61 Pre-Feasibility Study," AC141(NG6)D/28, AC141(NG6-SG4)D/15, NIAG-D(2001)5

Naval Sea Systems Command (NAVSEA), " NGIPS Technology Development Roadmap " NAVSEA Ser 05D / 349 of 30 Nov 2007

PMS 320, "Naval Power Systems Technology Development Roadmap," Approved April 29, 2013.

Sudhoff, S.D., S. F. Glover, S. H. Zak, S. D. Pekarek, E. J. Zivi, and D. E. Delisle , "Stability Analysis Methodologies for DC Power Distribution Systems," presented at the 13th International Ship Control Systems Symposium (SCSS) in Orlando, Florida, 7-9 April 2003.

**Dr. Norbert H. Doerry** is the Technical Director of the NAVSEA SEA 05 Technology Office. He retired in 2009 as a Captain in the U.S. Navy with 26 years of commissioned service, 23 years as an Engineering Duty Officer. In his final billet, he served for nearly six years as the Technical Director for Surface Ship Design. Dr Doerry is a 1983 graduate of the United States Naval Academy and a 1991 graduate of MIT. He is the 2008 recipient of the ASNE Gold Medal. He is a fellow of SNAME and a member of ASNE, IEEE and the Naval Institute. He has published over 35 technical papers and technical reports.

**Dr. John V. Amy Jr.**

Dr. John V. Amy Jr., CDR USN (Ret.), Ph.D., P.E. graduated from the U.S. Naval Academy with a B.S. in E.E. in 1983, and served as Anti-Submarine Warfare Officer on *USS Boone* (FFG 28). He then reported to M.I.T. where he earned a S.M. in E.E. & C.S. 1990, a Naval Engineer degree 1990, and a Ph.D. in "naval electric power systems" 1992. An Engineering Duty Officer, he subsequently was Assistant Project Officer for Aircraft Carrier Overhaul at Supervisor of Shipbuilding, Conversion and Repair, USN Newport News, VA. assigned to the refueling complex overhaul of *USS Enterprise* (CVN 65) and its subsequent post-shakedown availability. His next assignment was to the Engineering Directorate at the Naval Sea Systems Command. Initially Assistant Program Manager for Systems Engineering/Ship Integration within the Advanced Surface Machinery Programs, he was subsequently Deputy Program Manager for the Integrated Power Systems Program. Dr. Amy worked next in the program office of the Navy's Future Aircraft Carrier Program. As Deputy Assistant Program Manager for Requirements and Test & Evaluation, he supervised aspects of the technical integration of new electric power technologies into the CVNX design. Dr. Amy was next a member of the M.I.T. faculty, Associate Professor of Naval Construction and Engineering, where, in addition to faculty duties and research, he taught courses covering naval architecture, marine engineering and naval ship design. Following retirement from the Navy, Dr. Amy worked in the Power Systems division at BMT Syntek Technologies for six years and was involved in the power system design of DDG 1000, R&D for the Naval Sea Systems Command and the Office of Naval Research, and developmental design work for DARPA. Dr. Amy next served as Senior Advisor for EMALS Integration into CVN 78 in the Office of the Assistant Secretary of the Navy, Research Development and Acquisition. He presently is the Ships' High Energy Power Systems Director in the Engineering Directorate at the Naval Sea Systems Command.