Medium Voltage Direct Current (MVDC) for Shipboard Application

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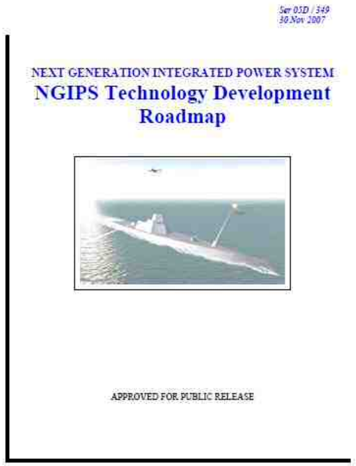
NSWC PD and NSWC CD

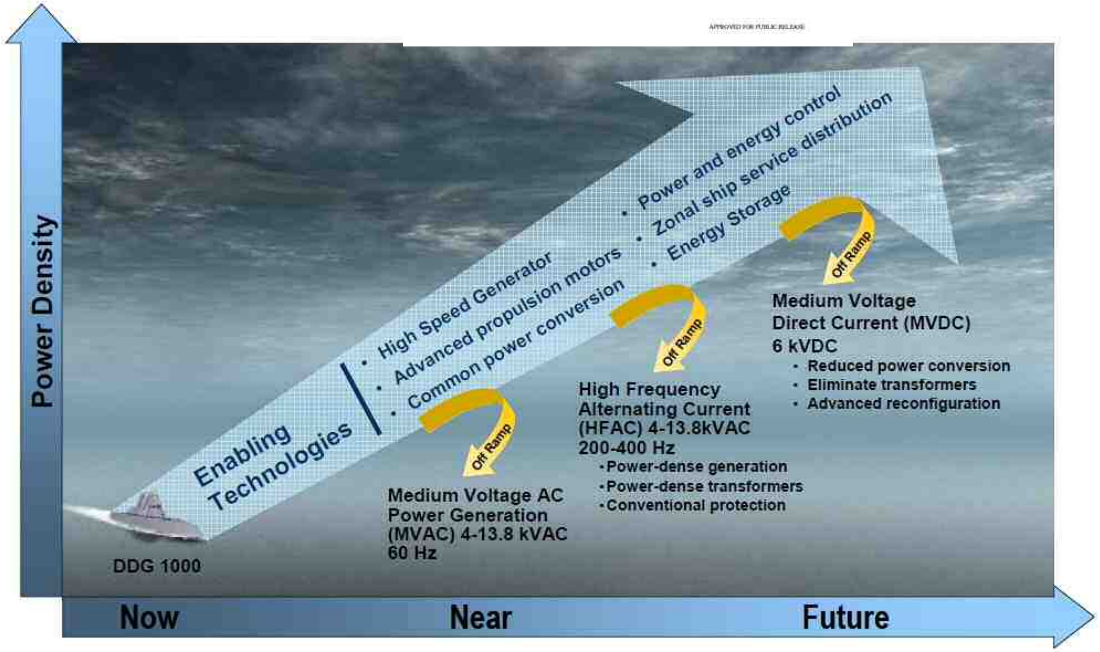
ONR MVDC Risk Reduction Program Review

22 – 23 September 2022

Background

- 2007 NGIPS Technology Development Roadmap identified MVDC as a desired future technology
- 2007 Shipyard Team Review of Next Generation Integrated System Architectures
  - Identified 13 risks associated with MVDC
  - All evaluated as High Risk
- Since 2007, multiple organizations have addressed the identified MVDC risks
  - ONR – Office of Naval Research
  - SBIR / STTR / RIF
  - PMS 320 – Electric Ships Office
  - ESRDC – Electric Ship Research & Development Consortium
  - IEEE
  - DOE – Department of Energy



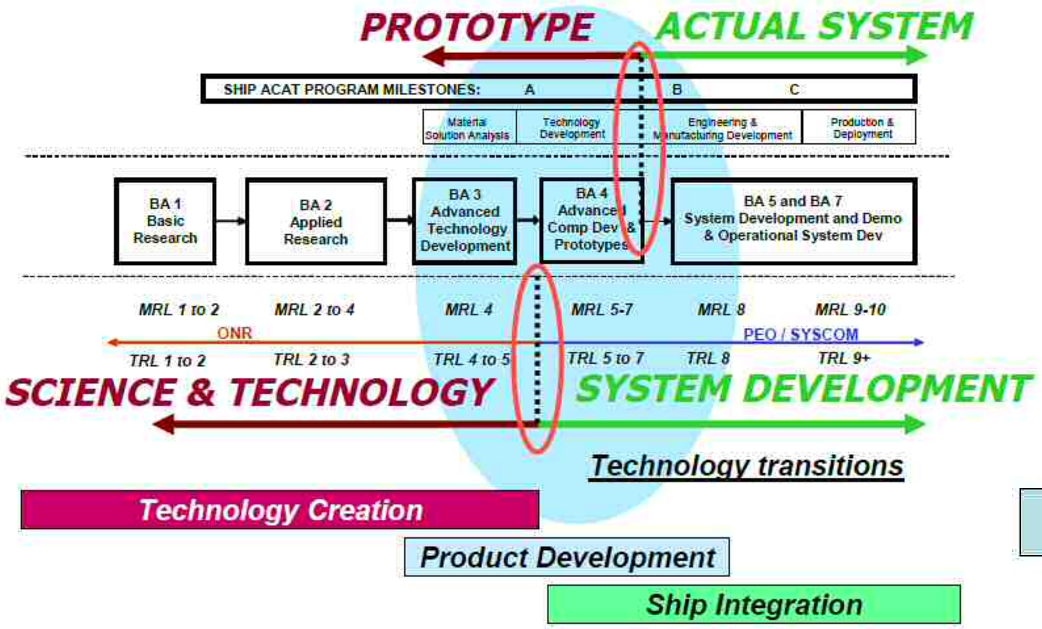


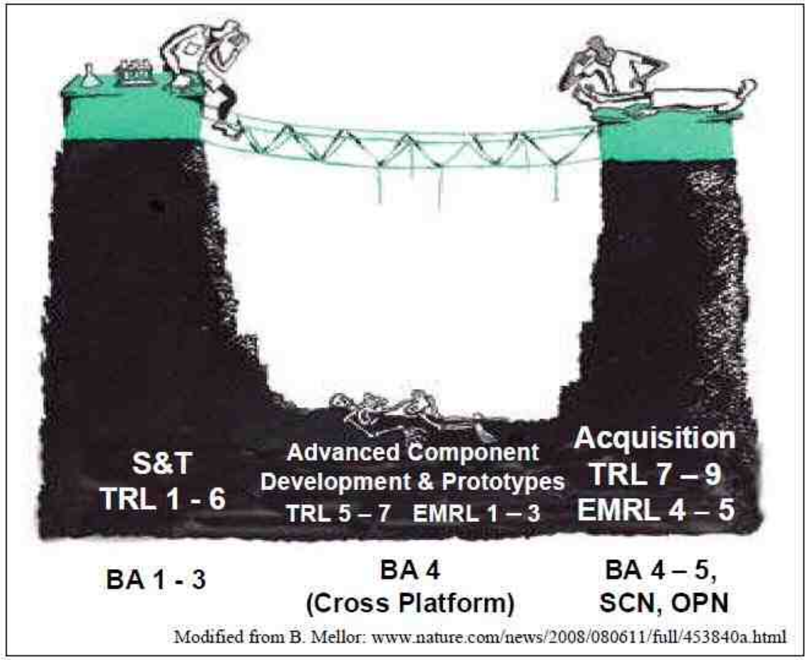
NGIPS = Next Generation Integrated Power System

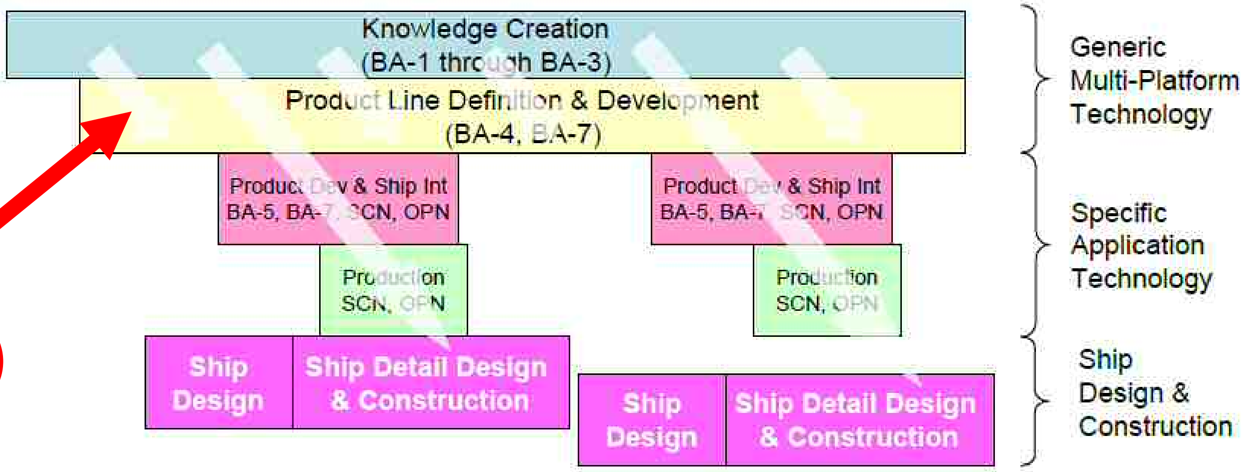
Why MVDC onboard ship?

- Better Dynamic Response for advanced weapons and sensors
  - No need to keep generators in synchronism
- Higher power density of some power system components
  - Generators (offset by need for rectifiers)
  - Can use full power rating of diesel engines
    (not limited to power at speeds that are sub-multiples of 3600 rpm)
  - Potentially switchgear (if using disconnect switches instead of breakers)
  - Potentially cable (no power factor – no inductive voltage drop: depends on voltage levels for comparison)
  - Propulsion Motor Drives (no need for “front end”)
- Faster paralleling of generators (no phase matching)
  - Shorter power outages (t2) or less energy storage.
- Decoupling power quality within a zone (low voltage) from power quality on the MVDC bus
  - Unlike MVAC – LVAC transformers where power quality on both MVAC and LVAC buses are linked.
  - Reduces system complexity.
- Efficiency about the same as an MVAC system
  - Variable speed operation of diesel engines improves efficiency
  - Offset by increased no-load losses of power conversion vs transformers
  - MVDC has reduced no-load losses associated with propulsion drives
- Lower fault currents – arc flash less of an issue

Where are we today?







Formerly PMS 320 (Disestablished 2021)

2007 Shipyard Team Review

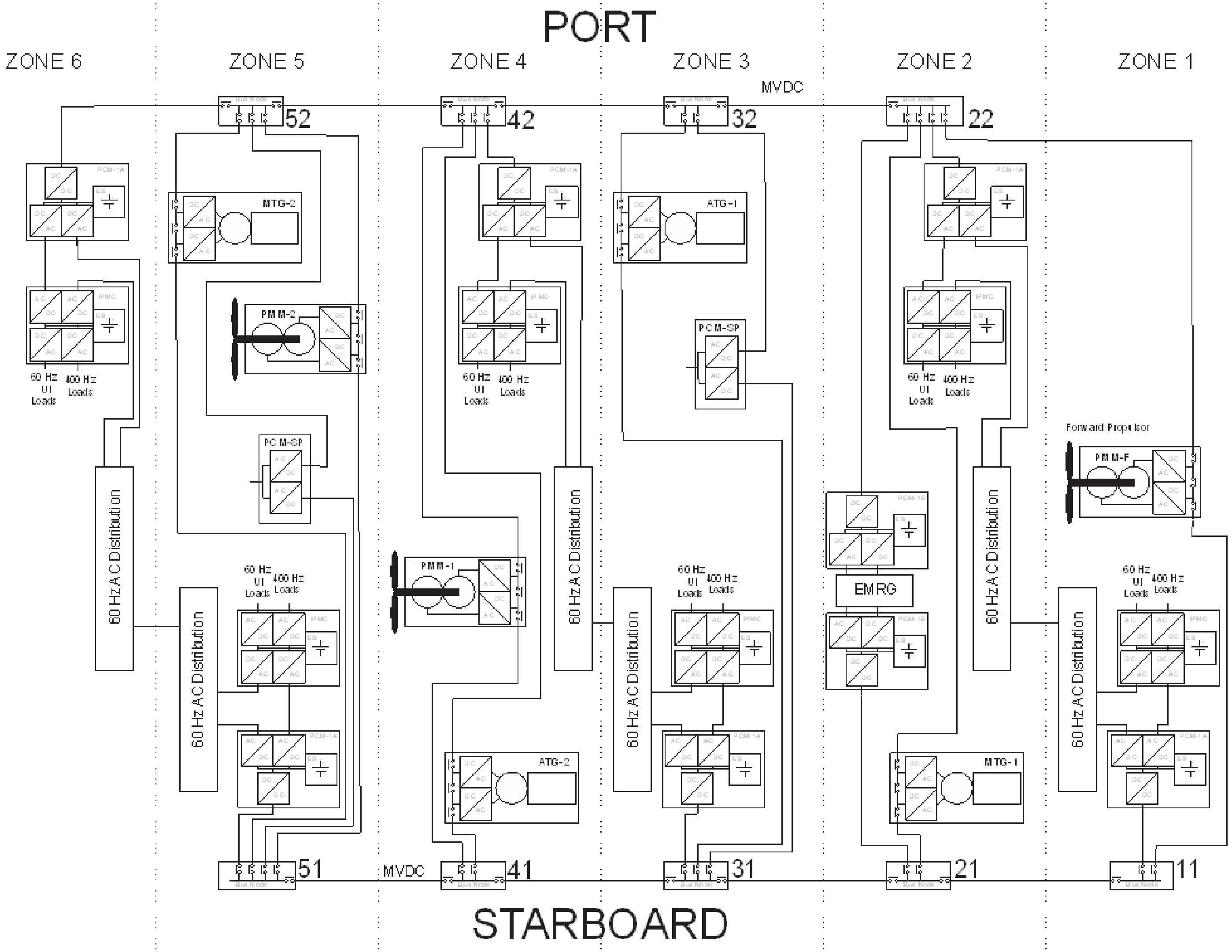
	HVDC Risk Title
HVDC #01	High Voltage DC Breaker/ Protection and Isolation System
HVDC #02	High Voltage DC Bulk Power Conversion
HVDC #03	High Voltage DC Switching Requirements
HVDC #04	High Voltage DC Bus Stability
HVDC #05	High Voltage DC Minimal industrial Base
HVDC #06	High Voltage DC Engineering and Design Standards, Requirements and Practices
HVDC #07	High Voltage DC Shore Power Interface
HVDC #08	High Voltage DC Bus Overvoltage Transient Stability
HVDC #09	High Voltage DC Ground Isolation Currents
HVDC #10	High Voltage DC Test Capability Infrastructure is Limited
HVDC #11	High Voltage DC System Integration Experience is Limited
HVDC #12	Potential Inability of High Voltage DC System to Foster a Fault Tolerant Motor Topology
HVDC #13	Risks Associated with Alternate HVDC System Architecture Without Circuit Breakers

All risks evaluated as High: Red

"The HVDC may offer advantages for long term platforms, assuming the risks can be successfully mitigated and that the assumed benefits can be realized"

"HVDC was deemed to require significant development prior to being considered for application on a future ship."

MVDC Reference Architecture



Fault Protection and Isolation

- Parts
  - Solid State Circuit Breakers (SSCB)
    - ONR FNC – water cooled 1 kV and 6 kV
    - RIF - B-Tran – air cooled 12 kV
    - LN2 Hybrid Breaker 6 kV
  - Disconnect Switches
    - SBIR N221-064 (entering Phase I)
  - Source fault current control
    - Many topologies available
  - Load Energy Storage
    - ONR / PMS 320 Energy Magazine
  - Protection Relay
    - Missing Link
    - ONR Developing theory

- System Design
  - STTR N16A-T009 (ended at Phase II)
  - Several Papers on topic
  - Strategies
    - SSCB only
    - Disconnect only
    - Hybrid
  - MVDC Reference Architecture
- Assessment:
  - Multiple methods feasible
  - "Right answer" depends on economics.
    - Need actual hardware to perform cost analysis
  - Need a protection relay
  - Risk moved from Red to Yellow

Medium Voltage Direct Current (MVDC) Protection Relays & Associated Sensors

Technology Objective: Develop a Fault Protection relay and associated sensors for 1 kV and 12 kV MVDC distribution systems to implement overcurrent and differential / directional protection in both breaker and breakerless architectures

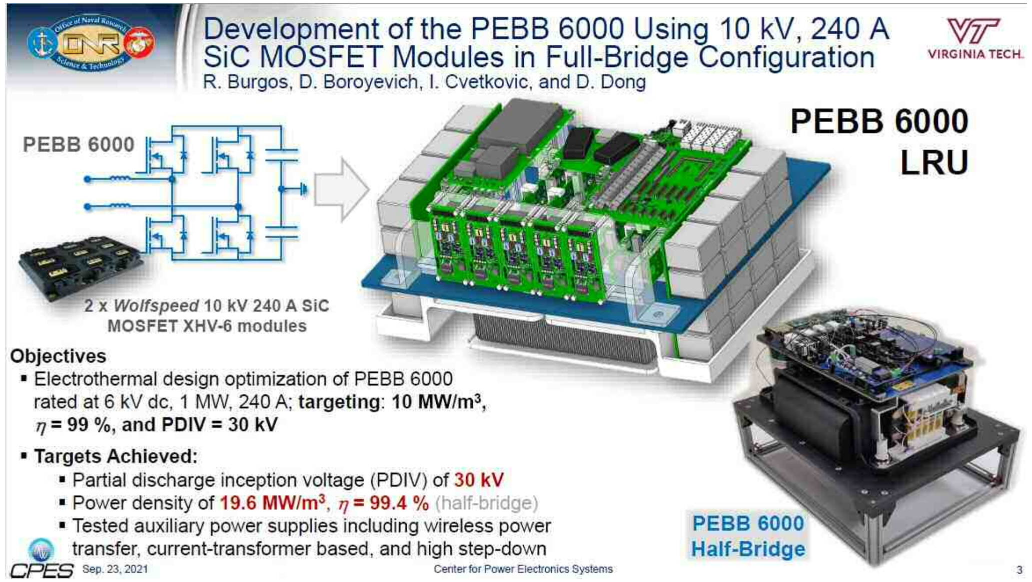
Technological Challenge/Risk: Minimizing false alarms by coordinating multiple current readings when fault currents rise with high di/dt, particularly in a bus topology supporting pulsed power loads. Proving robustness and reliability of MVDC current sensors. Enabling flexibility by simplifying effort required to integrate new loads over the ship's service life.

Navy/Program Requirement: MVDC systems promise improved affordability and power density over MVAC systems for future warships (such as future flights of DDGX) employing high power directed energy weapons and sensors. Fault protection relays are key to an MVDC system.
This effort directly supports the Navy's 2019 Naval Power and Energy Systems Technology Development Roadmap (TDR).

Benefit/Payoff: Reliable and affordable MVDC fault protection systems compatible with both breaker and breakerless fault protection strategies to enable integration of multiple high power pulsed weapons and sensors into warships. Reduce engineering effort required to integrate new loads over the ship's service life.

Transition/Acquisition Strategy: Test protection relays and associated sensors in the PMS 460 Integrated Power and Energy System Test Facility (ITF) to demonstrate technology readiness. Incorporate into ship design.

Bulk Power Conversion



ONR FUNDED

- Risk is that power conversion equipment may not meet power density requirements.
- Technology Developments
  - SiC component maturation
  - SiC converter designs
  - Improved high frequency transformers
  - Power Electronic Building Block (PEBB)
  - Better understanding of Common Mode Issues
- Assessment
  - High efficiency compact power conversion is now technically feasible.
  - Keeping costs under control may prove to be a challenge
  - Risk moved from Red to Yellow

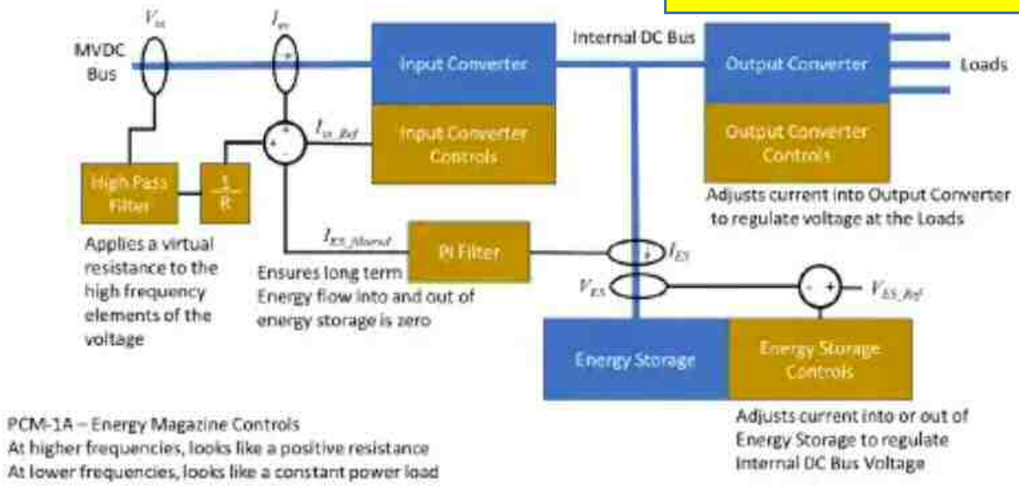
Switchgear Requirements

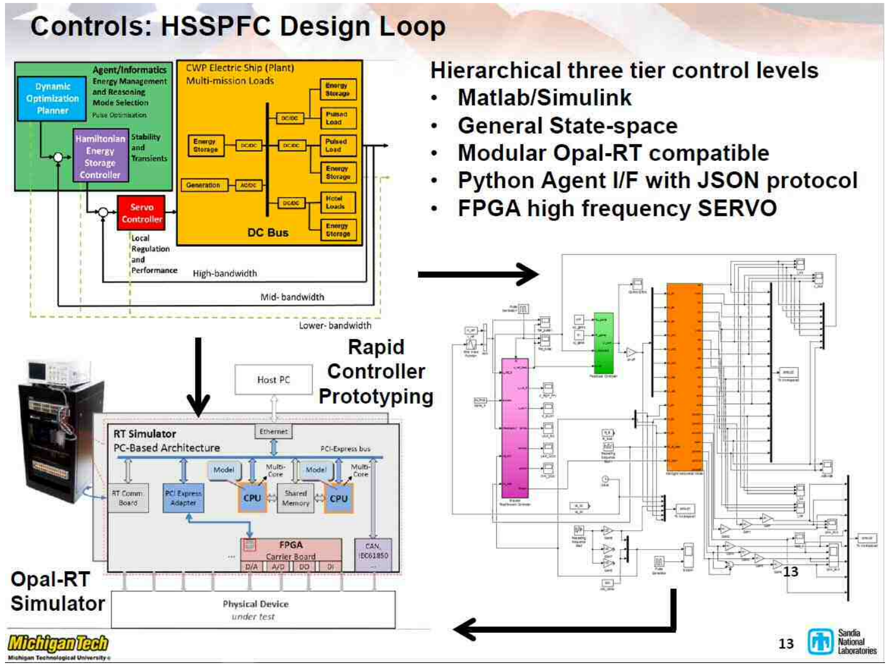
- Risk of availability of MVDC Switchgear as a standard product
- Technology Development
  - RIF developed requirements and preliminary designs for SSCB
  - SBIR N221-064 addressing for disconnect switches

- Assessment
  - Preliminary designs of MVDC switchgear exist.
  - Have not been prototyped.
  - Risk moved from Red to Yellow

Bus Stability

- Risk of constant power loads with negative impedance characteristics causing bus instability.
- Technology Development
  - Control Methods Have been develop to address bus stability
    - ONR
    - PMS 320 funded Sandia National Laboratories work
- Assessment
  - Technology exists to ensure MVDC bus stability
  - Trade-offs exist between control approach and distributed energy storage
  - Risk moved from Red to Yellow





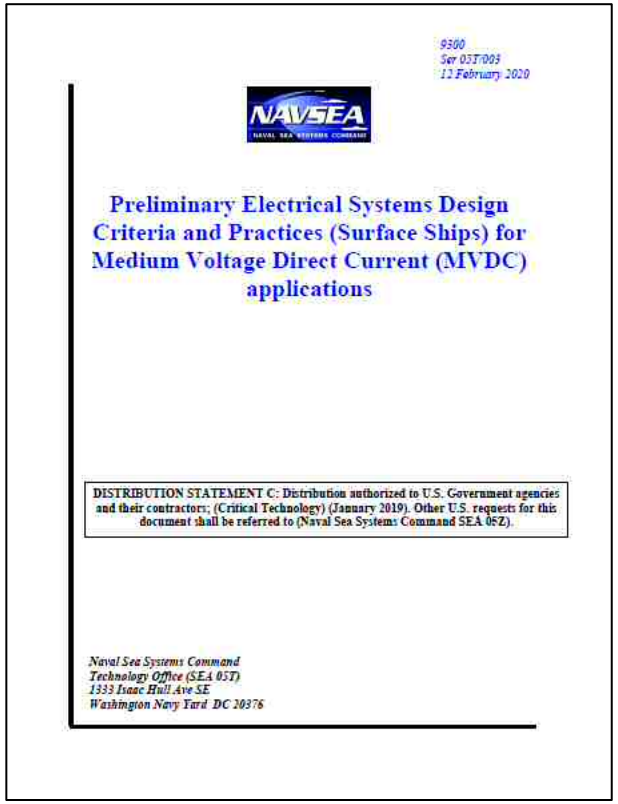
Minimal Industrial Base

- Risk is that MVDC will not have sufficient Logistics support
- Marine Machinery Association: MVDC Working Group
  - Currently has 25 member companies
- SBIR / STTR developing small businesses with MVDC experience
- ESRDC developing workforce
- Industrial base is expanding
  - Wind energy
  - Solar energy

- Assessment
  - Industrial Base is better, but should be even better.
    - Needs more work
  - Risk still red (but closer to yellow)

Engineering and Design Standards, Requirements and Practices

- IEEE 1709-2018 IEEE Recommended Practice for 1 to 35 kV Medium Voltage DC Power Systems on Ships
- IEEE 1826-2020 IEEE Standard for Power Electronics Open Systems Interfaces in Zonal Electrical Distributions Systems Rated above 100 kW.
- Norbert Doerry, "Preliminary Interface Standard, Medium Voltage Electric Power, Direct Current," Naval Sea Systems Command, Technology Office (SEA 05T), Ser 05T / 002 of 16 January 2020. Also available from DTIC AD1090170
- Norbert Doerry, "Preliminary Electrical Systems Design Criteria and Practices (Surface Ships) for Medium Voltage Direct Current (MVDC) Applications," Naval Sea Systems Command, Technology Office (SEA 05T), Ser 05T / 003 of 12 February 2020. (limited distribution) Available from DTIC AD1091262
- Norbert H. Doerry, "Impedance of Four-Conductor Cable," Naval Sea Systems Command, Technology Office (SEA 05T), Ser 05T / 011 of 2 Oct 2020. Available from DTIC AD1110943



9300
Ser 05T/003
12 February 2020

NAVSEA
NAVAL SEA SYSTEMS COMMAND

Preliminary Electrical Systems Design Criteria and Practices (Surface Ships) for Medium Voltage Direct Current (MVDC) applications

DISTRIBUTION STATEMENT C: Distribution authorized to U.S. Government agencies and their contractors; (Critical Technology) (January 2019). Other U.S. requests for this document shall be referred to (Naval Sea Systems Command SEA 05Z).

Naval Sea Systems Command
Technology Office (SEA 05T)
1333 Isaac Hull Ave SE
Washington Navy Yard DC 20376

- Assessment
  - Preliminary and issued standards exist … need more experience using them.
  - Risk Moved from Red to Yellow

Shore Power Interface

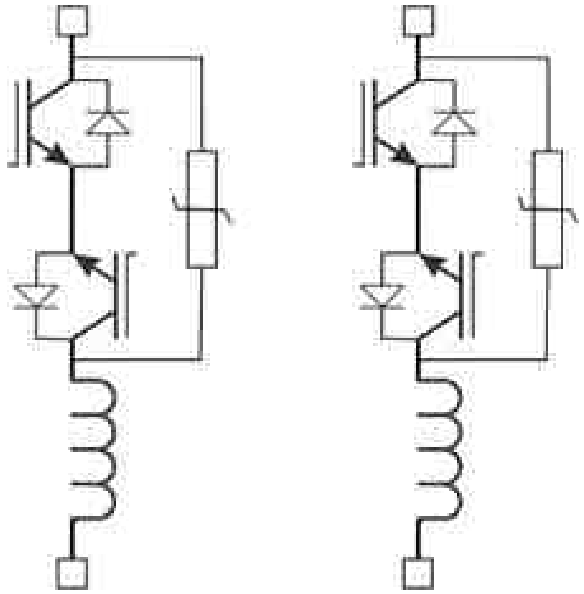
- Employ Navy MVAC shore power connections
- Use dedicated isolated power converter
- In future may explore commercial standards for shore power.

https://eslpwr.com/shore-power/

- Assessment
  - Technology exists, need to do engineering for a product
  - Risk Moved from Red to Yellow (perhaps green)

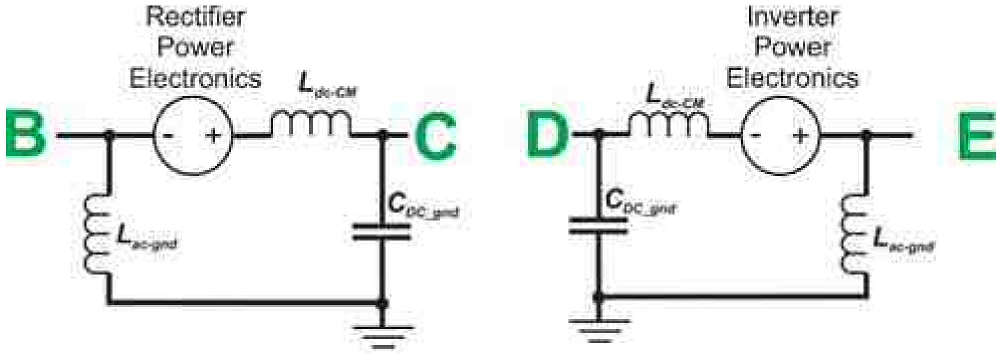
Bus Overvoltage Transient Stability

- SSCB incorporate surge suppression across the breakers to control transient overvoltages.
- Switchgear will also likely contain line to line and line to ground surge suppression to ensure power quality interface standard.

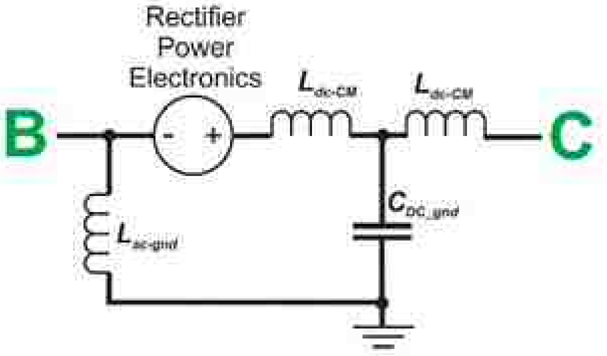


- Assessment
  - Technology exists, need to do engineering for a product
  - Risk Moved from Red to Yellow (perhaps green)

Ground Isolation Currents



(a)



(b)

- Common Mode Current / Voltages
- Much better understanding
  - ONR
  - STTR (N16A-T012) (in Phase 2.5)
  - ESRDC
- Can mitigate via …
  - Common mode filter design
  - Grounding networks
  - Converter design
  - Modulation scheme

- Assessment
  - Technology exists, need to do engineering for a product
  - Risk Moved from Red to Yellow (perhaps green)

Test Capability Infrastructure is Limited

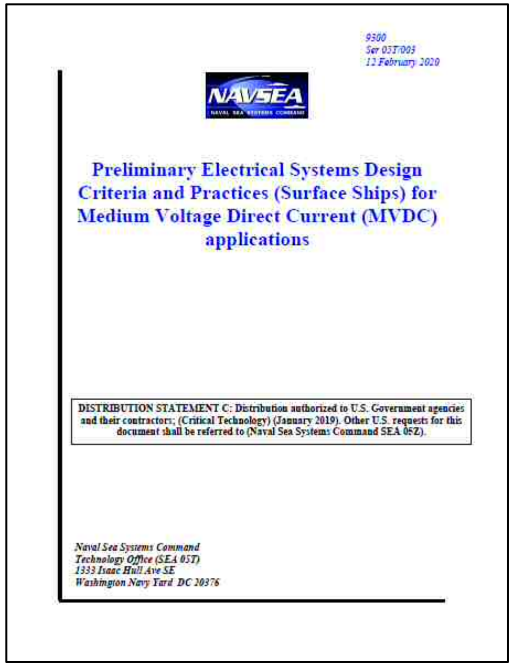
- MVDC is available at low power levels in many locations
- MVDC is available at moderate power levels
  - FSU CAPS (5 MW)
- MVDC is available at high power levels for short time periods via capacitor discharge
- A full scale high power test facility would be beneficial

https://www.caps.fsu.edu/about-caps/tour-the-caps-facilities/

- Assessment
  - Capabilities exist, they need to be improved and more prevalent
  - Risk Moved from Red to Yellow

System Integration Experience is Limited

- Risk that insufficient system integration of MVDC systems will result in cost growth, and addition of components that negatively impact power density.
- Have developed preliminary MVDC interface standard and preliminary design practices and criteria manual.
- Dynamic models of many components have been developed for system assessments.
- Shipyards have not been heavily involved in system integration efforts.



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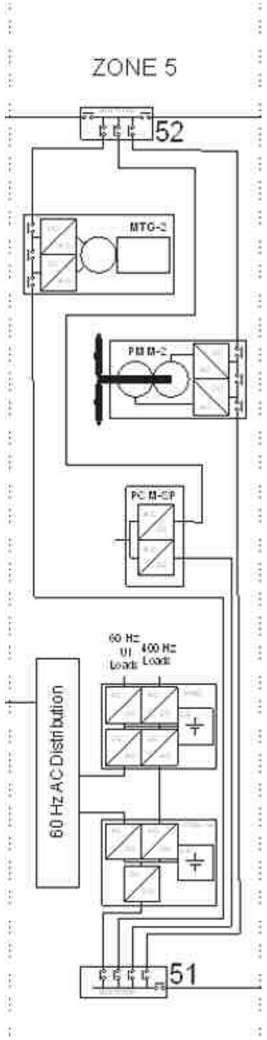
- Assessment
  - Dynamic models and standards improve chances of successful system integration.
  - Shipyards need more experience
  - Risk still red (but closer to yellow)

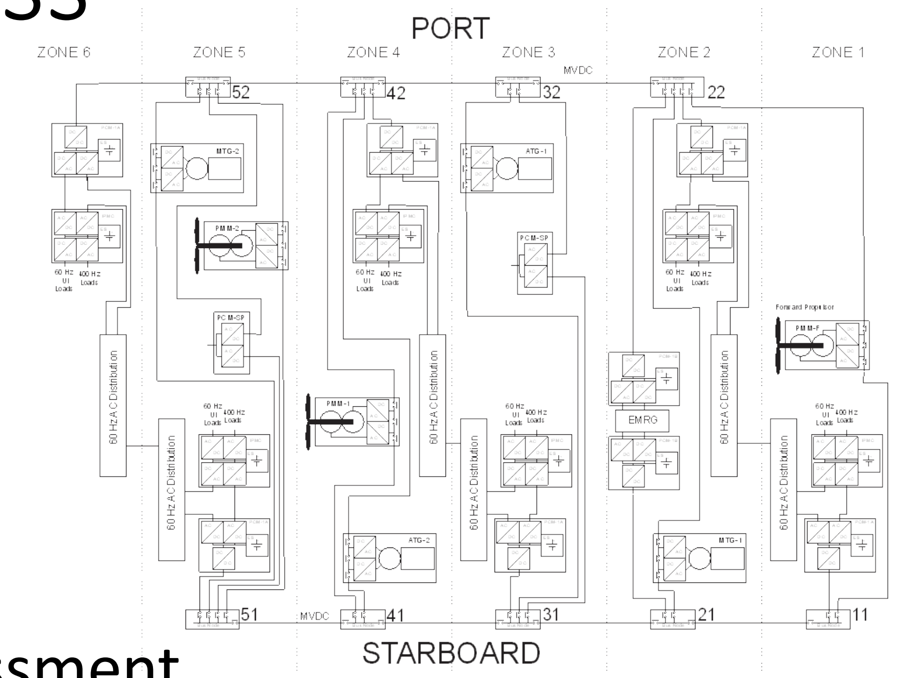
Potential Inability of MVDC system to foster a fault tolerant motor topology

- Phase shifting transformers on MVAC systems inherently provide a degree of fault tolerance not possible with MVDC systems.
- Proposed solution is to use a dual wound motor that is powered from independent MVDC buses.
- Assessment
  - Technology exists, need to do engineering for a product
  - Risk Moved from Red to Yellow (perhaps green)



Risks associated with breakerless architectures

- Risk that resorting to a breakerless architecture late can lead to schedule delays and cost growth.
- Breakerless architectures have been explored and found to be feasible with the right combination of power conversion, energy storage, protective relaying, and disconnect switches.



- Assessment
  - Conceptual designs of breakerless architectures have been developed
  - Can use existing technology for most elements – need protective relay
  - Have not yet prototyped at full scale.
  - Risk moved from Red to Yellow

Other technical topics

- MVDC Insulation – Partial Discharge and Space Charge
    - ONR addressing theory
    - SBIR N211-069 (entering Phase II)
- MVDC creepage and clearance
    - ONR addressing theory
    - STTR N22A-T011 (entering Phase I)
- MVDC Casualty Power System
    - SBIR N162-109 (completed Phase II)
- MVDC Coaxial Bus Pipe
    - SBIR N201-055 (in Phase II)
    - NSRP RA 19-01
    - NSRP RA 20-01

https://www.columbiagroup.com/capabilities/engineering/ship-design/medium-voltage-casualty-power-system/mvdc-casualty-power-system/

https://www.nsrp.org/wp-content/uploads/2021/03/Insulated-Bus-Pipe-IBP-for-Shipboard-Use.pdf

Risk Mitigation Summary

	2007	2022
Breaker / Protection and Isolation System		
Bulk Power Conversion		
Switchgear Requirements		
Bus Stability		
Minimal Industrial Base		
Engineering and Design Standards, Requirements, and Practices		
Shore Power Interface		
Bus Overvoltage Transient Stability		
Ground Isolation Currents		
Test Capability Infrastructure is Limited		
System Integration Experience is Limited		
Foster a Fault Tolerant Motor Topology		
Alternate Systems Archicture without Circuit Breakers		

Conclusion

- Technology Base for MVDC is robust
  - Reflects 15 year investment by ONR and NAVSEA
  - Most technologies at or beyond TRL 5
- Of 13 “Red” risks in 2007, all but 2 are no longer “Red”
  - Industrial Base
  - Systems Integration
- MVDC is ready to transition to Product Development
  - Advance component and system development to TRL 7 (cross platform)
  - To whom to transition?