SNAME Maritime Convention 2024
14-16 October 2024, Norfolk, VA

www.sname.org

Integrating Power Electronic Equipment into Shipboard Power Systems

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While incorporating power electronic equipment into ship designs offers many advantages, the ship integration process for power electronic equipment is not well understood. This paper details areas of consideration that require study or design activity prior to detail design, and what can likely be deferred until detail design. These areas of consideration include: suitability for marine applications, current limiting, power quality, common-mode currents and voltages, electromagnetic compatibility, equipment cooling, creepage and clearance, grounding system interaction, system stability, part load efficiency, margins and service life allowances, black start implications, real and reactive power sharing, conditioned based maintenance, modularity, hot swapping, cybersecurity, control systems interfaces, and machinery arrangements.

KEY WORDS: Electrical system; design (vessels); power electronics; system integration; variable frequency drive.

INTRODUCTION

Shipboard electrical power systems consist of electrical generation equipment (typically generator sets), electrical distribution equipment, power conversion equipment, centralized energy storage, and electrical power system controls; the role of the shipboard electrical power system is to provide electrical power to loads with the requisite power quality and quality of service. Historically (predominately 1980's and earlier; although in some cases, still occurring), the focus of marine engineering with respect to shipboard electrical power systems prior to detail design has centered on ensuring the generator sets and distribution equipment had the requisite power handling capability. The electric power load analysis (EPLA) embodies this focus. For details on conducting an EPLA, see T9070-A3-DPC-010/310-1 (Naval Sea Systems Command 2012) and IEEE Std. 45.1-2023.

Prior to detail design, consideration has also been given to determining the optimal location of the generator sets within the ship. Otherwise, the remainder of the electric power plant design was largely left for the shipbuilder to determine during detail design; the details of the electric plant design would not affect the ship-design-level space, weight, area, power or cooling (SWAP-C) requirements. Furthermore, one could be confident that the details involved with the remainder of the electric power plant design would likely not result in a finding of infeasibility of the overall electric plant design; the risk of having to perform a major redesign of all or portions of the electric plant during detail design was low.

Since the 1990's (in some cases even earlier), power electronic equipment have increasingly been incorporated into ship power systems. Modern power electronic equipment incorporate high current semiconductor devices, such as controlled rectifiers or transistors, to convert power of one voltage, frequency, and power quality standard to another; examples of shipboard equipment that may contain power electronic devices include:

- Frequency changers to supply 400 Hz or other special frequencies
- Solid state transformers
- Rectifiers
- DC-DC converters
- Power conditioners
- Motor drives
- Propulsion motor drives
- Power interfaces with energy storage
- Power interfaces with other green energy equipment such as fuel cells, photovoltaic systems, and wind turbines.
- Shore power connections
- High power sensors
- Mission systems

This paper is focused on power electronic equipment. In many cases, the equipment in the above list may be implemented using technology other than power semiconductor devices; integration of these implementations into shipboard power systems is not addressed by this paper.

The motivation for incorporating power electronic equipment has generally been to improve overall system efficiency, improve machinery arrangements to increase revenue opportunities, or to provide power of the type and quality needed for high power sensors or mission systems. In the future, particularly as ships incorporate green energy technologies, these trends are anticipated to continue; ships will increasingly incorporate power electronic equipment. Achieving regulatory or statutory emission requirements, fuel consumption objectives, effective energy storage utilization (to include minimizing ‘charge-discharge’ energy losses) and total ship power system performance will come to depend upon how well power electronic equipment is integrated within the shipboard power system design.

Integration is the process of connecting two or more parts together to form a system that meets customer needs. In the context of this paper, integration of power electronic equipment into shipboard power systems consists of the activities one should perform during the design phases to ensure the shipboard power system, once installed onboard ship, will operate as intended.

MIL-PRF-32168 and IEEE Std. 1566-2015 include good lists of variable / adjustable speed drive characteristics that should be defined in a purchase order. These characteristics are also common to many other power electronic equipment.

One of the challenges of integrating power electronic equipment onboard ship is that the equipment is typically based on designs intended for terrestrial industrial applications. This means that a marine engineer should evaluate the proposed equipment for suitability in the intended marine environment. IEEE Std. 1662-2023 describes differences between terrestrial and marine power systems that impact the design of power electronic equipment. IEEE Std. 1826-2020 provides additional guidance for power electronic equipment within a zonal electrical distribution system.

In the past, ensuring proper power ratings of power system components was sufficient; all of the details would work out later in the detail design. Now, prior to detail design, the following considerations should be evaluated to determine if additional study is warranted to ensure system feasibility:

- Suitability for marine applications
- Current limiting
- Power quality
- Common-mode currents and voltages
- Electromagnetic compatibility
- Equipment cooling
- Creepage and clearance
- Grounding system interaction
- System stability
- Part load efficiency
- Margins and Service Life Allowances
- Black ship start implications
- Real and Reactive Power Sharing
- Condition based maintenance
- Modularity
- Hot swapping
- Cybersecurity
- Control system interfaces
- Machinery Arrangements (cable entry – access – shock envelope, etc.)

Without adequate consideration and study, the details may not otherwise all work out in detail design. The level of detail of the study depends on what is needed to ensure feasibility; different ship designs may require different levels of detail. Assessing what studies need to be performed prior to detail design, and performing the studies, are becoming major drivers for the work performed by the modern marine engineer. Deferring integration work to detail design that may show the design infeasible could result in significant design rework, schedule delay, and cost overruns if the design is eventually found to be infeasible; addressing infeasibility as early as possible is key to keeping costs within budgets and avoiding schedule delays.

This paper explores each of these areas and provides guidance for what may require additional study prior to detail design, and what can likely be deferred until detail design. In some cases, classification society rules, specifications, or statements of work dictate that activities recommended here to be completed in detail design be instead completed prior to detail design.

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.

SUITABILITY FOR MARINE APPLICATIONS

In many cases, it is desirable to use power electronic equipment designed for terrestrial industrial applications. However, the marine environment can be considerably different from terrestrial industrial facilities. In particular, power electronic equipment should be evaluated for suitability in the areas of structural vibration, ambient temperature and humidity, inclined operation, roll and pitch angles, and seaway accelerations.

For commercial ships, applicable classification society rules and IEEE Std. 45.1-2023 should be consulted to determine limits for the marine environment. For naval vessels consult MIL-STD-167-1 for vibration; DOD-STD-1399 Section 301 for ship motions and inclined operation; and MIL-DTL-917 for temperature and humidity. Power electronics for naval applications should also consider shock requirements as defined in MIL-DTL-901. Shock design criteria for naval surface ship applications is provided in T9070-AJ-DPC-120/3010.

In particular, equipment containing liquids, such as liquid cooling, that are contained in a tank or sump should be examined to ensure proper operation when subjected to the inclinations and motions expected to be experienced onboard ship.

Prior to detail design, datasheets for power electronic equipment should be closely examined to assess suitability for marine applications. The manufacturer should be consulted to fill in knowledge gaps for areas not covered in the datasheets; the manufacturer's response should be included in the ship design documentation. In some cases, physical testing may be required to address the knowledge gaps.

For equipment that automatically switch between alternate ac supplies, it is important that the switch is of the type "break before make". A "break after make" switch can result in extensive damage due to out-phase paralleling of power sources; independent ac sources onboard ships are not likely to be in phase as can be expected in terrestrial applications.

For equipment where dc sources are paralleled using auctioneering diodes to individual loads, Doerry and Ashton (2019) and Doerry (2019) should be consulted to avoid potential issues with common-mode currents and voltage doubling under certain fault conditions. As described in Doerry (2019) Fig. 1 depicts a potential solution for avoiding these issues with two dc sources (V_a and V_b).

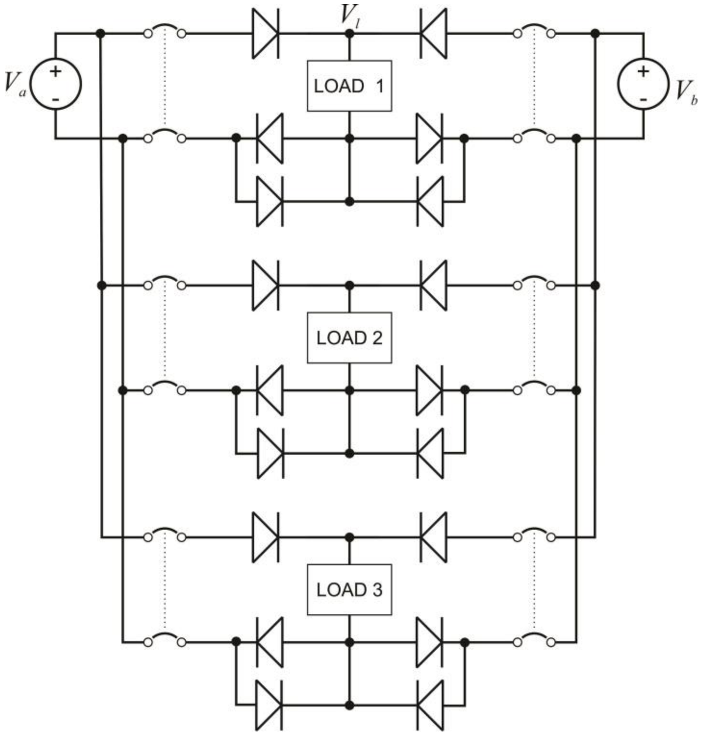

Fig. 1, Modified Symmetric Auctioneering Diode Configuration

CURRENT LIMITING

When sourcing power, power electronic converters typically regulate the voltage as long as the current remains below its rated value. When the rated current is reached, either due to an overload or a short circuit fault, the converter generally either shuts down immediately, or regulates the current to either the rated current or allows the current to rise to a somewhat higher short term current limit. If necessary, the voltage will be reduced to keep the load current at or below the current limit. Often, the power electronics will shut down after operating at or above the rated current for a limited amount of time that can range from seconds to minutes.

This current limiting behavior may be incompatible with the fault current characteristics needed to properly coordinate downstream circuit breakers and fuses. Fault current analysis (IEEE Std. 45.1-2023) should be performed to ensure circuit protection operates properly. Prior to detail design, representative distribution systems should be modeled and analyzed to ensure feasibility of the intended fault protection system. A more thorough analysis should be performed during detail design to establish protection device configuration settings.

During current limiting, power quality standards can fall outside of acceptable ranges as described by Doerry and Amy (2019). The impact on power quality is greater if the aggregated load contains constant power loads as compared to purely resistive loads. Hence, the power system design should seek to avoid overloading the power electronic converter.

To avoid current limiting due to overloading, the electric power load analysis (EPLA) should be prepared with care to ensure the likely maximum power demand will not exceed the power electronic converter power rating, especially in terms of its current rating and limit. The zonal load factor method, modeling and simulation load analysis method, or stochastic load analysis method described in T9070-A3-DPC-010/310-1 (Naval Sea Systems Command 2012) should be used to calculate the likely maximum power demand. In establishing load factors for cycling loads as described by Doerry and Amy (2019), the time scale of interest should be set equal to the amount of time the power electronic converter can operate at or above the rated current.

POWER QUALITY

Transient response and waveform distortion (such as harmonic distortion) of output voltages and input currents should be verified to meet interface requirements through analysis, simulation, and testing. These interface requirements are typically defined in class society rules, IEEE Std. 45.1-2023, or MIL-STD-1399 section 300 parts 1 and 2. In particular, the output power quality should be verified to meet interface standards when the load current includes worst case waveform distortion.

Prior to detail design, equipment datasheets for both the candidate power electronic equipment and load equipment should be studied; if there is any question of incompatibility, power quality analysis should be performed. Power quality analysis should also be performed during detail design to ensure the detail design will work properly.

When conducting analyses, frequencies should be considered up to at least 100 times the maximum observable switching frequency in the waveform of interest. Creating accurate models applicable to frequencies above 1 MHz can be challenging and may call for Thevenin methods described by Brovont (2018).

Where power quality requirements are not met, mitigation strategies detailed by ABS (2006) may be employed. These mitigation strategies usually include the incorporation of line reactors or harmonic filters. Prior to detail design, space and weight should be reserved for implementing the mitigation strategy during detail design (if needed).

COMMON-MODE CURRENTS AND VOLTAGES

The neutral voltage of a set of conductors with reference to another voltage potential is equal to the instantaneous average value of the voltages of the conductor set with respect to the reference voltage potential. The reference voltage potential is usually either the ship's hull (ground) or another neutral voltage; neutral voltages are also known as common-mode voltages.

The switching characteristics of power electronic converters usually result in a common mode voltage existing between input terminals and output terminals. The frequency content of this common mode voltage includes harmonics of the fundamental frequencies as well as harmonics of the switching frequencies; frequency content into the megahertz region is possible.

As an example, Fig. 2 depicts a simple three phase passive rectifier. Fig. 3 depicts the waveforms on the ac input and dc output with respect to the neutral of the ac input. Fig. 4 depicts the dc output and the ac input neutral voltage with respect to the neutral of the dc output. In Fig. 4, the middle near triangular waveform represents the inherent common-mode voltage between the input and output terminals (conductor sets) of this passive rectifier. In general, the voltage difference between the neutrals of the input and output of a converter constitutes the magnitude of the common-mode voltage source of that converter.

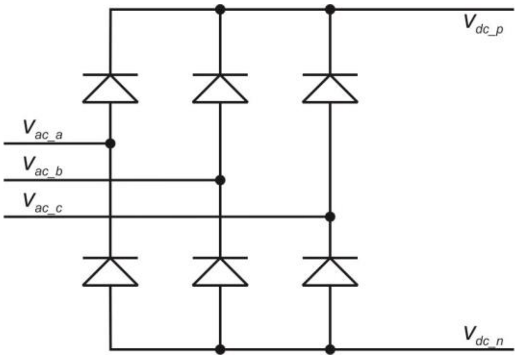

Fig. 2, Uncontrolled rectifier schematic

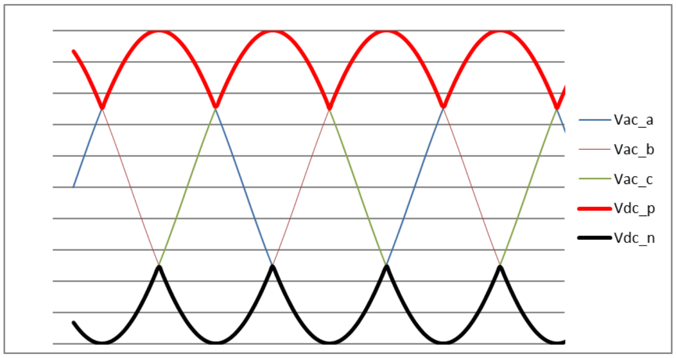

Fig. 3, Voltage waveforms with respect to neutral of ac input

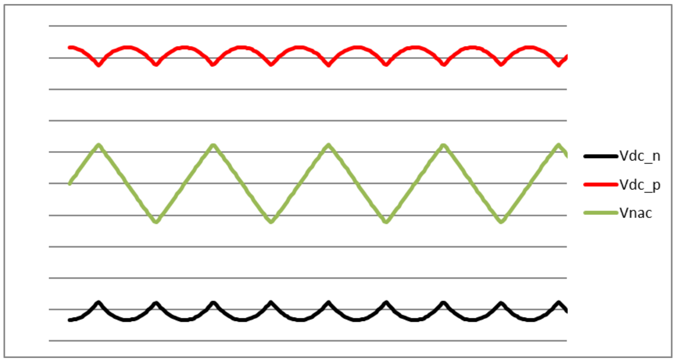

Fig. 4, Voltage waveforms with respect to neutral of dc output

The ship's hull and structure, parasitic capacitances, EMI filter capacitances, and other line-to-ground impedances provide a path for common-mode current to flow between the input and output terminals of the power electronics. These voltages and currents can be a source of EMI as well as a potential danger to ordnance and personnel. If mitigation steps are not taken, the distributed nature of the parasitic capacitances can lead to EMI effects happening far away from the power electronic converter creating the common-mode voltage. Troubleshooting and correcting these EMI effects becomes very difficult.

Doerry and Amy (2018) and IEEE Std. 45.1-2023 provide details for understanding the common-mode characteristics of power electronics. The common-mode circuit should be deliberately designed to keep the common mode currents geographically near the common mode voltage source. Common mode chokes and shunts can be used to minimize the flow of common mode current though the hull as well as the common mode voltage of the power distribution system cable.

Prior to detail design, if relevant physical testing is not possible, space and weight should be reserved for common-mode chokes and shunts should analysis during detail design prove they are needed.

If the power electronic equipment does not incorporate an isolation transformer, or if a dedicated isolation transformer is not provided, then some form of common-mode mitigation (chokes and/or shunts) is likely to be needed. Providing space and weight for this mitigation is imperative.

If multiple power electronic converters are cascaded, it may prove beneficial to create Thevenin equivalent models of the converters through testing. These models can be used to create best and worst case common mode performance of the system of cascaded converters as described by Brovont (2018) and Brovont and Pekarek (2017).

If possible, the testing to support Thevenin equivalent models should occur prior to detail design; however, in some cases the testing may not be possible until detail design.

During detail design, common-mode mitigation, if needed, should be designed, procured and tested.

ELECTROMAGNETIC COMPATIBILITY

Electromagnetic compatibility (EMC) seeks to ensure equipment work properly within the shipboard electromagnetic environment and do not negatively impact the electromagnetic environment to a degree to cause other equipment to not work properly. EMC requirements for military equipment are contained in MIL-STD-461; classification society rules should be consulted for non-military applications.

One of the challenges with specifying EMC requirements is that standards such as MIL-STD-461 are intended for equipment no larger than an equipment rack and with a rated current less than several hundred amps. Onboard ship however, power electronic converters can be significantly larger both in size and rated current. For these larger systems, it may be beneficial to establish separate limits (as a function of frequency) for common-mode voltages and currents, for line-to-line voltages, and for phase currents. An approach for establishing the common-mode limits for high power dc systems (above 1000 volts) is described by Doerry and Amy (2022).

For solidly grounded systems, one approach for achieving the EMI requirements is to use EMI filters that have a relatively large line to ground capacitance. If these same EMI filters are used in an ungrounded system, potentially damaging transient over-voltages can be produced by intermittent ground faults as described by Doerry and Amy (2023). EMI filters should be chosen that limit the line to ground capacitance to less than 0.1 μF for 60 Hz equipment as specified in MIL-STD-1399 Section 300, Part 1.

Prior to detail design, space and weight should be allocated for the EMI filters; the design of the EMI filters may be deferred to detail design.

EQUIPMENT COOLING

Typical choices for power electronic cooling include air cooling, freshwater cooling, chilled water cooling, and in some cases, seawater cooling. In any case, the cooling system should be adequate for rejecting the waste heat under all operating conditions.

While air cooling usually has the simplest of interfaces, the ship’s heating, ventilation and cooling (HVAC) system should be designed to remove the waste heat while keeping compartment temperatures and air velocities within specifications. In casualty conditions, and during a black start, means must be provided to ensure the air temperature is within specification limits for the power electronic equipment.

The connections for water cooling should be compatible with the power electronic equipment mounting method. Flexibility will be required if the power electronic equipment uses acoustic or shock mounts. If a shock requirement is specified, the water-cooling connection (as well as the electrical connections) should accommodate the shock excursion envelope.

If the cooling water temperature can fall below the dew point, which frequently occurs in shipyards and in the humid marine environment, the power electronic equipment should be designed to mitigate the possibility of condensation. Uncontrolled condensation can result in corrosion or electrical faults. Common ways to prevent condensation include insulation, equipment heaters, and controlling the flow rate of the cooling water.

Most power electronic equipment will shut down upon loss of cooling water flow. It may be desirable, especially during a black start, to allow the power electronics to operate at very low power in an air-cooled mode to facilitate powering critical equipment while the water-cooling system is not operative.

Prior to detail design, equipment datasheets should be studied to determine the cooling needs and cooling performance of candidate equipment. These needs should be reflected in the designs of the cooling system. The manufacturer should be consulted if needed information is not found in the datasheet. In some cases, testing may be desirable prior to detail design, or during detail design, to verify power electronic equipment performance and capability upon loss of cooling water flow or elevated air temperature.

Considerations for avoiding condensation may be deferred until detail design.

CREEPAGE AND CLEARANCE

Bare, energized or grounded conductors are usually found inside the cabinets of power electronic equipment. These conductors can include busbars, terminals, printed circuit board traces, connectors, and structure. Creepage and Clearance requirements ensure there is sufficient distance between energized conductors, and between energized conductors and ground, to prevent flashover. As shown in Fig. 5, clearance is the shortest distance through air between the two conductors; creepage is the shortest distance along the surface of an insulator between the two conductors. The required creepage and clearance distance is a function of the voltage between the two conductors and the degree of pollution of the air (clearance) or on the insulator (creepage). Classification society rules, IEEE Std. 45.1-2023, or MIL-DTL-917 should be consulted for determining the appropriate creepage and clearance distances. Because the pollution has a significant impact on the required creepage and clearance distances, one should locate power electronic equipment within spaces where the air is filtered, provide sufficient air filtration on the air intakes of the power electronic cabinets, or select power electronic cabinets that are sealed to the outside environment.

Prior to detail design, equipment datasheets should be studied to determine the air cleanliness requirements and the design line-to-ground voltages for creepage and clearance of candidate equipment. The line-to-ground creepage and clearance distances should be confirmed adequate for thetype of grounding system planned for the power electronic equipment. The manufacturer should be consulted if there is any uncertainty.

During detail design, if a grounding method other than solidly grounded is employed, testing should be performed to ensure adequate creepage and clearance.

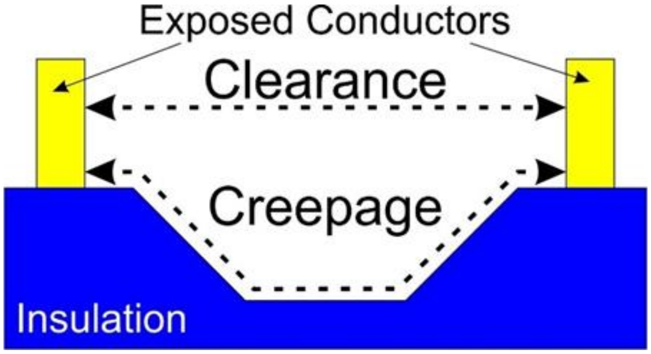

Fig. 5, Creepage and clearance.

GROUNDING SYSTEM INTERACTION

Power electronic equipment may be designed for operation in terrestrial power systems with a solidly grounded system. Shipboard systems may be ungrounded or high resistance grounded. Before detail design, candidate power electronic equipment should be verified to operate in an ungrounded or high resistance grounded system through examination of data sheets or through conversations with manufacturers. Some equipment will test for the presence of a solid ground, and if not present, will not operate.

During detail design, if not performed earlier, the impact of the grounding system on the power electronic equipment common mode behavior should be assessed via simulation and verified through testing.

SYSTEM STABILITY

Incorporating power electronics into a power system introduces the possibility of the resulting system being either small-signal (linear) unstable, or large signal (nonlinear) unstable.

Small signal stability can be addressed prior to detail design by establishing phase and gain margins, or other limitations on phase and gain, on each of the electrical ports of each of the power converters. As described by Williams (2004), Gholdston et. al. (2005) and Sudhoff et. al. (2003) and depicted in Fig. 6, these metrics require one to assume Laplace transform characteristics of interfacing equipment: admittance characteristics of the loads (L); and impedance characteristics of sources (S). If we set $G(s) = SL$, then the system is small signal stable if the roots of $1 + G(s)$ are in the complex left-hand plane. Bode diagrams are typically used to visualize these roots. In a Bode diagram, $G(j\omega)$ is expressed as $H(\omega)e^{j\Theta(\omega)}$ where j is the square root of -1. If we take the natural logarithm of $G(j\omega)$, Eq. 1 is obtained.

$$\ln(G(j\omega)) = \ln(H(\omega)) + j\Theta(\omega) \qquad (1)$$

A Bode diagram consists of plots of $H(\omega)$ in dB and $\Theta(\omega)$ in degrees, usually using a logarithmic scale for ω.

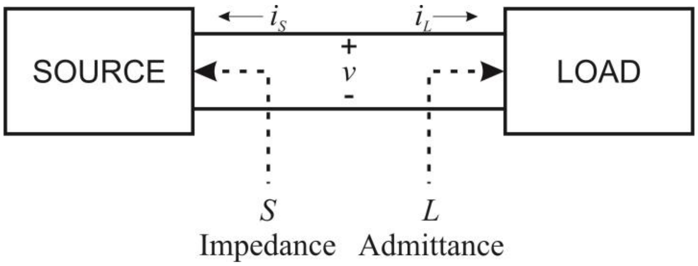

Fig. 6, Linear stability source impedance and load admittance

Small signal stability requires two conditions. First, the gain (in dB) at the frequency where the phase is 180° must be less than 0 dB. The difference between 0 and the gain is called the gain margin. Second, the phase at the frequency where the gain is 0 dB must not be 180°. The difference between this phase and 180° is the phase margin.

Prior to detail design, establishing bounds for these admittances and impedances of interfacing equipment should be done. Additionally, if the power electronic equipment impedance and admittance characteristics of candidate equipment are not provided in datasheets, manufacturers of power electronic equipment should be consulted to ensure the resulting limitations on phase margin and gain margin are achievable.

During detail design, the impedance and admittance characteristics of power electronic equipment should be determined or confirmed through testing. Subsequent analysis confirmed by modeling and simulation should be used to verify system stability. Finally, integrated system testing should be performed, if possible, prior to installation onboard ship.

Assessing non-linear stability is difficult prior to detail design, primarily due to the lack of detailed modeling data. Non-linear stability of systems is usually accomplished during detail design through system simulation of detailed time domain models; the results are compared against power quality interface standards to assess the nonlinear stability for the one operating point simulated. The detailed time domain models should be obtained from the manufacturer, or from testing. Many simulations, typically on the order of thousands, are conducted to cover the anticipated range of system operating points. Integrated system testing of key operating points should be used to validate the modeling and simulation.

PART LOAD EFFICIENCY

Understanding part load efficiency is important when integrating power electronic systems onboard ship. As described by Doerry and Parsons (2023) the losses of a power converter are generally dominated by a no-load loss and a load dependent loss proportional to the square of the current as shown in Eq. 2.

$$P_{Loss} = P_{noLoadLoss} + R_{loss} I_{out}^2 \qquad (2)$$

Efficiency is equal to the output power divided by the input power; the input power is equal to the output power plus the losses. For dc systems, power is equal to voltage times current; thus, the efficiency can be defined by Eq. 3.

$$\eta = \frac{\frac{P_{out}}{P_{rated}}}{\frac{P_{rated} R_{loss}}{V_{out}^2}\left(\frac{P_{out}}{P_{rated}}\right)^2 + \frac{P_{out}}{P_{rated}} + \frac{P_{noLoadLoass}}{P_{rated}}} \qquad (3)$$

Eq. 3 can be restated at rated output power to yield Eq. 4.

$$\frac{P_{rated} R_{loss}}{V_{out}^2} = \frac{1}{\eta_{RatedPower}} - \left(1 + \frac{P_{noLoadLoass}}{P_{rated}}\right) \qquad (4)$$

Assuming the output voltage is relatively constant, the no load losses are known, and the efficiency at rated output power is known, then Eqs. 2-4 can be used to estimate the efficiency and losses at any output power level. Note that at zero output power, the efficiency is zero; the no load losses cannot be determined from an efficiency curve. Fig. 7 depicts the efficiency and losses for a typical converter based on Eqs. 2-4. If the no load losses are not provided, but the efficiencies at multiple output powers are provided, then see Doerry and Parsons (2023) for methods of estimating the no load and full load losses.

At very low output power levels, the efficiency is very low and the losses can equal or exceed the output power. This is largely due to the contribution of the no load losses. In operating conditions where the online generation capacity is limited, the no load losses of the online converters should be considered when ensuring the online generation is sufficient to power the desired loads.

When multiple converters are paralleled, the total no load losses of the set of paralleled converters can be minimized by shutting off those converters that are not needed to serve the load.

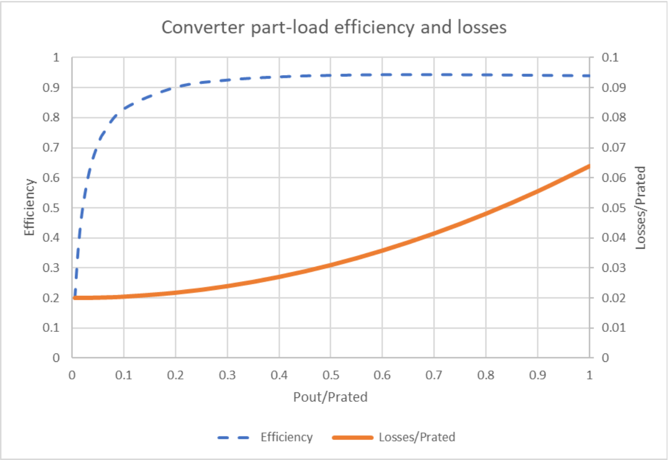

Fig. 7, Converter part load efficiency and losses

Prior to detail design, the part load efficiency of candidate power electronic equipment should be estimated based on information from datasheets and inquiries to the manufacturer. The part load efficiency data should be used as part of the EPLA for determining the required rating of power system equipment (including emergency generators and distribution), for calculating endurance fuel conditions, and for estimating annual fuel usage. In particular, part load efficiencies can have a significant impact in calculating the load for the shore, anchor, and emergency conditions.

During detail design, the part load efficiency performance should be confirmed via testing and the impact of any changes on the EPLA, endurance fuel calculations, and annual fuel usage calculations assessed.

MARGINS AND SERVICE LIFE ALLOWANCES

Margins and service life allowances are factors applied to the calculated maximum demand load to determine the minimum required rating of the supplying power electronic equipment. Margins account for the uncertainty associated with estimating the maximum demand load; Service life allowance accounts for growth in load while the ship is in-service due to equipment degradation and installation of new equipment. IEEE Std. 45.1-2023 provides recommendations for margins and service life allowances:

Detail Design	5 % for repeat designs
	20% for new designs
Construction	5 % for repeat designs
	20% for new designs
Service Life Allowance	
	20% (1% per year for 20 years)

Because of the limited ability of power electronic equipment to provide power in excess of their rating for more than a few seconds, careful attention should be made to ensure the value chosen for margin appropriately mitigates the uncertainty associated with the load estimate; the load estimate is typically based on load factors that represent an average over a time much longer than a few seconds. In some cases, performing load characterization tests of the load equipment may provide sufficient data to justify reducing the amount of required margin.

If the power electronics equipment is implemented using power modules where additional power rating can be incorporated after ship delivery, then the cabinet and common elements of the power electronics should have capacity to include the service life allowance, but the original outfitting of power modules need not consider the service life allowance; additional power modules may be added as needed.

The appropriate margins and service life allowance should be employed prior to detail design and during detail design.

BLACK START IMPLICATIONS

A black start occurs when the electrical system is re-energized from a complete power outage onboard the ship. Power electronic equipment may require control power and cooling water to start. If either the control power or cooling water is dependent on equipment powered by the power electronics, a means to start the power electronic equipment may not exist.

To ensure the power electronic equipment can be started, the following options should be considered:

- Provide the control power source and the cooling water source with a reliable uninterruptible power supply with sufficient power and energy rating. The uninterruptible power supply should incorporate health monitoring and report via the machinery control system whether it is healthy or not.
- Derive the control power from the input side of the power electronic converter and not the output.
- Enable the power converter to start in a low power mode that can power the cooling water source without cooling water present. This option also requires the use of controls to ensure non-cooling water related loads are not powered until the power electronic converter has full capability.

A design structure matrix as described by Eppinger and Browning (2012) may prove useful in identifying feedback loops that may preclude being able to recover from a complete power outage.

The process for conducting a black start should be developed and simulated prior to detail design and verified through more detailed simulation and possibly testing during detail design. This process should be documented in the electrical power system concept of operations (EPS-CONOPS) as detailed in IEEE Std. 45.1-2023.

REAL AND REACTIVE POWER SHARING

If the power electronic converter outputs are intended to be paralleled with other sources, a means for sharing real power and for ac systems, reactive power should be implemented. If no such means is provided, one of the sources will usually attempt to provide all of the real power, overload, and shutdown, causing the remaining sources to overload and shutdown in sequence. If a means for reactive power sharing is not implemented for ac outputs, large circulating currents (reactive power flow) can occur between the sources, resulting in current limiting, and sequential shutdown of paralleled converters.

For dc outputs, real power can be shared by using a droop characteristic of the voltage as a function of real power (Fig. 8) or through power sharing signals. For ac outputs, real power is typically shared through a droop characteristic of the frequency as a function of real power (Fig. 9(a)) or through real power sharing signals; reactive power is typically shared through a droop characteristic of the voltage as a function of apparent power (Figure 9(b)) or through reactive power sharing signals. See IEEE Std. 45.1-2023 and Doerry (2017) for additional details.

Figs. 8-9 depict droop characteristics for dc and ac systems respectively. In dc systems, the system voltage (V_{op}) along with the droop curve for each generator determines the amount of power provided by each generator. Since the load power (P_{LOAD}) must also equal the sum of the power provided by the generators, the system naturally converges on a system voltage where all the droop curves and the power balance are satisfied. The droop curves for ac systems operate in a similar manner to determine the system voltage and frequency (f_{op}).

The ability of paralleled power electronic converters to share real and reactive power should be confirmed prior to detail design through close examination of the datasheets, modeling and simulation, or testing. More detailed modeling and simulation, or testing, should be accomplished during detail design.

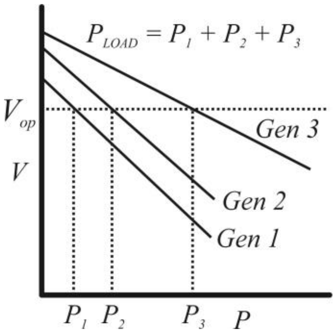

Fig. 8, Power sharing for dc systems using droop

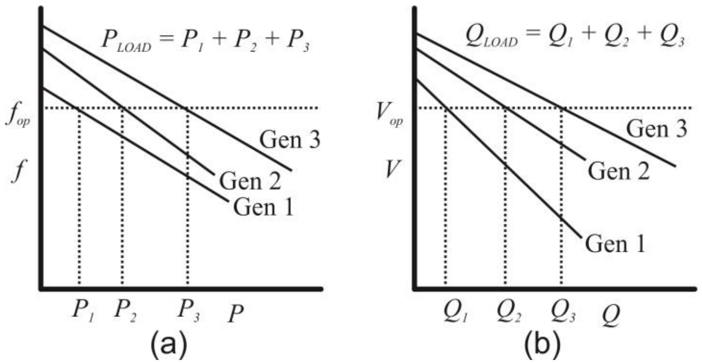

Fig. 9, Power sharing for ac systems using droop: (a) Real Power (b) Reactive Power

CONDITION BASED MAINTENANCE

If possible, power electronic equipment that incorporate sensors and algorithms to assess the need for maintenance should be chosen. The assessment should provide sufficient warning time before failure to enable replacement parts to be ordered and received to preclude operational down time. The amount of warning time provided should be used to determine if replacement parts are stocked onboard for immediate replacement, held ashore and shipped to the ship for replacement at the next port, or installed during the next maintenance period. Ideally the condition assessment would provide enough warning time to enable deferring the maintenance to the next maintenance period.

The output current of the power electronic converter can also be used to assess the material condition of loads. Many loads employ controllers that enable continued operation under degraded condition; operability of the load is not an indicator of the health of the load. However, the waveform properties of the load current can often indicate wear or other failures in the load. Cycling loads for example, can cycle more frequently, or may be "on" for longer than normal. These indicators can be used to diagnose maintenance issues for these loads. See Patnode et al. (2023) and Green et al. (2023) for additional discussion.

A strategy for performing condition-based maintenance should be developed prior to detail design and implemented during detail design.

MODULARITY

Modular power electronics may allow multiple power converters onboard ship to employ the same power modules. This is facilitated if power modules can be paralleled; power (or other attribute) ratings can be achieved by paralleling multiple smaller modules. Sharing modules among power electronic converters, each customized for a different task, simplifies logistic support and crew training.

Usually, the rating of each of the power modules is chosen such that the maximum anticipated load can be safely supplied with one module removed in a "n+1" configuration. If the maximum anticipated load requires all the power modules (in an "n" configuration) then either operational procedures, or the control system must be capable of reducing the load supplied by the power electronics to enable powering the remaining loads when one module is not operational; the power electronics control system must be able to detect when a module is no longer functional.

In some cases, supplying sufficient inrush current to loads may require more modules, or modules of higher rating, than that required for the maximum anticipated load. Prior to and during detail design, inrush current needs of loads should be identified; if the inrush current needs become limiting, means to modify the behavior of the loads to reduce inrush current should be explored.

The inrush current for motors without soft starting can be approximated by their Locked Rotor Amperage (LRA) rating. The LRA depends on the motor design; it can be on the order of five to six times the nameplate Full Load Amperage (FLA).

The approach for modularity should be established prior to detail design. This approach should be examined for feasibility by ensuring the availability of equipment that can support the approach. The approach should be implemented during detail design.

HOT SWAPPING

Modular power electronic equipment may include the ability to hot swap power modules. Hot swapping enables, without shutting down equipment, replacing one of two or more modules having their outputs paralleled.

The connectors between the power electronic cabinet and the modules typically use different length pins to enable safe connection and removal. The longest pins, which engage first upon connection and disengage last upon removal, are used to establish a protective ground (also known as an equipment group) and possibly a system ground. The remaining pins may be of several different lengths depending on the application. These pins can include control power, control signals, pre-charge current, and main power. In general, the controls are designed to prevent current from flowing in the main power pins during the connection and removal process. In some systems, a physical locking device prevents connector removal if current is flowing in the main power pins.

The pre-charge current, if provided, is intended to reduce or eliminate inrush current on the main power pins. The pre-charge current is a low magnitude current typically used to charge filter capacitors or provide magnetizing current to transformers within the module. Often the pre-charge current is provided via a resistor connected to one of the main power pins.

Hot swapping of power modules requiring liquid cooling require special provisions for enabling the connection and disconnection of the cooling system. In some cases, the power modules are cooled by contact with a cold plate that is part of the power electronics structure.

For power electronic equipment where the voltage on any of the connector pins is not safe to touch (typically above 40 volts) when a module is removed, a shutter or other mechanism is provided to prevent a hazard to personnel.

Hot swap modules should fail safe. The likely failure modes of the modules should not preclude their safe removal when the equipment is energized. Some systems require the operator to initiate the hot swap through a control system; the control system only allows the hot swap to occur if it determines it is safe to do so.

If the modules are heavy, fixtures should be provided during the connection and removal of the modules to ensure the motion of the module is safe; the probability that the module will fall or otherwise damage equipment or injure personnel is low. This is particularly important if the module replacement is intended to be performed at sea when the ship is rolling, pitching, and potentially slamming.

The capability of hot swapping failed power modules can be a key enabler to achieving quality of service requirements. Quality of service seeks to ensure the power provided to critical loads is reliable; power quality interruptions are of short enough durations that the critical loads can continue to function during the interruptions. See IEEE Std. 45.1-2023 for additional guidance on quality of service.

The requirement for hot swapping should be established prior to detail design. This requirement should be examined for feasibility by ensuring the availability of equipment that can support hot swapping. Hot swapping should be implemented during detail design.

CYBERSECURITY

Traditionally, cybersecurity for shipboard electrical systems has focused on limiting or prohibiting data connectivity external to the ship. The cyber threat was assumed to be outside the boundaries of the ship. Recently however, focus has shifted to threats internal to the ship to include individuals allowed access onboard, computer systems that are compromised by viruses, and by malicious code being hidden in components provided through the supply chain.

The ship's overall cybersecurity architecture should be developed prior to detail design. During detail design, the specifications for power electronic converters should include cybersecurity provisions consistent with the ship's overall cybersecurity architecture. See IEEE Std. 45.2-2023 and ABS (2016, 2023, and 2023A) for additional guidance on shipboard cybersecurity.

CONTROL SYSTEM INTERFACES

Specifications for the control system interfaces should be developed prior to detail design. These specifications should define the allowable protocols, the monitoring and control messages that should be supported, the expected performance of the equipment in response to control messages, and cybersecurity requirements. Study of equipment datasheets or conversations with manufacturers should confirm the requirements can be met. Guidance for the control architecture of high power electronics is provided by IEEE Std. 1676-2010.

As described in IEEE Std. 45.3-2015, the control system interface requirements should be reflected in an Interface Control Document (ICD) prior to detail design, and updated to reflect the implemented interface during detail design. During detail design, components should be verified to ensure they meet the requirements in the ICD. System performance should be verified through simulation and/or testing.

MACHINERY ARRANGEMENTS

Machinery arrangement requirements for naval ships are provided in MIL-STD-3045. These requirements include provisions for:

- Access to equipment and machinery.
- Machinery access routes for replacement equipment and parts.
- Continued operation if bilges are flooded.
- Protection of personnel.
- Protection of material and equipment.
- Protection of machinery from weapons effects.
- Noise and vibration.
- Installation details.
- Lifting gear and special tools.
- Electrical terminal height.

Machinery arrangement requirements for commercial ships are generally part of classification society rules; the requirements of MIL-STD-3045 should additionally be reviewed for applicability.

Guidance for how machinery arrangements are conducted is provided by Kinney and Funkhouser (1987) and Resner (1981).

Guidance for installing electrical equipment is provided in MIL-STD-2003-2B.

Particular attention should be provided to the arrangement of energy storage systems; these systems typically contain power electronic equipment. Energy storage systems have large components, typically require integration with multiple auxiliary systems, and require special provisions to address fire hazards. Class rules and regulations should be consulted.

Arrangement drawings are normally prepared prior to detail design; these drawings should enable the provisions listed above. The remainder of the machinery arrangement efforts is completed in detail design.

CONCLUSIONS

Power electronic equipment are increasingly found onboard ship. Their proper integration into the ship design requires a number of areas of consideration. This paper detailed integration activity that the marine engineer should consider performing during the design stages prior to detail design, and those activities that unless required by contract or class rules, may be deferred, under normal conditions, to detail design. A summary of the areas of consideration and recommendations is provided in Table 1.

Table 1. Summary of areas of consideration and recommendations.

Area of Consideration	Prior to Detail Design	During Detail Design
Suitability for marine applications	Examine datasheets; testing if necessary	Confirm through analysis and testing
Current limiting	Modeling and simulation	Confirm through analysis and testing
Power quality	Examine datasheets; analysis if necessary	Confirm through analysis and testing
Common-mode currents and voltages	Provide space and weight for mitigation; testing for Thevenin equivalent models if possible	Confirm through analysis and testing
Electromagnetic compatibility	Provide space and weight for EMI filters	Design, analysis, and testing of EMI filters
Equipment cooling	Base cooling system design on datasheets; testing if necessary.	Confirm through analysis and testing
Creepage and clearance	Examine datasheets; testing if necessary	Testing for application in power systems with grounding other than for which equipment was designed for.
Grounding system interaction	Examine datasheets	Confirm through analysis and testing
System stability	Examine datasheets; establish bounds for admittances and impedances; perform analysis	Confirm through analysis and testing
Part load efficiency	Examine datasheets and if necessary, consult manufacturer	Confirm through analysis and testing
Margins and Service Life Allowances	Employ and manage design margin allocated to design prior to detail design	Employ and manage design margin allocated to detail design.
Black ship start implications	Modeling and simulation	Confirm through modeling and simulation and through testing.
Real and reactive power sharing	Examine datasheets, modeling and simulation; or testing	More extensive modeling and simulation and testing.
Condition based maintenance	Develop strategy	Implement strategy
Modularity	Establish approach	Implement approach
Hot swapping	Establish requirement for hot swapping (if beneficial)	Implement how swapping to meet requirement
Cybersecurity	Develop architecture	Include appropriate language into procurement specifications.
Control system interface	Develop control interface requirements and document in ICD	Confirm through modeling and simulation and testing
Machinery arrangements	Create initial machinery arrangement drawings	Finalize machinery arrangement drawings

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