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MVDC Distribution Systems

ABSTRACT
MVDC is anticipated to enable integrating advanced electric weapons and high power sensors into surface combatants. These advanced high power and pulse systems will be required to counter the evolving capabilities of competitor navies. This paper details certain design considerations for an MVDC distribution system including the electrical power system concept of operations, MVDC bus capacity, cable and bus duct, cable shielding, voltage regulation and bus stability, dual output generators, and creepage and clearance requirements.

INTRODUCTION
The U.S. Navy is beginning a revolution in ship self-defense and area-defense through the development and fielding of high power sensors, high power electronic warfare systems, solid state lasers (SSLs) and electromagnetic railguns (EMRG). These new weapon systems will counter the anti-access / area denial strategies of potential adversaries by:

- Greatly increasing the amount of ordnance each ship can carry
- Achieving a favorable cost exchange ratio (the cost of shooting down a cruise missile / unmanned air vehicle (UAV) is less than the cost of the cruise missile / UAV),
- Enabling our warships to operate where they need to in order to implement distributed lethality.

With stochastic and/or high power ramp rates, these high power and pulse loads present significant challenges to the design and implementation of naval power systems. In traditional AC power system, a considerable amount of energy storage buffering, at great expense, is required to ensure the power system remains both statically and dynamically stable.

On the other hand, Medium Voltage DC (MVDC) power systems promise to support these advanced electric loads with higher power density and more affordably than achievable with AC systems. The advantages and characteristics of an MVDC system as compared to AC systems are detailed by Doerry and Amy (2015A, 2015B, 2015C and 2016).

Figure 1 depicts an MVDC reference architecture from Doerry and Amy (2016) that will serve as the basis for the remainder of this paper. In this diagram, main turbine generators (MTGs) are power generation modules (PGMs) with a large (typically greater than 10 MW) rating while auxiliary turbine generators (ATGs) have a lower rating (typically less than 10 MW). PMMs are propulsion motor modules and consist of the motor drive and propulsion motor. PCM-1As are power conversion modules that convert the MVDC bus voltage (nominally 12 kV) to the type of power required by its loads. PCM-1As can provide multiple outputs at various standard AC and DC. voltages. PCM-1As contain energy storage and are capable of isolating zones from disturbances on the MVDC bus or in other zones. Another term for a PCM-1A is an energy magazine. PCM-1B is functionally equivalent to a PCM-1A, but has a larger power rating and is intended for loads requiring over 10 MW. PCM-SP is a converter for interfacing with shore power. The IPMC is a point-of-use power converter generally conforming to MIL-PRF-32272A but with energy storage.

The reference architecture has the following characteristics as detailed by Doerry and Amy (2016):

a. The MVDC distribution system is normally operated as an independent port and starboard bus.

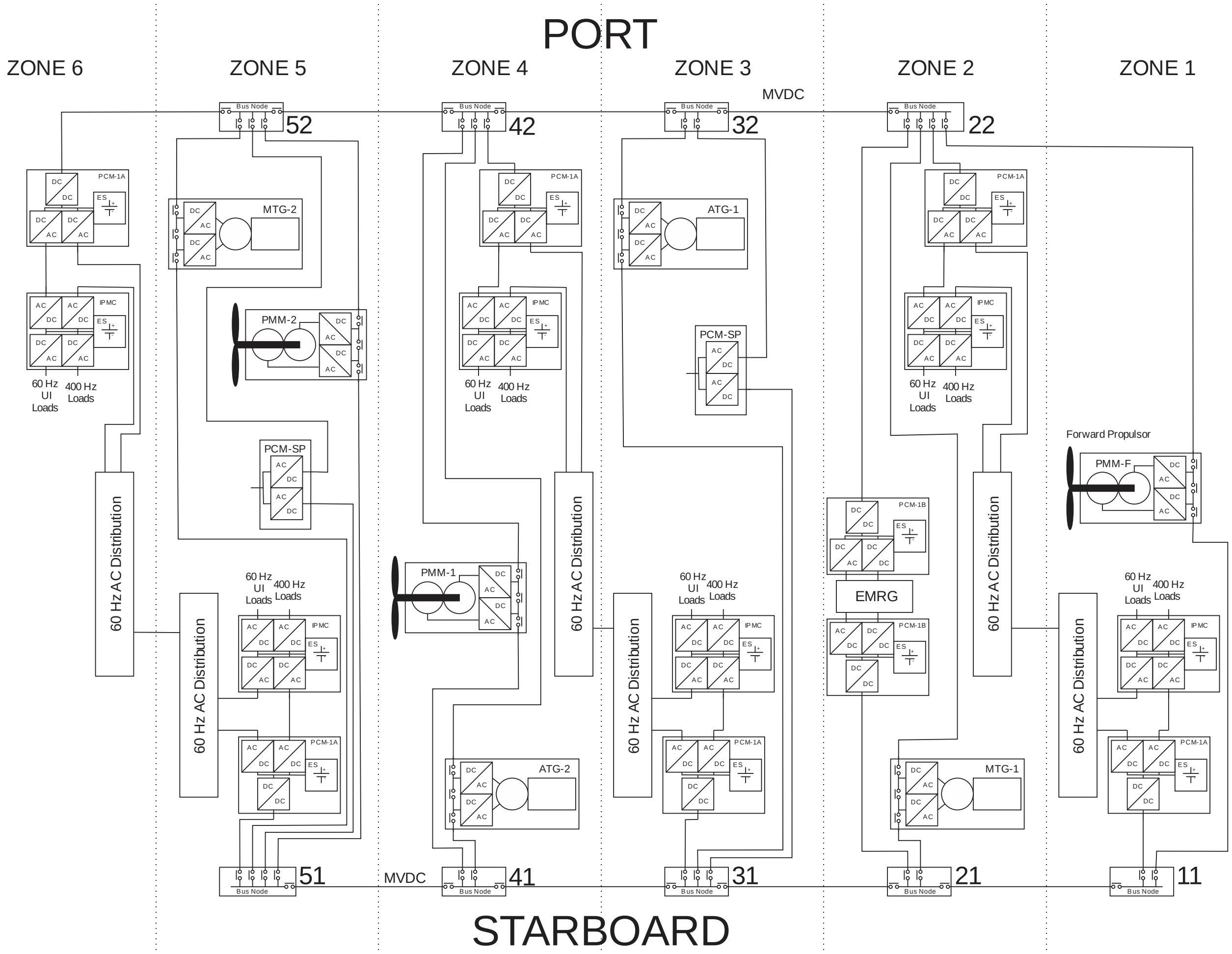

Figure 1: MVDC Reference Architecture

b. Bus nodes are used to configure the buses and connect power system components to the buses. Disconnect switches can interrupt or close only a fraction of their rated current carrying capacity and are used for all loads. If circuit breaker functionality is provided by any power system component acting as a source, disconnect switches may be provided for these source components as well, otherwise circuit breakers are used instead of disconnect switches. Controls within the bus node prevent opening of disconnects carrying current greater than their interruption capability.

c. Power generation modules normally provide power to both buses at the same time. Generators have two sets of windings driving individual rectifiers to power each bus. Each set of windings and each individual rectifier (which can be modular) are rated for half the total rating of the prime mover. By using controlled or active rectifiers, load can be equally shared among online generators.

d. Power generation modules may have a cross connect, which is normally disconnected, to enable providing power to a single bus in response to faults on the other bus. If the cross connect is provided, the feeders from the power generation modules to the bus nodes should be capable of handling the full rating of the power generation module (or of the port and starboard bus if less).

e. PCM-1As power ship service loads, and high power loads rated below 1 MW within a zone. The PCM-1A is normally powered from a single bus. In general, the power drawn from the MVDC buses by all the PCM-1As should be evenly applied to the port and starboard buses. Where possible, PCM-1As in adjacent zones or functionally redundant PCM-1As within a single zone should connect to alternate buses. For each type of in-zone distribution (e.g. 440 VAC), an installed cross-connect between zones or between functionally redundant PCM-1As within a zone (fed from different MVDC buses) is used in case a PCM-1A is unpowered or out of service. The cross-connect is normally not powered.

f. If there are an odd number of zones, one of the zones may have two PCM-1As powered from different buses. Normally this zone would not be an “end zone” and this zone would serve as an alternate source of power for either no other zones or for both adjacent zones (one alternate from each PCM-1A) (never to just one zone). Each of the two PCM-1As is sized to split the zonal load between them, and serve as the alternate for mission critical equipment should one of the PCM-1As not be in-service. Since the middle of the ship often has a considerable amount of loads, consider locating two PCM-1As in one of the middle zones.

Alternately, one zone in the ship (not an “end zone”) may serve as the alternate source of power for the zones forward and aft of it.

g. PCM-1As have energy storage to power loads within the zone. To prevent the PCM-1A from feeding current into an MVDC bus fault, PCM-1As have unidirectional power flow from the MVDC bus. PCM-1As can use their internal energy storage to selectively power the loads within its zone to effectively appear as virtual energy storage on the MVDC bus without actually providing power to the MVDC bus. The PCM-1A energy storage acts as a “negative load” enabling power on the MVDC bus to be redirected from the PCM-1A to another MVDC load (such as a railgun). The amount of current supplied to in-zone loads from the energy storage is based on a droop characteristic of the MVDC bus voltage. If the MVDC bus voltage drops sufficiently, the energy storage completely supplies the in-zone loads it serves.

h. Moderately large loads between roughly 500 kW and 1 MW are powered from an independent and dedicated output stage from a PCM-1A within the zone. An alternate source of power is provided from another independent and dedicated output stage from a different PCM-1A (sourced from the opposite MVDC bus) in the same zone or in an adjacent zone. Roughly the same amount of power from moderately large loads should be assigned to each bus. To balance loads on the port and starboard bus, it may be necessary for the normal supply for a moderately large load to be supplied by the adjacent zone with the alternate feed from the zone the load is in.

i. Large loads above about 1 MW (such as the electromagnetic railgun (EMRG) and propulsion motors) draw power roughly equally from the port and starboard buses. Care must be taken to ensure the port and starboard buses remain independent.

j. For the railgun, a PCM-1B represents the power electronics and energy storage for the interface to the MVDC bus. If an energy storage buffer for large loads is needed, the energy storage may be designed to provide power to the MVDC bus to power other loads and PCM-1As.

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ELECTRICAL POWER SYSTEM CONCEPT OF OPERATION

The MVDC reference architecture depicted in Figure 1 is certainly a very early conceptual electric power system design. Presently, no specific ship-level Concept of Operations (CONOPS) exists; instead, general, less detailed, combatant operating scenarios provide a basis for a very conceptual Electric Power System CONOPS (EPS CONOPS). In addition to there being no ship-level CONOPS, no Electric Plant Load Analysis (EPLA), or list of electric loads, exists. Absent these, though, an EPS CONOPS, as described in the recommended practice IEEE 45.3-2015, can provide insight into MVDC electric power system behaviors.

Operating (Readiness) Conditions – A future combatant ship with an MVDC electric power system may be viewed similarly to ship classes operating today. Its operating conditions may include anchored, berthed pierside, restricted maneuvering, peacetime cruising, wartime cruising (Condition III), general quarters (Condition I), general quarters modified for anti-submarine warfare (Condition IAS), flight quarters and underway replenishment. In the anchored and berthed pierside conditions, typical electric power users are hotel services; propulsion equipment may be kept in a state to rapidly transition to underway conditions. Additionally, maintenance actions, including deactivating and galvanically isolating equipment may be a significant consideration while anchored and berthed pierside. In the restricted maneuvering, flight quarters and underway replenishment conditions, propulsion equipment and safety of navigation equipment may be the mission systems with the highest priority. The peacetime cruising condition may place demands upon equipment, primarily control systems, to achieve energy efficiency. Conditions III, I, and IAS are clearly focused upon the warfighting mission systems equipment and required propulsion.

Operational Scenarios – Here, two operational scenarios provide insight. The first is a nominal scenario; the ship is anchored, transitions to restricted maneuvering, transitions to peacetime cruising, transitions to wartime cruising, transitions to Condition I, reverts to restricted maneuvering, then ends in berthed pierside condition. The second scenario is a restoration scenario; the ship is in a dark ship condition with some stored energy then transitions to peacetime cruising. The two scenarios provide insight into the MVDC electric power system, albeit at a conceptual design level-of-detail.

Ship Speed and Electric Load Estimates – The reference architecture of Figure 1 shows two propulsion motor modules (PMMs) aft and a forward propulsor PMM. The ratings of these PMMs must be capable of propelling the ship to its required speeds, principal among them the transit speed and full speed. The forward propulsor provides forward / aft separation of propulsion capability, thus improving survivability; if steerable, it also can improve maneuverability in the restricted maneuvering condition. The question for the designer of such a ship is what rating for the forward propulsor will meet ship mobility requirements. Here, owing to electric propulsion, the ratings of the three PMMs are driven solely by ship speed requirements, not available prime movers' ratings.

The reference architecture of figure 1 shows four Power Generation Modules (PGMs), two larger MTGs and two smaller ATGs. The relationship between the installed ratings of PGMs and the propulsion electric power demand for the ship's required speed must consider several sometimes competing concerns. First, traditionally the U.S. Navy has required "n+1" redundancy for electric generators in mechanical drive ships bud has not required "n+1" redundancy for propulsion. Because integrated power system and integrated power and energy system designs combine the functionality of electrical power generation for ship service loads and propulsion, the criteria for integrated systems captures the intent of "n+1" redundancy for ship service loads without providing for "n+1" redundancy for propulsion loads. Second, the installed ratings of PGMs, particularly with regards to both the total installed capacity and the difference in ratings of the ATGs and MTGs, must consider the ability to economically match generation to electric load, which is the sum of propulsion electric load and hotel / mission system electric load. Third, having designed integrated energy storage to be available at the system-level of the electric power system, a key feature of the MVDC reference architecture, provides greater flexibility in adjusting 'plant lineups' to match online PGM capacity to the time varying aggregate electric load. Specifically, traditional naval electric power systems had to match online generation to current electric load using either a t2 (generator start time – see IEEE 45.3-2015) response time or load shed; the MVDC reference architecture enables providing electric power changes with a t1 (reconfiguration time – see IEEE 45.3-2015), or faster, response time, a t2 response time, or by affecting changes via control systems to the aggregate electric load.— All three of these can be accomplished autonomously.

Looking at this discussion from the electric propulsion demand perspective, typically electric propulsion load demand varies relatively slowly. For the peacetime cruising condition, the PMM controls should be designed to operate in a mode that presents a constant power draw to the electric power system with its prime movers, for fuel efficiency. Propulsion load demand can vary more rapidly, for example, when the ship is in the underway replenishment condition, in the limiting sea state for such a condition, attempting to maintain constant speed alongside a replenishment ship. In this condition, the PMM controls should be designed to operate in a mode that maintains constant rotational speed despite the stochastic sea state variations; such will cause rapid torque variations in the PMM motors, which lead to current variations from the PMM drives, which in turn lead to sub-t2 propulsion load variations. Here again, the MVDC reference architecture enables providing these electric power changes with a t1, or faster, response time, recognizing that in the underway replenishment condition there will be redundant PGMs online.

Mission System Information - Looking at this discussion from the mission system demand perspective for Conditions I, IAS and III, as the mission systems are brought online with the increased readiness posture, a relatively high "base mission system" demand is likely to be observed with stochastic, rapidly pulsed high energy / high power demands superimposed as the ship engages. The MVDC reference architecture provides these stochastic, rapidly pulsed high energy / high power demands superimposed on a relatively high "base mission system" demand with a t1, or faster, response time, using the PCM 1As and PCM 1Bs with their integrated energy storage. For Conditions I and III conditions, all available PGMs will likely be online. Condition IAS may present quite a different mission system demand. If a low acoustic and / or electromagnetic and / or IR signature(s) is(are) required, all rotating machinery, PGMs notably here, could be secured and the ship powered, for limited time, from the integrated energy storage.

Electric Load Information – Potentially non-compliant loads must interact with power management. The motivation for pursuing MVDC is to provide highly dynamic, pulsed mission system electric loads in the most compact and affordable electric power system possible. The classic approach for the U.S. Navy has been to design the electric power system and the mission systems to subscribe to an electric power interface standard. Compliant mission systems would cause no deleterious effects to the electric power system or its other electric power users. In attempting to supply challenging future mission systems affordably, advanced, active power management techniques, including mission system / machinery control system interactions offer the possibility of extracting the greatest dynamic performance from the electric power systems for a given power capacity or energy storage capacity. These control system interactions may involve negotiated maximum power limits and maximum power 'ramp rate' limits for pulsed loads. These are discussed in Doerry and Amy (2015A, 2015B, 2015C and 2016) and Naval Sea Systems Command (2016).

Electric Power System Machinery Lineups – Taken together, the dual wound generators proposed for PGMs in the MVDC Reference Architecture, the fault detection-localization-isolation functionality proposed for PGM rectifiers / PCM 1As / PCM 1Bs / PMMs, and disconnects within bus nodes, simplify the nominal electric power system machinery lineups to merely identifying which PGMs are supplying power. In operation, MVDC bus reconfigurations would solely be in response to fault isolation. Distinctions such as "ring bus" or "single bus", "islanded mode" or "split bus" have no meaning. All online PGMs would be sharing load via a droop characteristic, obviating the need for PGMs to synchronize. The dual generator windings ensure galvanically distinct port and starboard MVDC buses.

Speed, Ship Service Load and Lineup Curves – Given the very early conceptual electric power system design level of detail, lineup curves with details pertaining to PGM ratings, speed-power relationships and so on are premature. Fundamentally, the lineup curves for an MVDC integrated power and energy system would be very much like those for an MVAC integrated power system ship, like DDG 1000. One difference would be for the condition where all of the PGMs would be taken offline for signature reasons; speed and electric load versus endurance time curves would need to be developed and provided to the crew. Another point about lineup curves, the controls available in the converters that interface directly with the MVDC bus offer the possibility of autonomously generating lineup curves based upon available PGMs.

Nominal Scenario Narrative – The ship is anchored. All of the integrated energy storage, located within PGMs and PCMs, is charged to nominal levels. One of the smaller PGMs is online, this for fuel efficiency and possibly reduced emissions. Its dual windings supplying the distinct port and starboard buses; the integrated energy storage obviates the need for a second online generator. All of the PMMs, including their auxiliary systems, are energized and ready for operation. As the ship sets Sea and Anchor Detail to get underway, additional PGMs, perhaps all, are brought online to ensure redundancy and power continuity to propulsion and navigation during the restricted maneuvering condition. The aggregate electric load is shared, through droop, by all of the online PGMs. Upon reaching open water and securing from Sea and Anchor Detail, the ship transitions to peacetime cruising in consideration of its intended transit speed. Based upon the aggregate electric load – propulsion plus mission / hotel systems, the objective is to supply the aggregate electric load from the PGM(s) with the lowest (combined) specific fuel consumption (SFC) rate. If the aggregate electric load matches the rating of a single PGM which provides the lowest SFC rate, then the integrated energy storage and autonomous controls allow operation on a single PGM; the other PGM(s), required for redundancy during the restricted maneuvering condition can be taken off-line and placed in standby or secured for maintenance. Should a higher transit speed be needed, perhaps the larger PGM would possess the preferred SFC rate; a lower transit speed could mean the smaller PGM would possess the preferred SFC rate. To transition to wartime cruising, with its emphasis on warfighting mission systems equipment and required propulsion, a balance between redundancy with online PGMs and husbanding fuel so as to increase time-on-station / mission endurance must be achieved. The net effect of this balance would be to have additional PGM(s), relative to peacetime cruising, brought online.—That would be the only change in 'plant lineup'. The MVDC bus requires no reconfiguration for these changes in ship's condition. Similarly, when the ship transitions to Condition I, the only change to the 'plant lineup' would be to bring all PGMs online so as to provide the greatest power to mission systems and propulsion and the greatest degree of redundancy and survivability possible to the ship. Securing from general quarters, to revert to the restricted maneuvering condition say, may involve simply securing a PGM, or not. When the ship is in the berthed pierside condition, all of the PGMs may be secured, or placed in standby, while the ship receives shore power. The typical engineering plant portion of the Officer of the Deck (OOD) turnover would simply be to state which PGMs were online, which were in standby and which were not available; no mention of bus configuration is warranted.

Restoration Scenario Narrative – What constitutes a "dark ship" start? Hitherto, a "dark ship" condition has been one where no generators are operating. Diesel and gas turbine generator sets used stored energy in the form of compressed air flasks, or batteries, or small battery-started emergency diesels or gas turbines to start the ship service generators. Except for eschewing air flasks as energy storage in favor of electrical energy storage, the means for starting PGMs in a MVDC electric power system will likely remain electric motors. What will be different with MVDC integrated power and energy systems will be how energy storage is integrated, via controls, into the operation of the MVDC integrated power and energy system and where, physically, the energy storage is located. The energy required to start the PGM prime mover itself, i.e. the electric starting motor, and the energy required for all of the auxiliary systems required for PGM operation, e.g. lubrication, cooling, rectifier, controls, must be directly accessible by the PGM. This comes down to details of the design implementing the MVDC integrated power and energy system. Is the energy storage required for starting located within the PGM? Is dedicated energy storage located proximate to the PGM? Would the PGM use energy storage within a PCM1, or other, associated with the electric zone where the PGM is located to power its start? Certainly to a degree, the ship's survivability requirements and design approach will influence these implementation details.

MVDC BUS CAPACITY

The amperage rating of the port and starboard bus segments (connecting the bus nodes) can have a significant impact on the size, cost and weight of the cables, bus duct, or bus pipe comprising the bus segments and the bus nodes. These bus segments should be able to carry the maximum anticipated current over the ship's service life. If sized too small, the ship must either be subjected to operational limitations, or the bus segments and bus nodes must be upgraded in-service (usually at great expense). The design problem is therefore to determine a reasonable upper-bound on the current that a bus segment will be expected to carry over its service life.

The easiest upper bound is to have the bus segments be capable of handling all the power generated by PGMs (both ATGs and MTGs) on each bus. As an example, using Figure 1 and the arbitrarily assigned ratings of Table 1 for the PGMs, each bus segment would be capable of 37 MW. At a nominal system voltage of 12 kV, this translates into a bus current of 3.1 kA. However, the bus voltage may be less than the nominal. If the lower bound of the draft voltage specification is used (NAVSEA 2016), this voltage could be 0.84 x 12 kV = 10.1 kV. The bus current requirement would then be 3.7 kA. Using 3.7 kA to size the buses and bus nodes would provide a very conservative estimate that would be larger, heavier, and more expensive than what is really needed.

Table 1: Example of PGM Ratings

PGM	Port Bus Rating (MW)	Starboard Bus Rating (MW)	PGM Rating (MW)
MTG-1	16.5	16.5	33
ATG-1	2	2	4
ATG-2	2	2	4
MTG-2	16.5	16.5	33
Total	**37**	**37**	**74**

The first refinement to this estimate can be made by observing that the PGMs are distributed along the ship. The maximum power that a cable could carry would be the larger of the sum of the PGM ratings on either end of the cable. Table 2 shows the reduction in bus segment ratings that are possible when taking account of the longitudinal distribution of the PGMs. In the center of the ship, the maximum anticipated current is half of the previous estimate.

Table 2: Example cable maximum current accounting for PGM longitudinal distribution

Bus Segment (bus node – bus node)	Generation Forward (MW)	Generation Aft (MW)	Max Current (kA) at 10.1 kV
11-21	0	37	3.7
21-31	16.5	20.5	2.0
31-41	18.5	18.5	1.8
41-51	20.5	16.5	2.0
22-32	16.5	20.5	2.0
32-42	18.5	18.5	1.8
42-52	20.5	16.5	2.0

Note that in Table 2, the forward most and aft most bus segments have the largest maximum current, even though the loads in these zones will likely never require this amount of current. These estimates can be further refined by accounting for the distribution of both PGMs and loads using the limiting load flow method described by Doerry and Amy (2016).

Table 3 provides arbitrary power values to each of the loads of Figure 1. The power levels should represent the maximum expected power for each load. For the PCM-1As this would be the load aggregation used to determine the rating of the PCM-1A (including margin and service life allowance). The highest load predicted by the zonal load analysis method of T9070-A3-DPC-010/310-1 (NAVSEA 2012) is an example of one way of aggregating zonal loads. Note that these loads are intended to provide upper bounds for the bus segment ratings and generally are not required to be consistent as would be required for a whole ship electric power load analysis. By using the worst-case loads, one does not need to consider the details of how the ship will be operated. In many cases, these rules will not have been determined in early stage design to assist in estimating the required bus segment capacities. The results of the limiting load flow analysis are shown in Table 4. Note that for many of the bus segments, the required current rating is about half of the original estimate based on total generation capacity alone. The required rating for the bus segment between bus nodes 11 and 21 is less than 10% of the value estimated using generation capacity alone.

The current rating of cable, bus duct, bus pipe, switchgear, and other segments of the bus typically are available in discrete sizes. Hence the actual installed capacity will be the required maximum current rounded up by an integral multiple of the current rating of each paralleled component or the next component rating. For example, if four conductor cables are used, and each cable is rated for 750 amps, then all but one bus segment would require three cables (2.25 kA total), and the remaining one (between bus nodes 11 and 21) would require only one.

Table 3: Example maximum load power

Load	Bus Node	Power (MW)
PMM-F	11	1.5
PMM-F	22	1.5
PMM-1	41	17.5
PMM-1	42	17.5
PMM-2	51	17.5
PMM-2	52	17.5
EMRG	21	9
EMRG	22	9
PCM-1A Zone 1	11	0.5
PCM-1A Zone 2	22	0.6
PCM-1A Zone 3	31	1.7
PCM-1A Zone 4	42	0.4
PCM-1A Zone 5	51	0.3
PCM-1A Zone 6	52	1.0

Table 4: Example limiting load flow

Bus Segment (bus node – bus node)	Limiting Load Flow (MW)	Current (kA) at 10.1 kV for Limiting Load Flow
11-21	2	0.2
21-31	16.5	1.6
31-41	18.5	1.8
41-51	17.8	1.8
22-32	16.5	1.6
32-42	18.5	1.8
42-52	18.5	1.8

As more is known about the equipment and concept of operations of the ship, a more detailed load flow analysis can be conducted for each operating condition and equipment line-up as well as for special conditions. A more detailed analysis may also be required to ensure the bus segments are sufficiently sized to accommodate emergency situations where one or more bus segments are out of service. The manner in which these survivability analyses are conducted and their impact on bus segment required ratings will depend on how the survivability requirements are defined.

CABLE AND BUS DUCT

Within an MVDC power distribution system, several factors need to be considered with respect to the choice of the type of conductors to use. Cables can be used with 1, 2 or 4 conductors per cable, bus pipe with 1 conductor, or bus duct with 2 conductors may be employed. Because most medium voltage applications are 3 phase AC, the commercial availability of 2 and 4 conductor cables or bus duct for MVDC applications is limited. The type of conductors used in the distribution system of an MVDC system can have a measurable impact on the magnetic signature of the ship. As explained by Holmes (2008) a ship's steel hull does not appreciably shield magnetic fields below about 10 Hz. As such, the conductor geometry should be chosen to control magnetic fields. Furthermore, the magnetic fields from the distribution system can result in the ship structure becoming permanently magnetized in a phenomenon called residual magnetism. The relationship of a materials magnetic flux density (*B*) measured in teslas to the magnetic field strength (*H*) measured in Amp-turns/meter is typically depicted in a *B-H* curve as shown in Figure 2. Magnetic material *B-H* curves exhibit a hysteresis characteristic; residual magnetism B_R, is the value for *B* when *H* is zero. Residual magnetism can also result from the ship's motion through the Earth's magnetic field. Degaussing and deperming are traditional methods for controlling residual magnetism due to the Earth's magnetic field. Hence if the magnetic field in the ship's structure resulting from the ship's power system can be kept below that of the Earth's magnetic field (between 25 and 65 microteslas) the traditional degaussing and deperming approaches should be sufficient in future ship designs.

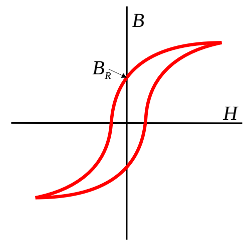

Figure 2: B-H Curve with hysteresis for magnetic material

Figure 3 depicts three configurations for MVDC bus conductors. Configuration (a) would be typical for a four conductor cable. Configuration (b) is possible with single conductor cable, two conductor cable, single conductor bus pipe, or two conductor bus duct. Configuration (c) is simply two sets of configuration (b) conductors. In these figures, the current in the odd number conductors flow in the opposite direction as the current in the even number conductors.

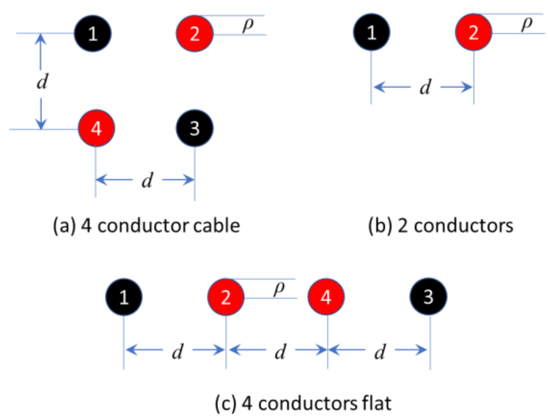

Figure 3: Conductor configurations

The magnetic signature from a bus can be calculated using equation (1). Figure 4 presents the magnitude of the magnetic field as a fraction of the Earth's magnetic field (using 25 microtesla) for a 4000 amp bus. Note that the magnetic field is directly proportional to the current, so the curve for a bus carrying less (or more) current will be proportional. This figure clearly demonstrates the superiority of 4 conductor configurations over the 2 conductor configuration. While the field from the 2 conductor configuration is still small, it is likely still detectable. The field from the 4 conductor configurations are roughly two orders of magnitude less.

Figure 5 clearly shows the importance of minimizing the separation of conductors. Insulation requirements, and the need for the free flow of air for thermal management will provide a lower limit for this separation distance.

Figure 6 shows that as expected, the magnetic field drops the further one is away from the bus.

$$B_i = \frac{\mu_0 I_i}{2\pi\sqrt{(x-x_i)^2+(y-y_i)^2}} \qquad (1)$$

Where

B_i is the magnetic field from conductor i at (x, y) (teslas)
$\mu_0 = 4\pi\times10^{-7}$ H/m = permeability of free space
(x_i, y_i) are the coordinates of conductor i.
I_i is the current in conductor i.

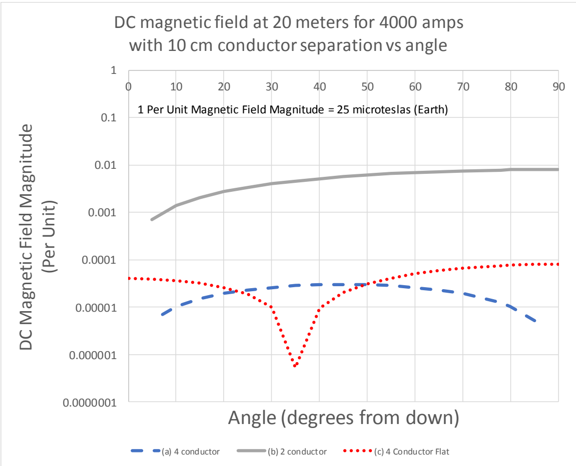

Figure 4: DC Magnetic field magnitude as a function of angle

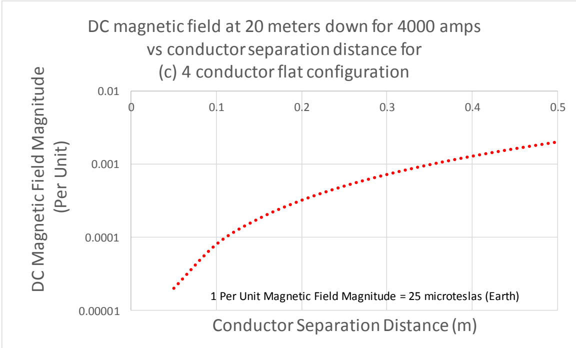

Figure 5: Impact of separation distance on magnetic field

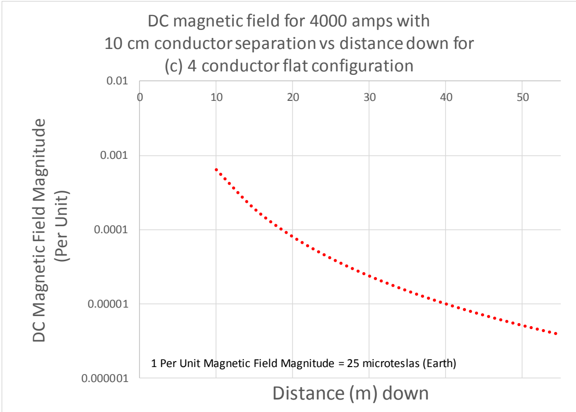

Figure 6: Impact of Distance on Magnetic Field

While the above discussion was focused on the ship's magnetic signature due to the current in the MVDC Bus, the impact of the MVDC bus on residual magnetism of the ship structure must also be considered.

While a 2000 amp bus pipe is commercially available, its magnetic signature in a 4 conductor flat configuration (configuration (c)) is on the order of the Earth's magnetic field for up to 0.7 meters away as shown in Figure 7. This may have negative impact on arrangements. Increasing the number of conductors (thereby decreasing the current per conductor) or decreasing the conductor separation distance should be further explored.

Single conductor cables will likely be limited to less than 1000 amps based on bend radius requirements. Hence multiple sets of cables will be required which should reduce the magnetic field in ship structure to below the Earth's magnetic field in less than 0.5 meters.

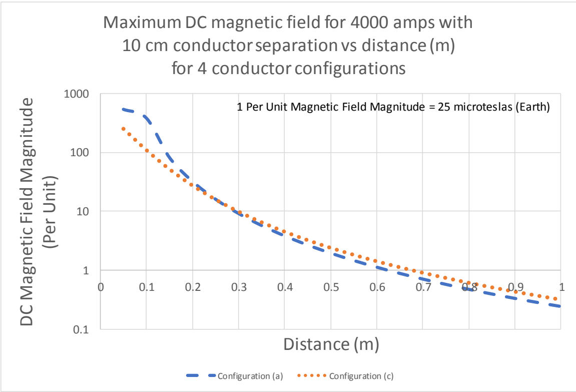

Figure 7: Impact of nearby distances on Magnetic Fields of 4 conductor bus pipe (2000 amp each)

Because of bend-radius concerns, a four conductor cable capable of 4000 amps is likely not achievable. More likely, each conductor will be limited to an ampacity on the order of 375 amps, or a total of 750 amps per cable. Multiple cables would be paralleled to achieve the bus rating. Multiple cables will not result in a ship's magnetic signature being higher than the maximum indicated in Figure 4. Figure 8 demonstrates that if the cable can be kept more than 0.3 meters from structure, the structures residual magnetism should be dominated by the Earth's magnet field and not the cable. The cable trays, cable ties, bulkhead penetrations, and deck penetrations may be subject to fields considerably higher than the Earth's magnetic field. More analysis is required to understand what should be done, if anything, in these areas. Non-magnetic material cable trays (such as stainless steel or composites) may be beneficial.

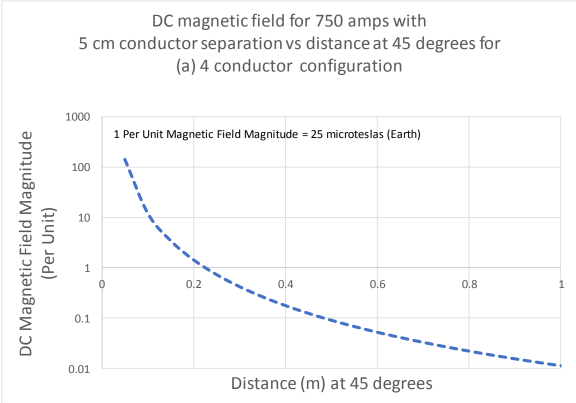

Figure 8: Impact of nearby distances on Magnetic Fields of 4 conductor cable (configuration (a))

In the electrical analysis of an MVDC system, inductance properties of the MVDC bus are needed to understand bus dynamics, particularly during faults and transients. While the actual inductance will be a function of bus geometry and interactions with ship structure, an approximation for bus inductance can be made based on the assumptions of a long straight wire in free space using the method described by Overbye and Baldick (2010). As greater detail of the bus topology is known, more exact methods should be used to approximate the bus inductance (and capacitance).

The partial self inductance L_S (per unit length) of a long straight wire of radius ρ in free space is given by:

$$L_S \approx \frac{\mu_0}{2\pi} \ln \frac{R}{r}$$

Where R is the distance from the conductor (Note that the total inductance has no meaning without a return path)

$$r = \rho e^{-\frac{\mu_r}{4}}$$

For $\mu_r = 1$ (assume permeability of insulators is the same as free space):

$$r \approx 0.78\rho$$

Similarly the partial mutual inductance M (per unit length) between two long parallel conductors d apart is given by

$$M \approx \frac{\mu_0}{2\pi} \ln \frac{R}{d}$$

Note: these equations assume the conductors are much longer than the other dimensions.

For a bundle of conductors, the flux for a given conductor is given by the sum of the flux contributions by all the conductors (either self inductance or mutual inductance). Assuming a very large R that is essentially the same for all the conductors the flux for conductor 1 of configuration (a) is given by:

$$\lambda_1 = \frac{\mu_0}{2\pi}\left[i_1 \ln \frac{R}{r} + i_2 \ln \frac{R}{d} + i_3 \ln \frac{R}{d\sqrt{2}} + i_4 \ln \frac{R}{d}\right]$$

$$\lambda_1 = \frac{\mu_0}{2\pi}\left[i_1 \ln \frac{1}{r} + i_2 \ln \frac{1}{d} + i_3 \ln \frac{1}{d\sqrt{2}} + i_4 \ln \frac{1}{d}\right] + \frac{\mu_0}{2\pi}[i_1 \ln R + i_2 \ln R + i_3 \ln R + i_4 \ln R]$$

Since for the differential mode currents: $i_1 + i_2 + i_3 + i_4 = 0$, the second term is zero:

Hence:

$$\lambda_1 = \frac{\mu_0}{2\pi}\left[i_1 \ln \frac{1}{r} + i_2 \ln \frac{1}{d} + i_3 \ln \frac{1}{d\sqrt{2}} + i_4 \ln \frac{1}{d}\right]$$

now the currents are all assumed equal, but for the differential mode currents, the even ones are negative ....

$$\lambda_1 = \frac{\mu_0}{2\pi} i_1 \left[\ln \frac{1}{r} - \ln \frac{1}{d} + \ln \frac{1}{d\sqrt{2}} - \ln \frac{1}{d}\right]$$

$$\lambda_1 = \frac{\mu_0}{2\pi} i_1 \left[\ln \frac{d}{r\sqrt{2}}\right]$$

Hence the inductance of conductor 1 is

$$\lambda_1 = L_1 i_1$$

$$L_1 = \frac{\mu_0}{2\pi}\left[\ln \frac{d}{r\sqrt{2}}\right]$$

Since two conductors are in parallel for each phase, the inductance for each phase is half

$$L_{config\_a} = \frac{\mu_0}{4\pi}\left[\ln \frac{d}{r\sqrt{2}}\right]$$

Compare this to the equation for the phase inductance for 2 conductors (configuration (b)) and 4 conductors (configuration (c)):

$$L_{config\_b} = \frac{\mu_0}{2\pi}\left[\ln \frac{d}{r}\right]$$

$$L_{config\_c\_odd} = \frac{\mu_0}{4\pi}\left[\ln \frac{2d}{3r}\right]$$

$$L_{config\_c\_even} = \frac{\mu_0}{4\pi}\left[\ln \frac{2d}{r}\right]$$

Note that the inductances of the even numbered conductors is not the same as for the odd numbered conductors for configuration (c).

See Figure 9 for a comparison of the calculated 2 conductor and 4 conductor cable inductance per phase.

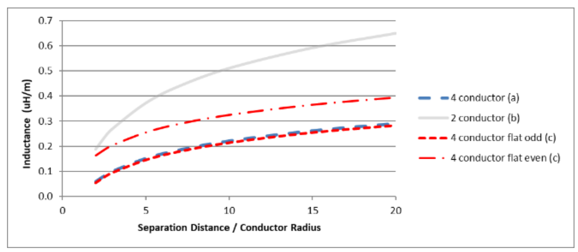

Figure 9: Phase inductance of 2 conductor and 4 conductor cable

CABLE SHIELDING

A cable shield is typically a conductive layer of copper composed of either braided strands or tape. This shield can be used to either reduce electromagnetic radiation, or to control electrostatic fields. Normally, each conductor in a cable will have an individual shield, and the overall cable will have a shield that is insulated from the conductor shields. (Figure 10) How to properly terminate these shields at connection points has been the subject of considerable discussion.

In discussions with shipyard engineers, academia, and warfare center personnel, there is a general agreement (but not universal) that the shields of each individual conductor should only be connected to "ground" (the ship's hull) on one end. Keeping this shield at a uniform ground potential helps ensure the electrostatic fields have a constant gradient from the energized conductor to the shield and the electrostatic field will not exceed the dielectric strength of the insulator anywhere inside the cable. While capacitive coupling of the conductor to the conductor shield will cause high frequency currents to flow through the shield, the relatively short length of shipboard cables should not result in shield voltages exceeding limits for safety (typically around 40 volts).

The overall cable shield should be grounded at both ends. Because the separation distance between the shield and the conductors is likely to be considerably less than between the conductors and the current path through the structure, the inductance of the path through the conductors and shield is likely less than the path through the conductors and ship's structure. Consequently, most of the AC common mode current through the cable will likely use the overall cable shield as a return path instead of the ship's structure. To a certain degree, the magnetic field of the shield will counter the magnetic field of the common mode current, thereby limiting the magnetic signature of the cable as well as reducing Electromagnetic Interference.

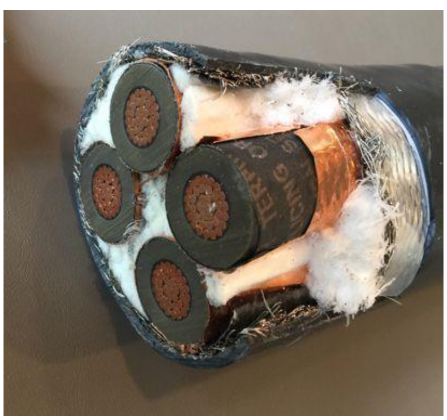

Figure 10: Four conductor cable (15 kV) with conductor shield and overall shield

In general, the common mode current in a feeder cable or bus should be less than about 10 amps to ensure safe operation. To account for unusual situations, the overall cable shield should be able to carry on the order of 15 amps when the cable conductors have a current equal to their current rating.

VOLTAGE REGULATION AND BUS STABILITY

Doerry and Amy (2016) describe a droop based method for regulating the system voltage in a manner that automatically brings energy storage online when needed. This method does not rely on communicating control signals among sources of power while still enabling a distributed approach to regulating system voltage. While the draft MVDC interface standard (NAVSEA 2016) is consistent with this approach, it does not specify this method of bus voltage regulation; other possible methods may also be employed.

For the MVDC system to be stable, the following three conditions must hold:

- A satisfactory steady state solution must exist. The solution is satisfactory if power quality requirements are met. The voltage regulation method is the means for achieving the satisfactory steady-state solution.
- The system when operating at the steady state solution must be small-signal stable. (also called static stability or linear stability)
- The system must be dynamically stable. For dynamic stability to exist, system must behave such that when the system has an initial condition that is far from the steady state solution, the system must converge to the state steady solution while meeting transient power quality requirements and not damaging equipment. (also called large-signal stability)

In the MVDC reference architecture of Figure 1, all the loads are controlled by power electronics (PCM-1A, PCM-1B/EMRG, and PMMs). Normally these loads would behave as constant power loads (CPLs) with negative incremental resistance. Doerry and Amy (2016) discuss potential methods for addressing the small signal stability of a system with CPLs through the PGM controls.

Another approach is to have the fast dynamics of the load controls behave as a positive incremental resistance, and achieve a constant power characteristic via slower dynamics as depicted in Figure 11. Missing from this figure are control elements to implement droop characteristics should the MVDC bus voltage drop because of insufficient PGM capacity online. While Figure 11 applies to PCM-1A, a similar strategy can be employed for PCM-1B/EMRG and the PMMs.

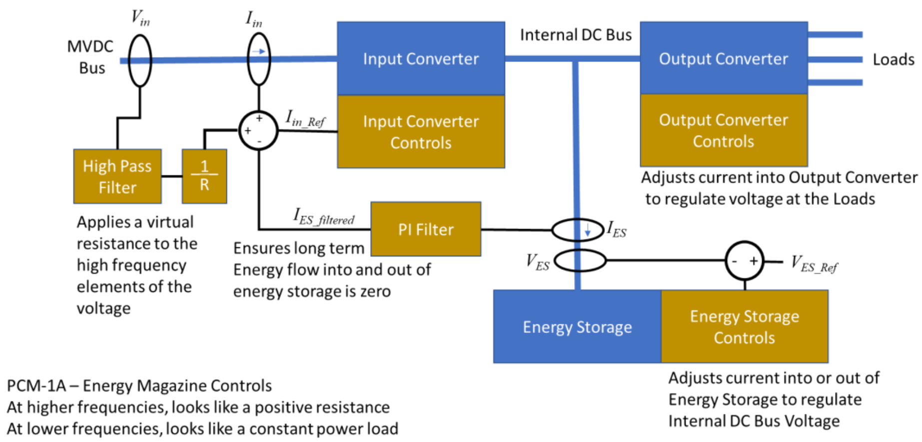

Figure 11: Control Strategy for PCM-1A to facilitate small signal stability (under normal operation)

Still another approach to small signal stability is offered by Adam Mills (2017) who suggests that an adaptive, multi-rate linear-quadratic regulator (LQR) system controller offers the benefit of requiring less system capacitance for small-signal stable performance as compared to more traditional approaches.

Nonlinear methods may be required for dynamic stability. To achieve dynamic stability, the dynamic flow of energy into and out of the multiple intentional and parasitic energy storage elements of the system must be considered. Too much (or too little) energy stored in one element can lead to violations of transient power quality requirements.

Robinett and Wilson (2012) propose focusing on exergy instead of the energy of a system by using Hamiltonian methods. Since energy can be neither created nor destroyed, the total energy of a closed system remains constant. However, not all of a system's energy is available to accomplish useful work. Exergy is the portion of a system's energy that is available to be used. In contrast to energy, exergy is destroyed during an irreversible process. The Hamiltonian is a measure of stored exergy.

Hamiltonian methods have been proposed for controlling terrestrial microgrids with a large fraction of renewable generation (wind or photovoltaic). See for example, Weaver et al. (2015) or Wilson et al. (2012). In general, the power produced by these renewable generation elements are determined by the environment and are largely stochastically independent from the load. Energy storage must be appropriately controlled to balance generation and loads. Shipboard systems have an analogous challenge, except it is the loads, particularly large pulse loads, that are stochastic.

In examining the different control methods, one system trade-off becomes apparent. If a cyber-secure, survivable, and high bandwidth control system network exists, then the control methods proposed by Mills and by Robinett and Wilson should reduce the requirement for energy storage onboard the ship. Less energy storage should be less costly, lighter, and take up less volume -- all good attributes.

However, the Navy has historically desired the ability to for its power system to operate during outages of the control network. This intolerance for dependency on control networks is not absolute, the Navy has accepted cross-compensation hard wired connections between voltage regulators and speed governors to enable parallel operation of multiple AC generators at a constant voltage and frequency. Similarly, the multi-function-monitors used to coordinate circuit breakers in AC zonal systems also use dedicated hard wire connections to communicate fault information.

Hence the ability to deploy many of these advanced control algorithms will depend on the survivability and reliability of the control systems they reside in.

DUAL OUTPUT GENERATORS

The MVDC reference architecture depicted in Figure 1 includes PGMs that have two independent outputs simultaneously powering the port and starboard buses. While it would be possible to mount two physical generators on a single shaft to independently power the two buses, the solution most likely to be cost effective and power dense is to use a single generator with two sets of stator windings. Each set of stator windings would have a dedicated rectifier connected to the MVDC bus.

With a dual stator winding generator, simple passive rectifiers alone will not be sufficient to implement controlled power sharing of paralleled PGMs on both buses. The passive rectifiers do not provide an independent means of controlling their output voltages and therefore cannot implement a voltage regulation method such as droop. An additional power conversion device would be required to provide this independent controllability.

Alternately, a controlled rectifier (typically employing silicon controlled rectifiers) or an active rectifier (such as a modular multilevel converter) can be used to convert the AC power from the generator to the DC voltage needed to independently implement power sharing on each of the two buses.

While the two outputs of the PGM must be independently controllable and must be galvanically isolated from each other, the two outputs are still coupled electromagnetically through the mutual inductance of the stator windings and sharing of the same field, and electromechanically through the generator rotational speed. Early investigations by Rashkin et al. (2017) reveal that the coupling between the stator windings is important over short timescales, while the electromechanical coupling is relevant over longer time scales. While this work employed permanent magnet generators and passive rectifiers, the transients experienced on one bus due to faults or disturbances on the other bus appear to be within the capability of a controlled or active rectifier to regulate. Further work is needed to verify this assertion.

With two outputs, it is not obvious as to the best way to control the excitation current in a wound-rotor synchronous machine. With one output, the field excitation current is adjusted by the voltage regulator to regulate the voltage at the one output. With two outputs, it is not obvious which voltage to use, or how to combine the voltages, to provide an input to the voltage regulator. This is particularly important if one of the buses is faulted. It may be better to directly regulate the flux with a flux regulator rather than employ a voltage regulator. The controlled / active rectifier will then regulate the output voltage. Further work is needed to better understand the proper design of the field excitation controls as well as the controls for the rectifiers.

CREEPAGE AND CLEARANCE

Validated creepage distance and clearance distance guidance for shipboard MVDC system equipment do not exist at this time. As defined in MIL-DTL-917F (NAVSEA 2014):

"Creepage distance along the surface of an insulating material is the shortest distance between uninsulated energized parts or between an uninsulated energized part and ground."

"Clearance distance is the shortest point-to-point distance in air between uninsulated energized parts or between an uninsulated energized part and ground."

One way to address the lack of guidance for creepage and clearance is to insulate all energized parts. If an energized part is insulated, creepage and clearance does not apply. This may not be always possible, so guidance would be useful.

Clearance is related to the dielectric strength of air which is about 3 kV/mm (or 0.33 mm/kV). However this figure should not be used directly because of the impact of humidity, contamination, voltage spikes, and non-uniform electric fields. Based on experience with AC systems, safety factors on the order of 20 to 45 are typically applied in the guidance provided by classification societies and standards. (higher voltages typically have a lower safety factor)

Until actual experiments are conducted to characterize the shipboard environment for MVDC applications, the authors recommend the following clearance guidance which is generally consistent with existing guidance for AC systems where AC peak voltages correspond to the DC voltages:

6 kV	72 mm
12 kV	112 mm
18 kV	153 mm

Creepage requirements are intended to protect equipment primarily from breakdown due to surface contamination and breakdown of the insulator surface in a process called tracking. The tracking phenomena in DC systems however, differ from those in AC systems, so correlating experience with AC systems to DC systems is fraught with danger. As expected, creepage requirements are generally larger than clearance requirements and can depend on metrics for pollution and on the properties of the insulating surface (Typically either the Comparative Tracking Index (CTI) or the Proof Tracking Index (PTI)).

Until actual experiments are conducted to characterize the shipboard environment for MVDC applications, the authors recommend the following creepage guidance based on extrapolating from existing guidance for AC systems.

Main Switchboards and Generators

Voltage	Creepage Distance (mm) for CTI			
	300 V	375 V	500 V	>600 V
6 kV	113	108	99	90
12 kV	220	210	194	180
18 kV	330	315	292	270

Other high voltage equipment

Voltage	Creepage Distance (mm) for CTI			
	300 V	375 V	500 V	>600 V
6 kV	83	80	75	70
12 kV	166	160	150	140
18 kV	249	240	225	210

CTI = Comparative tracking index as defined in IEC 60112

As stated above, using this guidance does entail risk because of the questionable validity of applying AC criteria to DC systems for creepage requirements and the unknown characteristics of the shipboard environment. Fully insulating all energized parts is preferable to relying upon the proposed creepage guidance. Once the shipboard environment has been properly characterized for MVDC applications, updated guidance should be incorporated in a revision to MIL-DTL-917. Until then, interim guidance should be incorporated in the Electrical Systems Design Criteria and Practices manual (T9300-AF-PRO-020).

CONCLUSION

Affordably powering advanced electric weapons and high power sensors in future surface combatants may favor the use of MVDC power systems. This paper details certain design considerations for an MVDC distribution system including the electrical power system concept of operations, MVDC bus capacity, cable and bus duct, cable shielding, voltage regulation and bus stability, dual output generators, and creepage and clearance requirements.

Continued research, development, and demonstration will be needed to make MVDC a reality in our future Navy.

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