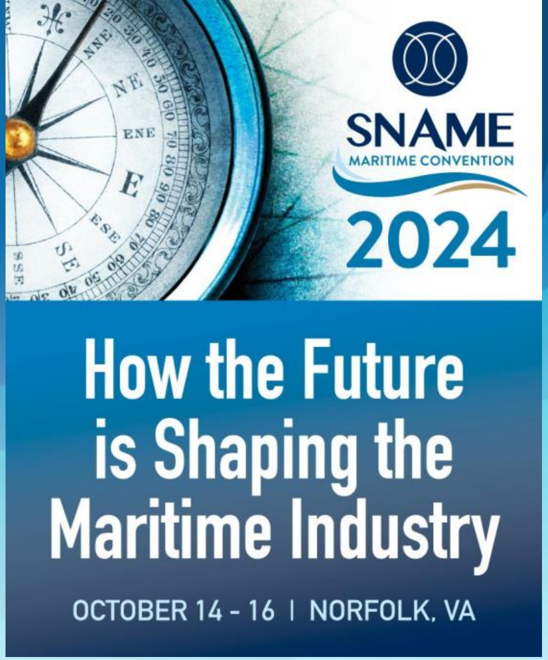


Integrating Power Electronic Equipment into Shipboard Power Systems

Presented by: Norbert Doerry and John V. Amy Jr.

Introduction

Successful Integration of power electronic equipment into shipboard power systems requires more design effort than was previously needed:

- 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
- Condition-Based Maintenance
- Modularity
- Hot Swapping
- Cybersecurity
- Control System Interfaces
- Machinery Arrangements

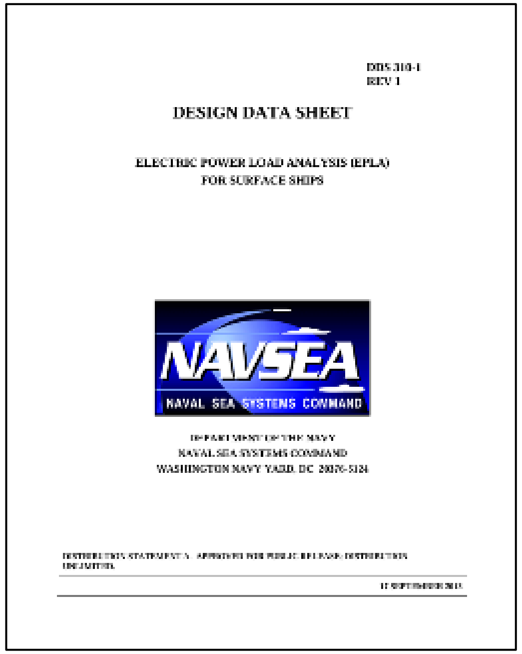
Suitability for Marine Applications

- Structural Vibration
- Ambient temperature and humidity
- Inclined operation
- Roll and pitch
- Seaway accelerations
- Normal and alternate sources not in phase
- Prior to Detail Design
  - Study datasheets
  - Contact OEM
- Detail Design
  - Verify suitability

USS Sterett (DDG 104) transits heavy seas.

Current Limiting

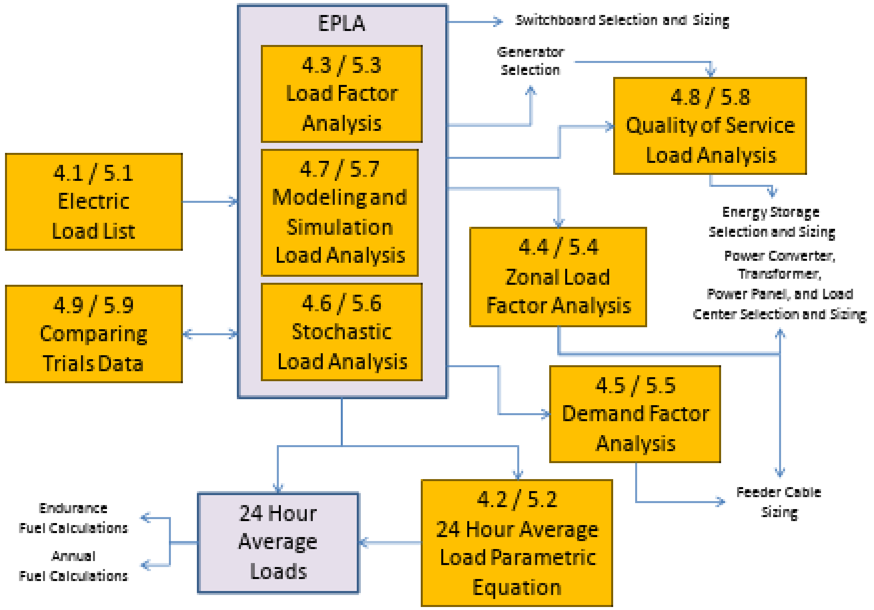
- Power electronic equipment typically have limited overload capability
  - Current limit to rated current or to a higher current limit for a short period of time (seconds to minutes)
  - Shut down after overload period reached
- Important to ensure power electronic equipment is not overloaded
  - Electric Power Load Analysis (EPLA)
- Prior to detail design
  - Model representative systems to determine feasibility of fault protection strategy
- Detail Design
  - Perform more detailed analysis
  - Develop protection device configuration settings


DDS 310-1
REV 1

DESIGN DATA SHEET

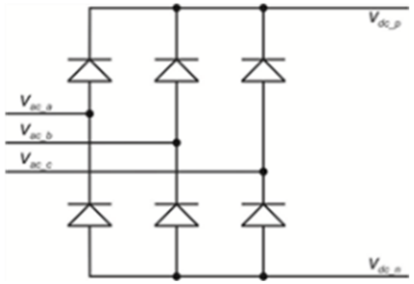
ELECTRIC POWER LOAD ANALYSIS (EPLA)
FOR SURFACE SHIPS

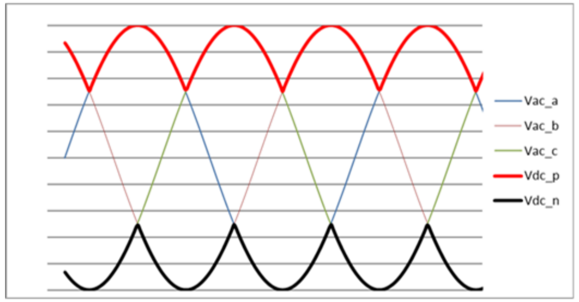
DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND
WASHINGTON NAVY YARD, DC

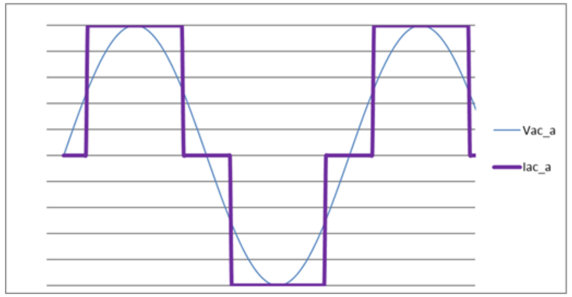


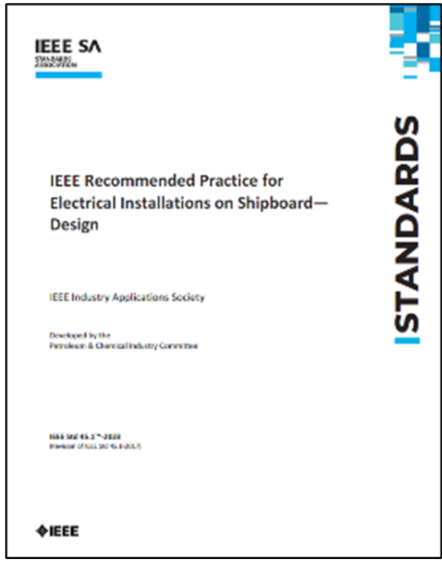
Power Quality

- Need to ensure power electronic equipment can adhere to power quality requirements
  - Voltage waveform properties on outputs when load current waveforms are distorted but still within specification
  - Current waveform properties on inputs when source voltage waveforms are distorted but still within specification
- Prior to detail design
  - Study data sheets
  - Contact OEM
- Detail design
  - Perform detailed power quality analysis



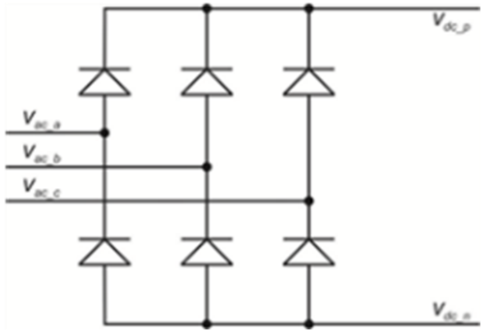


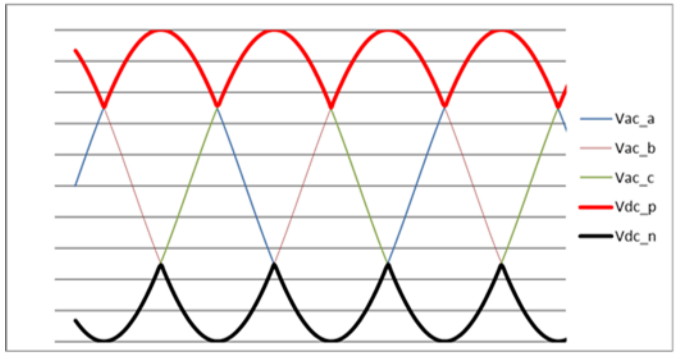


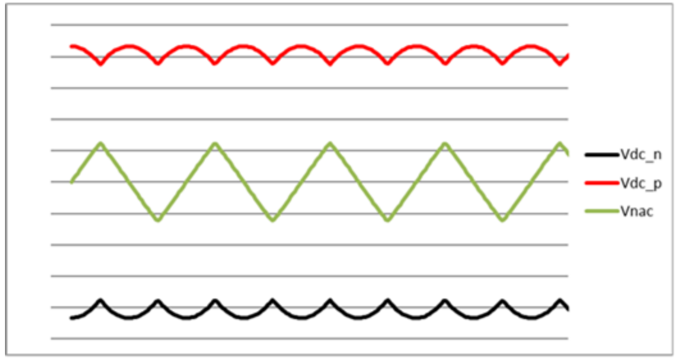


Common-Mode Currents and Voltages

- Common-mode voltage is the instantaneous average voltage of a set of conductors with respect to another voltage potential
  - Property of a set of conductors, not necessarily any single conductor.
- Power electronic equipment typically have a common-mode voltage between an output terminal (set of conductors) and an input terminal (set of conductors)
  - This common-mode voltage drives a common-mode current through the ship's hull via parasitic capacitance and EMI filter capacitors connected to the hull.
  - The common-mode circuit should be deliberately designed to avoid problems. (such as EMI)
- Prior to detail design
  - Reserve space and weight for common-mode mitigation
  - If possible, develop Thévenin equivalent models
- Detail design
  - Perform testing to support Thévenin equivalent models (if needed)
  - Design, procure, and test common-mode mitigation.

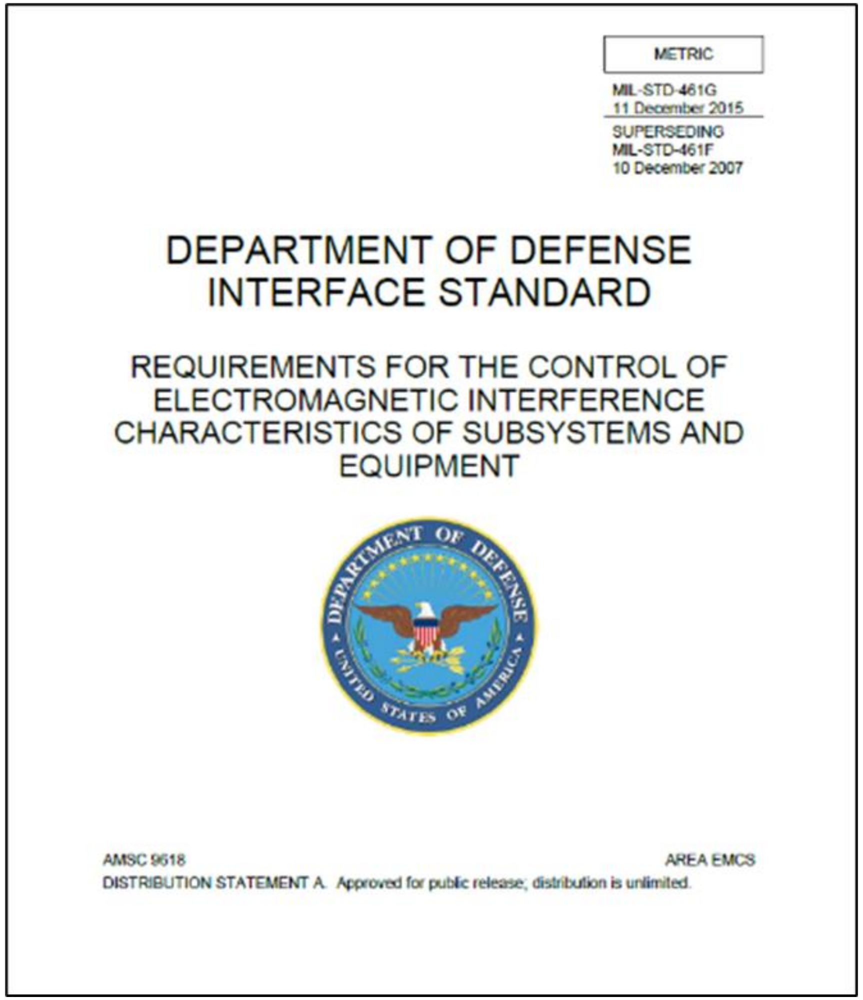






Electromagnetic Compatibility

- For rack size equipment, test methods such as MIL-STD-461 can be used.
- For large equipment, consider specifying common-mode properties independently from non-fundamental differential mode waveform properties.
- Prior to detail design
  - Reserve space and weight for EMI mitigation
- Detail design
  - Design, procure, and test EMI mitigation


METRIC

MIL-STD-461G
11 December 2015
SUPERSEDING
MIL-STD-461F
10 December 2007

DEPARTMENT OF DEFENSE
INTERFACE STANDARD

REQUIREMENTS FOR THE CONTROL OF
ELECTROMAGNETIC INTERFERENCE
CHARACTERISTICS OF SUBSYSTEMS AND
EQUIPMENT

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

AMSC 9618 AREA EMCS
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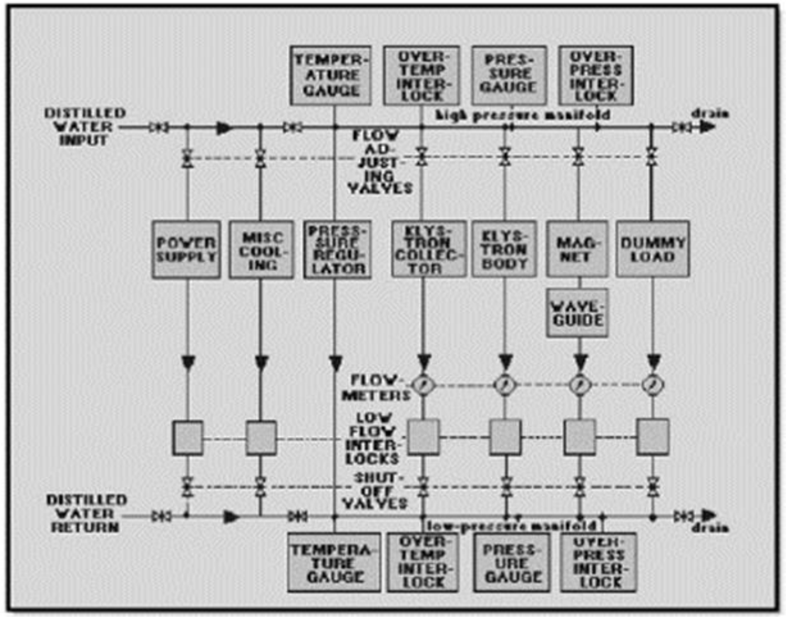
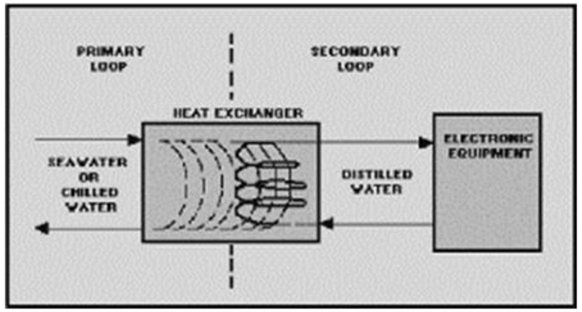
Equipment Cooling

- Options
  - Air cooling
  - Fresh water cooling
  - Chilled water cooling
  - Sea water cooling
- Considerations
  - Flexible connections for shock or acoustic mounted equipment
  - Condensation prevention
  - Enable restricted operation with loss of cooling
- Prior to design
  - Study data sheets
  - Contact OEM
- Detail design
  - Testing to very performance due to loss of cooling
  - Condensation mitigation



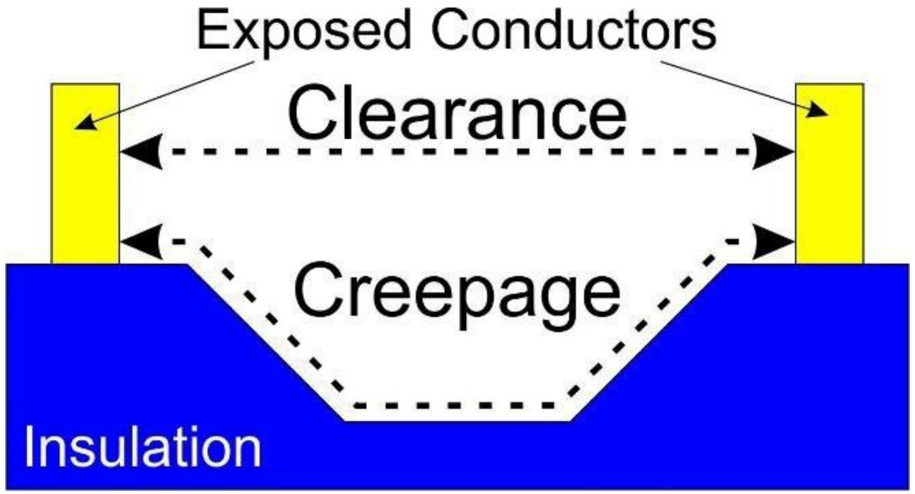


Note: a pump should be shown in the distilled water loop

Navy Electricity and Electronics Training Series
Module 18-Radar Principles NAVEDTRA 14190A

Creepage and Clearance

- Clearance
  - “Air Distance” between two conductors that could be of different potential.
- Creepage
  - Distance along the surface of an insulator between two conductors that could be of different potential.
- Requirements
  - Creepage and Clearance requirements intended to prevent flashover.
  - A function of the pollution environment.
- Prior to detail design
  - Study data sheets – contact OEM
  - Locate power electronics in rooms with filtered air, or
  - Ensure power electronic equipment have adequate air intake filters, or
  - Hermetically seal power electronics.
- Detail design
  - Test for compatibility with grounding system

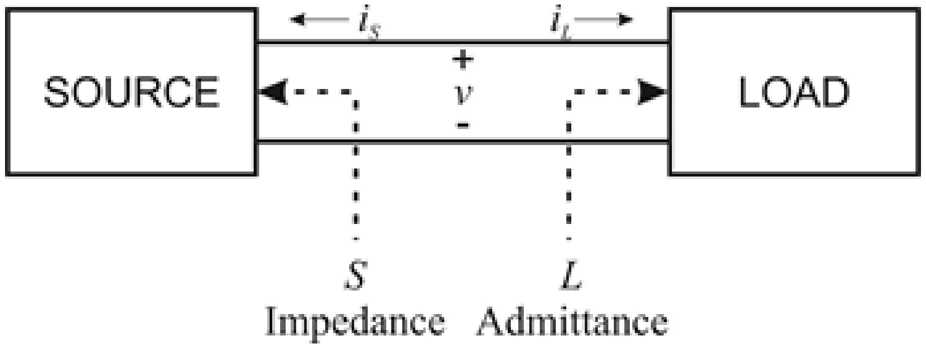


Grounding System Interaction

- Power electronic equipment may be designed for terrestrial applications with a solid ground
  - May not function correctly in a shipboard ungrounded or high resistance grounded system.
  - May sense the lack of a solid ground and immediately shut down.
  - May have undesirable common-mode characteristics
- Prior to detail design
  - Study data sheets
  - Contact OEM
- Detail design
  - Assess interaction with grounding system via simulation
  - Verify through simulation

System Stability

- Small Signal Stability
  - Gain Margin
    - $\ln(H(\omega))$ must be less than 0 when $\theta(\omega)$ = 180 degrees.
    - How much less is the Gain Margin
  - Phase Margin
    - $\theta(\omega)$ must not be 180 degrees when $\ln(H(\omega))$ = 0.
    - The difference is the Phase Margin
- Large signal Stability
  - Usually assessed through time-domain simulations.
  - Requires detailed models normally not available until detail design.
- Prior to detail design
  - Study data sheets – contact OEM
  - Establish bounds for admittances and impedances
- Detail design
  - Determine admittance and impedance characteristics through testing.
  - Verify system stability through simulation



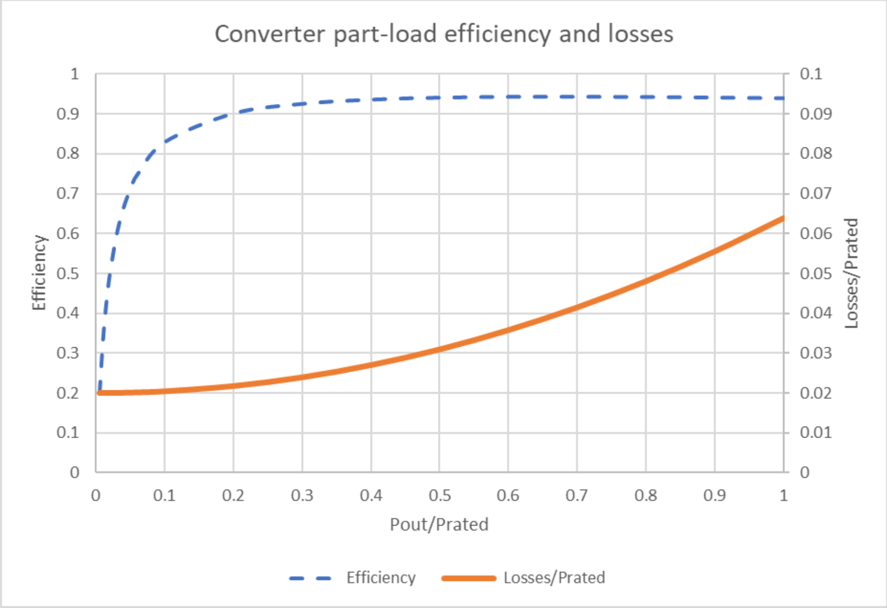
$$G(s) = S(s)L(s)$$
$$G(j\omega) = H(\omega)e^{j\theta(\omega)}$$
$$\ln(G(j\omega)) = \ln(H(\omega)) + j\theta(\omega)$$

Part Load Efficiency

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

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

- The losses in power electronics can be modelled as a constant no load loss plus "I^2R" losses
  - Efficiency is 0 at no load
  - Losses can dominate at low loads
- If power electronics is composed of multiple modules in parallel, desirable to turn off modules at low power to improve system efficiency.
- Prior to detail design
  - Study data sheets – contact OEM
- Detail design
  - Verify through testing



Margins and Service Life Allowance

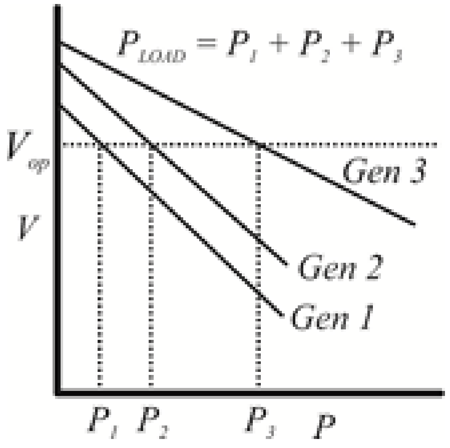
- Margins
  - Account for uncertainty in estimated loads
    - Varies from 5% to 20% depending on repeat design or new design
- Service Life Allowance
  - Account for future growth in load
    - Typically 20% or 1% per year of service life.
- Margins may be consumed during the design and construction process.
- Ship should deliver with the full Service Life Allowance.

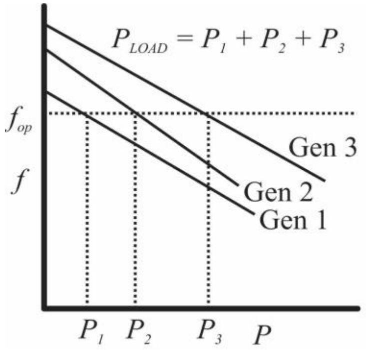
Black Start Implications

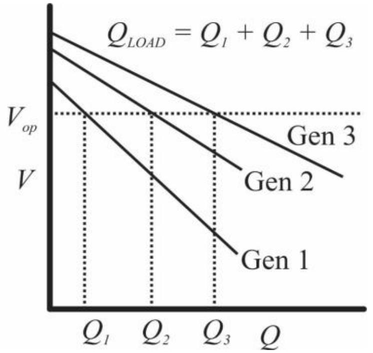
- Possible interaction between cooling system and electrical system.
- Considerations:
  - Provide UPS for control power and cooling system.
  - Derive the control power from the input side of a power electronic converter.
  - Enable power electronic converter to operate at low power without liquid cooling.
- Prior to detail design
  - Black start process should be developed.
  - Document in EPS-CONOPS.
- Detail design
  - Verify process through simulation and possibly testing.

Real and Reactive Power Sharing

- Real Power sharing among paralleled sources needed to prevent cascading overloading of sources.
- For ac systems, reactive power sharing among paralleled sources needed to prevent large circulating currents from overloading sources.
- Droop is one means for real and reactive power sharing.
  - Dc systems: As the voltage drops, source provides more power
  - AC systems: As the voltage drops, source provides more reactive power. As the frequency drops, source provides more real power.
- Other types of control signals can be used to implement real and reactive power sharing.
- Prior to detail design
  - Study data sheets – contact OEM
- Detail design
  - Detailed Modeling and Simulation
  - Testing







Condition Based Maintenance

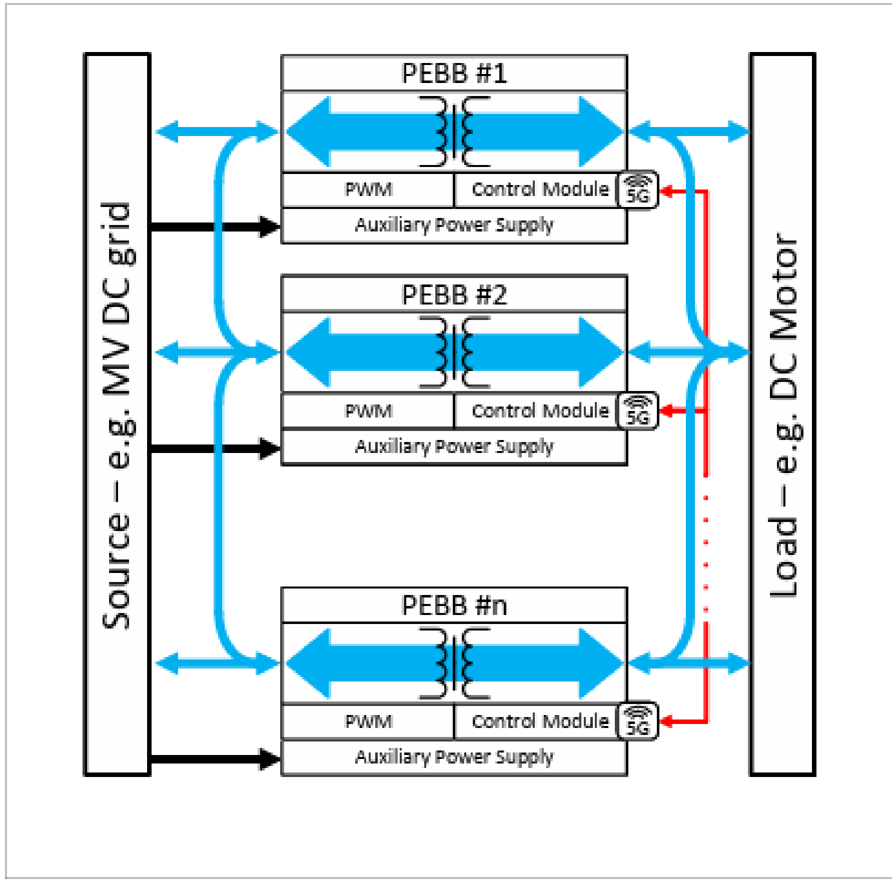
- Power Conversion Equipment should be able to determine the need for maintenance before a failure occurs.
  - Time Horizon 1: in time to obtain replacement parts.
  - Time Horizon 2: in time to defer maintenance to next maintenance availability.
- Output current can also be used to assess the material condition of loads.
- Prior to detail design
  - Develop CBM strategy
- Detail design
  - Implement the strategy

Onboard USS Carl Vinson (CVN 70)

US Navy Photo 171031-N-UD666-

Modularity

- Paralleled power modules.
  - N+1 allows for one to be out of service.
- Inrush current demands may require more modules than steady-state power requirements.
  - Locked rotor amps (LRA) of motors.
- Can provide “slots” to meet service life allowance but provide modules to meet service life allowance at delivery.
  - Populate modules as need appears.
- Prior to detail design
  - Develop modularity approach
- Detail design
  - Implement the modularity approach



Sebastian Baba, Serafin Bachman, Marek Jasinski, and Hong Li. “Evaluation of Modular Power Converter Integrated with 5GNetwork.” Energies 2021, 14(21), 7355; https://doi.org/10.3390/en14217355

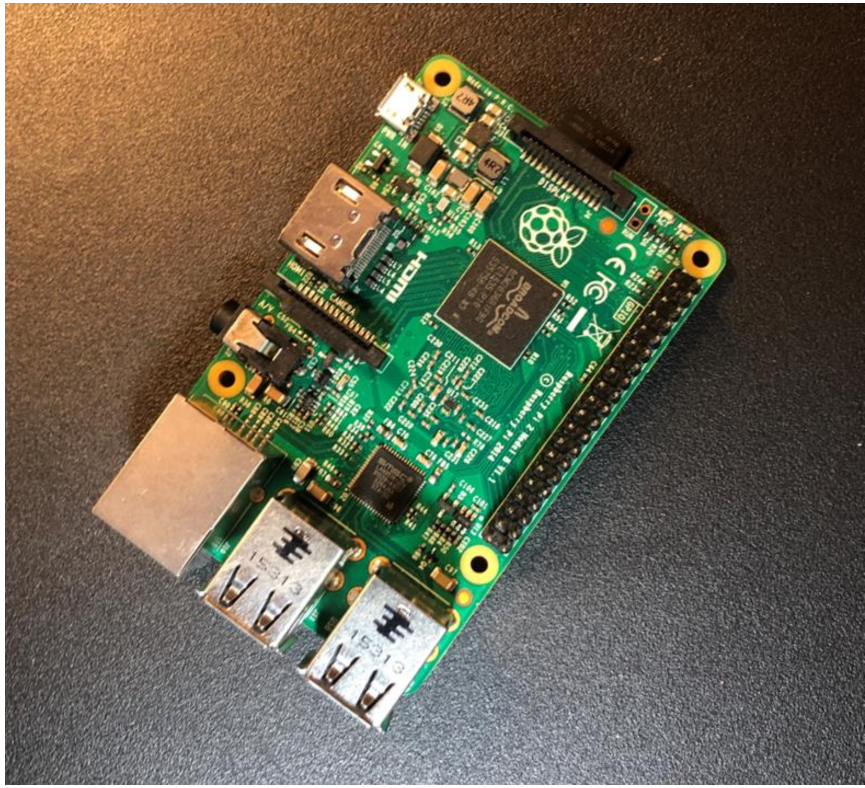
Hot Swapping

- Hot swapping allows one to replace power modules (or other type of module) without turning off the equipment.
- Connectors pins may be of different lengths to control what connects first and disconnects last
  - Longest typically the equipment ground (protective earth)
  - Pre-charge circuit
  - Main power
  - Control power - Control signals
- Safety Devices
  - Shutters on connector
  - Locking devices
  - Fail safe
  - Removal / Insertion fixtures
- Cooling
  - Connector
  - Cold Plate
- Prior to detail design
  - Develop Hot Swap approach
- Detail design
  - Implement the Hot Swap approach

Four hard disks forming a RAID array

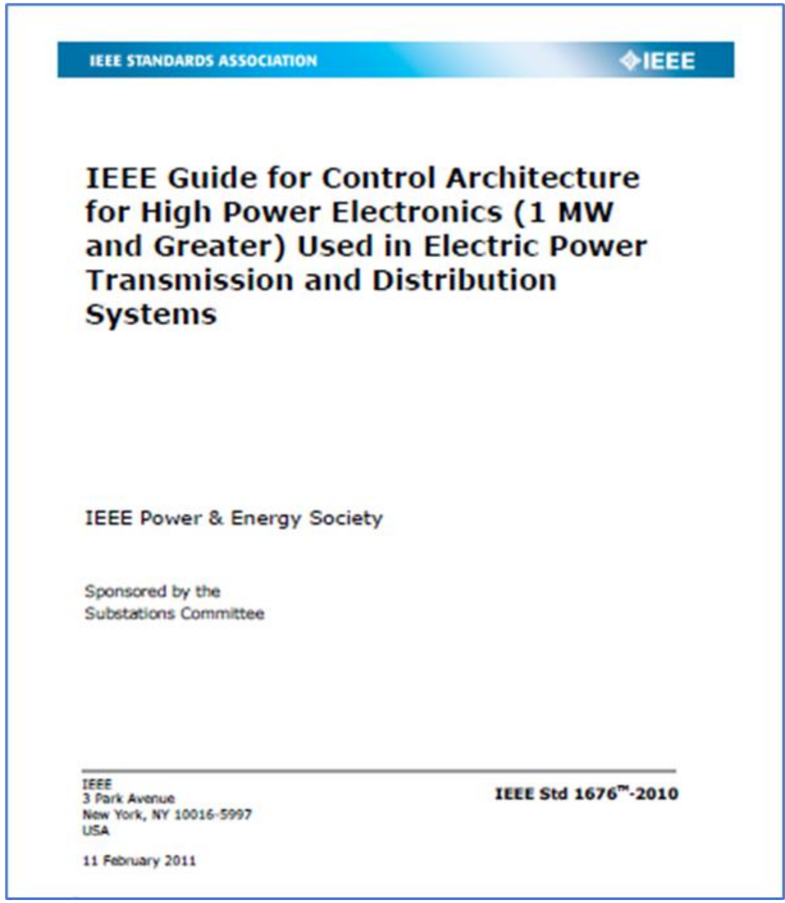
Cybersecurity

- Traditionally, threats were assumed to be from outside the ship
- Threats can occur from everywhere
  - Individuals onboard (or off) the ship
  - Compromised computer systems connected to the machinery control system
  - Malicious code hidden in components provided through the supply chain
- Cybersecurity must now be designed to an integrated architecture; an ad hoc approach layered after the fact will no longer work.
- Prior to detail design
  - Develop the cybersecurity strategy and architecture
- Detail design
  - Implement the cybersecurity strategy and architecture



Control System Interfaces

- Prior to detail design
  - Develop control system architecture
  - Control system interfaces should be understood
  - Document control system interfaces in an Interface Control Document (ICD)
  - Develop specifications for the control system
    - Allowable protocols
      - Types of messages
      - Expected equipment performance when messages received
    - Cybersecurity requirements
- Detail design
  - Update the ICD
  - Verify components meet the ICD
  - Verify system performance through simulation and/or testing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IEEE Guide for Control Architecture for High Power Electronics (1 MW and Greater) Used in Electric Power Transmission and Distribution Systems

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11 February 2011

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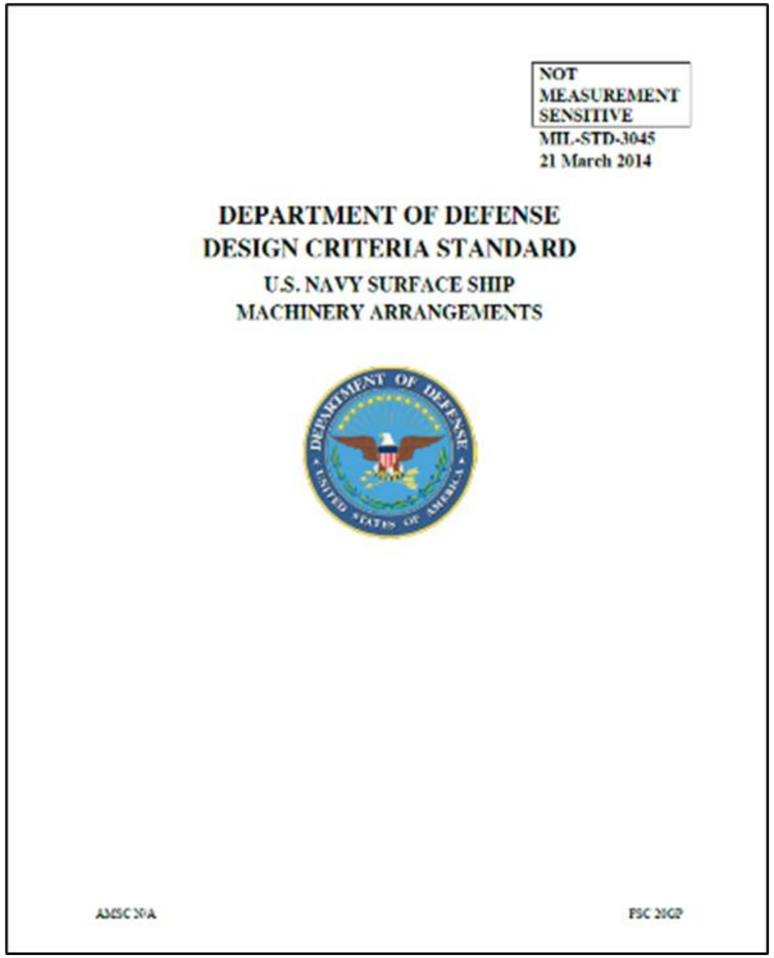
Machinery Arrangements

- Considerations
  - 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.
- Prior to Detail Design
  - Prepare machinery arrangement drawings
- Detail Design
  - Remainder of machinery arrangement effort



Conclusions

- Power Electronic Equipment are increasingly found on ships.
- Proper integration into the ship design requires one to consider the many aspects discussed in this presentation.
- Some integration activities should occur prior to detail design.
- Other integration activities may be deferred to detail design.

Thank you for your attention this concludes the presentation

Questions?