Naval Power and Energy Systems Technology Development Roadmap

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Naval Power and Energy Systems
Technology Development Roadmap

10/8/15

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17 June 2015

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Executive Summary

This Naval Power and Energy Systems (NPES) Technology Development Roadmap (TDR) is an update to the Naval Power Systems Technology Development Roadmap signed by COMNAVSEA on 29 April 2013. The 2013 NPS TDR updated the Next Generation Integrated Power System (NGIPS) Technology Development Roadmap issued in November 2007. The purpose of the NPES TDR is to align platform electric power systems and mission systems developments and to enable capability based budgeting.

This update continues to include back fit of technologies into ships already in service and ships under construction, as well as forward fit into new ships. It continues the approach of deriving electric requirements and evolving technology alternatives to reflect the needs of the Navy community. Office of the Chief of Naval Operations (OPNAV) resource sponsors, acquisition program offices, and the Navy technical community participated in a rigorous roadmap process that evaluated capabilities and technologies, projected NPS needs, aligned technologies with needs to identify technology gaps, and provided recommendations to fill those gaps.

Future platforms and general requirements are identified in the Navy's 30 year shipbuilding plan and other Department of Defense (DoD) and Navy guidance documents. Given historical technology development cycles and insertion time periods, planning must begin now to shape technologies necessary to support out year ships. A primary driver for NPES is to enable capability for legacy and mod repeat platforms while simultaneously supporting future ships. The NPES TDR responds to the emerging needs of the Navy and, while specific in its recommendations, it is inherently flexible enough to adapt to changing requirements and threats that may influence the 30 year shipbuilding plan. The TDR is updated biennially.

Advanced mission systems such as weapons and sensors remain the capabilities most relevant to NPES. However, this update includes the following adjustments to other relevant capabilities:

- Communications & information security / cybersecurity have been added to advanced weapons and advanced sensors as primary drivers of NPES
- Arctic operations and unmanned systems have been added as secondary drivers
- Flexible ship features and mission modules with their supporting interfaces have been added with impact to be determined
- Operational energy, renewable energy, and alternative fuels have been removed as power system drivers and are now included as ubiquitous requirements

The 2013 NPS TDR introduced the concept of a common, modular, scalable intermediate power system that could be used across multiple mission systems and ship installations. This concept, known as Energy Magazine (EM), is discussed in additional detail including results of completed work, additional recommended development, and leveraging EM into an advanced, affordable power system architecture to support new future surface ships. This advanced power architecture is anticipated to incorporate multi-use distributed energy storage as well as advanced controls and energy management within an Integrated Power System (IPS) and result in a fully Integrated Power and Energy System (IPES). Specific recommendations for near-term development (2016-2025) include the following major areas as well as other recommendations:

- Demonstrate a full scale, modular, scalable EM
- Develop advanced MVDC circuit protection and demonstrate at full scale an MVDC power distribution system
- Develop advanced energy storage options for existing and future systems

- Develop advanced controls to provide total ship power and energy management for multiple dynamic high power loads from multiple and shared energy generation and storage devices, and interface with the ships combat system to anticipate, allocate and pre-position power and energy
- Develop a Ship Continuity and Quality of Power Model that has the capability to perform dynamic end to end analysis from the shipboard voltage interface up to and including the loads
- Develop and demonstrate a prototype IPES for notional future surface combatants including advanced ship wide thermal management
- Develop energy recovery technologies suitable for operation in Navy applications

During the mid-term period (2026-2035) the engineering development and integration of actual ship hardware for future platforms will be necessary and include the following:

- Build and test engineering development models (EDMs) and first article production components for all critical technologies determined to be required to meet platform capability and power density requirements
- Complete and validate the detailed, real time IPES electric and control system modeling and simulation (M&S) capabilities including power mission systems and hardware in the loop options for critical capabilities for all platform variants
- Conduct IPES testing for all platform variants at a land based test site to verify electric integration of the power and energy system, IPES modularity, and integration of the power system control and combat and mission systems
- Demonstrate a full-scale shipboard energy recovery system if Science and Technology (S&T) investments in the near-term have matured the underlying technology sufficiently

In the far-term (2036 and beyond), it is likely that Navy platforms will have numerous high powered mission systems operating simultaneously, that the Navy will introduce additional flexible and modular ships designed to accommodate multiple payload packages, that commercial advances in energy storage and computing capability will continue, and that these technological advances will result in ship systems and mission systems that will become more intelligent and autonomous. The following supporting developments are recommended in the far-term:

- Build and test an advanced, flexible, adaptable, intelligent and upgradeable shipboard electric distribution system to:
    - Eliminate centralized load centers and switchboards using inline circuit protection, converters, etc.
    - Accommodate modular and upgradeable energy storage
    - Reduce electric distribution system weight
    - Provide autonomous reconfigurable power transmission paths
    - Provide adequate circuit protection
    - Leverage commercial developments in energy storage and computing capability
- Demonstrate technology advancements, such as advanced conductors, fuel cells, and autonomous controls, whether developed through Navy investment or independently pursued by industry, that support the Navy's approach to product area utilization

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1.0 Introduction

1.1 Purpose

The *Naval Power Systems TDR* was signed by COMNAVSEA on 29 April 2013, and included a commitment to a biennial update. This 2015 release represents the fulfillment of that commitment and is a focused refresh of the 2013 document. The 2015 *Naval Power and Energy Systems Technology Development Roadmap* includes the addition of energy in the document's title, intended to highlight the importance of energy management and energy storage as part of fully integrated power and energy systems aboard naval ships.

The primary purposes of the NPES TDR are to align electric power and energy system developments with warfighter needs and to enable capability based budgeting. Additionally, this NPES TDR is intended to:

- Establish planning information in order to provide appropriate, mature technologies to meet platform timelines – providing the right technology to the Fleet at the right time
- Establish a common thread for electric power and energy systems requirements across Navy platforms
- Guide and coordinate Navy and DoD investments in affordable electric power and energy technologies and products
- Develop common terminology and increase communication with industry
- Influence investment decisions by other government agencies, academia, and private industry

The NPES TDR retains several tenets from previous TDR releases. These include a focus on reducing total ownership costs, cross platform commonality, providing suitable quality of service, power continuity, and open architecture.

This NPES TDR is not intended to provide the acquisition strategy or development strategy for individual ship platforms or programs. The specifics of individual development efforts will vary in terms of funding, progress, technical and programmatic issues, and future plans. Specific plans and actions are more properly addressed in the context of those particular programs.

1.2 Background

In 2006, the Chief of Naval Operations directed that a NGIPS flag level steering board be established to provide guidance and oversight of power systems development, conduct a comprehensive review of the technical challenges, and recommend a path for fielding electric power and energy systems subsequent to DDG 1000 Class. The Board was directed to consider both surface ship and submarine future requirements and the power infrastructure for electric weapons and sensors, as well as opportunities to back fit technology to improve the capability and fuel utilization of the current fleet. It was further directed to consider the proper pacing and focus of these efforts with respect to the available S&T / Research and Development (R&D) budgets.

In 2007, as a result of that flag board's recommendations, Assistant Secretary of the Navy for Research, Development and Acquisition (ASN RDA) established the Electric Ships Office (ESO) within Program Executive Office (PEO) Ships, organizationally known as PMS 320, to develop and provide smaller, simpler, more affordable, and more capable electric power systems for all

Navy platforms.[1] The ESO Executive Steering Group (ESG) was established to provide centralized leadership. The *NGIPS TDR*[2] was signed in December 2007 and described potential future IPS' developments in terms of various architectures as well as a functional breakdown of modules and architectures.

The 2013 NPS TDR updated the 2007 NGIPS TDR, and changed the name to include naval power systems to embrace a broader scope. The 2013 version included back fit of technologies into ships already in service and ships under construction, forward fit into new ships in the 30 year shipbuilding plan, a focus on energy efficiency and energy security, a new approach to deriving electric requirements, and descriptions of evolving technology alternatives.

1.3 Current Landscape for Naval Power and Energy Systems

Since the release of the NPS TDR in 2013, several developments have occurred within the Navy that impact NPES:

- NAVSEA issued a new strategic business plan[3] with four mission priorities:
  - "It's All About the Ships"
  - Workforce excellence and judiciousness
  - Culture of affordability
  - Cybersecurity
- NAVSEA awarded a contract for the Engineering and Manufacturing Development (EMD) Phase of the Air and Missile Defense Radar (AMDR) in October 2013[4]
- Initial Operating Capability (IOC) date for the Solid State Laser (SSL) is FY 2022
- PCU ZUMWALT (DDG 1000) was christened on 12 April 2014 and testing / activation for the IPS is underway
- The DDG 1000 Class is being considered for installation of the electromagnetic rail gun
- PEO Ships released the *Flexible Ship Roadmap* on 30 May 2014 which describes numerous technologies and characteristics with potential to help achieve adaptability, modularity, scalability, commonality, and reduce costs both for back fit on our existing fleet and for future warships
- The Navy's 2015 30 year shipbuilding plan was forwarded to Congress on 01 July 2014[5]
- The Navy's 2016 30 year shipbuilding plan[6] was forwarded to Congress on 2 April 2015 as an update to the 2015 30 year shipbuilding plan
- The amphibious assault ship USS AMERICA (LHA 6) was commissioned on 11 October 2014.[7] LHA 6 is the first ship of the class and features a hybrid electric propulsion system that couples two 35,290 shaft horsepower gas turbines and two 5,000 horsepower auxiliary propulsion motors.

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[1] United States. Department of the Navy, PEOSHIPS INST 5400.8, 30 November 2007.
[2] Naval Sea Systems Command, Washington, DC. "Next Generation Integrated Power System (NGIPS) Technology Development Roadmap," 30 November 2007.
[3] Naval Sea Systems Command, Washington, DC. "Strategic Business Plan for 2013-2018", 2nd Edition.
[4] *U.S. Navy Fact Sheet - AIR AND MISSILE DEFENSE RADAR (AMDR)* [Online]. Available: http://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=306&ct=2
[5] Deputy Chief of Naval Operations. "Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for FY2015," June 2014.
[6] Deputy Chief of Naval Operations. "Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for Fiscal Year 2016," April 2015.
[7] *U.S. Navy Fact Sheet - Amphibious Assault Ships - LHA/LHD/LHA(R)* [Online]. Available: http://www.navy.mil/navydata/fact_print.asp?cid=4200&tid=400&ct=4&page=2

- A Solid State Laser was demonstrated on the USS PONCE in the first quarter of FY15
- The DDG 51 Hybrid Electric Drive (HED) system successfully completed its Factory Acceptance Test (FAT) and hardware was delivered to the Naval Ship Systems Engineering Station (NAVSSES) in January 2015.
- The *DoD Energy Policy* was issued on April 16, 2014, and states "It is DoD policy to enhance military capability, improve energy security, and mitigate costs in its use and management of energy."
- A *Cooperative Strategy for 21st Century Seapower* was issued in March 2015 and states that as the Navy develops the future force, it will value energy as a critical resource across all naval missions to enhance our operational reach, energy security, and energy independence

These significant recent developments reinforce that NPES are a critical enabler for current and future ships. Since the 2013 NPS TDR, the recognition of the critical importance of improved NPES has increased inside the Navy, in conversations with our international partners, in the press, as well as within industry and academia. The 2013 NPS TDR has shown to be an effective tool for engagement with industry. Industry partners have provided suggestions, feedback and offered proposed solutions to the challenges identified in the 2013 NPS TDR. The document retains the focus and format of the 2013 NPS TDR with additional depth and revisions as required. The technology sections have been significantly revised to reflect technology advancements. Requirements have been updated to incorporate evolving planning for high energy systems and the Navy's 2016 30 year shipbuilding plan. Additional information regarding IPS' that fully integrate energy storage has been incorporated.

1.4 Technology Development Roadmap Construct

In developing the NPES TDR, the Navy adopted the *Fundamentals of Technology Roadmapping* approach developed by Sandia National Laboratories[8] and tailored it to meet the needs of naval power systems. The approach outlines the following as key steps in developing a technology roadmap:

- NPES TDR - Identify the "product" that will be the focus of the roadmap
- Requirements pull - identify the critical system requirements and their targets
- Technology push - specify the major technology areas, their drivers and their availabilities
- Current and projected technologies - align available technologies with requirements technologies where possible
- Identify Gaps - identify technology availability gaps based on required needs and provide development recommendations

Figure 1 illustrates the approach used in drafting the NPES TDR. The Sandia process was modified to suit the Navy's unique environment. This refresh followed the same general process but focused on areas requiring significant additional effort based on reviewer feedback, technology developments or emerging requirements.

[8] O.H. Bray and M.L. Garcia, "Fundamentals of Technology Roadmapping," Sandia National Laboratories, Albuquerque, NM, SAND97-0665, Distribution Unlimited Release Category UC-900, April 1997.

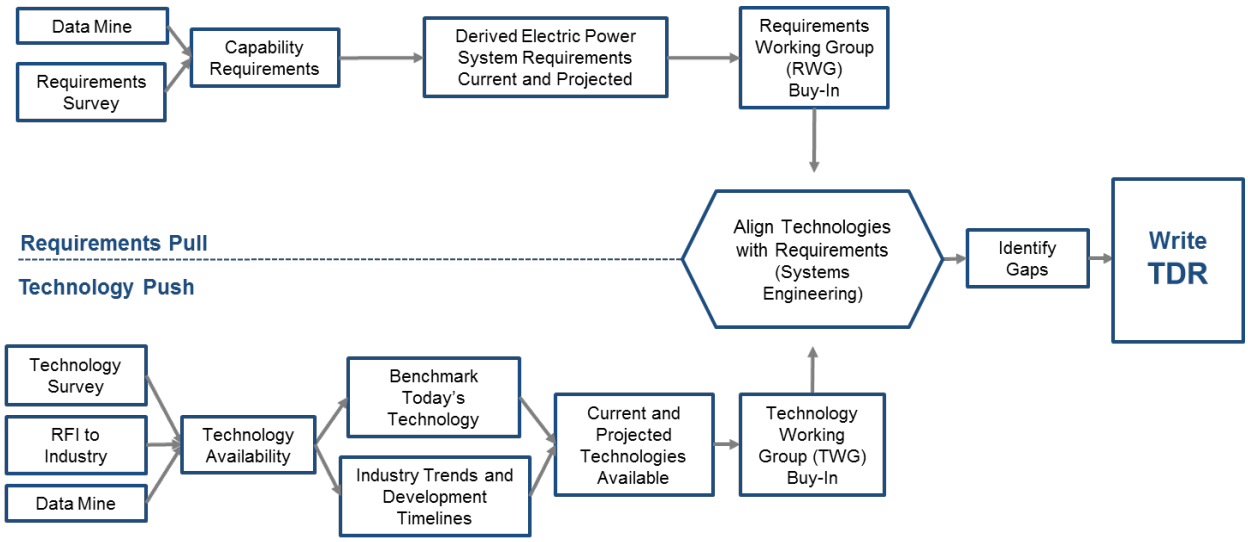


Figure 1: TDR Writing Approach

To facilitate the roadmap update, a Requirements Working Group (RWG) and a Technology Working Group (TWG) with representation from all organizations in the ESO ESG were convened as shown below in Table 1:

Table 1: TDR Writing Organization

Requirements Working Group	Technology Working Group
Lead: OPNAV N96B1	Lead: Electric Ships Office
Electric Ships Office	Naval Reactors
Naval Reactors	NAVSURFWARCENDIV Philadelphia[9]
OPNAV N97	ASN (RDA)
OPNAV N96	ONR
OPNAV N95	PEO Carriers
OPNAV N45	PEO IWS
PEO Subs	PEO Ships
PEO Carriers	PMS 405
PEO IWS	NAVSEA 05
PEO LCS	Subject Matter Experts as needed
PMS 405	
NAVSEA 05	
UK Royal Navy (ESG Member)	

The RWG was led by the Technical Director of the Chief of Naval Operations, Surface Warfare Directorate (OPNAV N96B1). The function of the RWG was to establish capability requirements from which current and projected electric power systems requirements could be derived. The TWG was led by the Assistant Program Manager for Technology Transition, Electric Ships Office. The function of the TWG was to benchmark today's technologies, determine industry trends, and establish current and projected available technologies. RWG and TWG activities were conducted in parallel and later aligned through a systems engineering approach to identify gaps where future electric power system requirements could not be met by available

[9] Naval Surface Warfare Center Carderock Division, Ship Systems Engineering Station will become Naval Surface Warfare Center Division Philadelphia, effective 01 October 2015.

technologies.

2.0 Deriving Requirements

2.1 Requirements Derivation Methodology

The RWG was responsible for establishing capability requirements. The RWG used a combination of direct interviews and surveys of stakeholders as well as thoroughly reviewing overarching Department of Defense and Navy guidance documents. From these data sources, Navy fleet capability requirements were documented and later organized into categories. These requirements begin with basic "need" or "shall" statements that describe certain capabilities. For example, "Shall Project Power Despite Anti-Access/Area Denial Challenge" is a capability requirement derived from the *National Security Strategy*.

The identified capability requirements were then grouped based on the Universal Naval Task List (UNTL) to ensure a common reference framework for requirements across the Navy and Marine Corps. The established groupings represent general areas that the sourced capability requirement statements fall into, with the understanding that more analysis must be completed to determine exact mission systems and electric power requirements.

This NPES TDR identifies mission systems that satisfy Naval capability requirements and affect NPES technology developments for the near-term (0-10 years), mid-term (10-20 years), and far-term (20-30 years). These three timeframes align with the Navy's FY16 30 year shipbuilding plan shown in Table 2. Mission systems currently integrated in the Navy and those programs in development were considered and recorded. Through collaboration with the appropriate program offices and leveraging recent investigations, mission systems that require significant electric power were identified and their specific power needs derived.

Table 2: Long-Range Naval Battle Force Construction Plan[10]

	Near-Term (5-10 yrs)										Mid-Term (10-20 yrs)										Long-Term (20-30 yrs)									
	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Aircraft Carrier			1					1					1					1					1					1		
Large Surface Combatant	2*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	2	3	2	3	2
Small Surface Combatant	3	3	3	2*	3	3	3	3	3	3					1		1	1	1	2	2	2	3	4	4	4	4	4	2	3
Attack Submarines	2	2	2	2*	2	1	2	2	1	2	1	1	1	1	1	1	1	1	1	1	2	2	2	2	1	2	1	2	1	2
Ballistic Missile Submarines						1			1		1	1	1	1	1	1	1	1	1	1										
Amphibious Warfare Ships	1	1			1		1	1	2	1	1	1	2	1	1	1	1				1				2		1		2	1
Combat Logistics Force	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1										1		2
Support Vessels		2	1	2	1	1	2	3	2	1			1	1	2	2	2	2	1											
Total New Construction Plan	9	10	10	9	10	9	11	13	12	10	6	6	9	7	9	8	9	9	6	6	7	6	9	9	10	8	9	10	8	10

* = Flight Upgrade ○ = New Ship Class Insertion

Note: Dates correspond to the year the ship is authorized. Flight Upgrade and New Ship Class Insertion points are found in the FY16 Shipbuilding Plan language on pages 6 & 11-13 and in the FY15 Shipbuilding Plan on pages 12-13 & 15. These annotations are unique to the TDR and not explicitly shown in either reference.

Figure 2 illustrates the general path used to establish capability requirements, determining applicable mission systems, and then deriving electric power system requirements to accomplish those capabilities.

[10] Deputy Chief of Naval Operations. "Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for Fiscal Year 2016". April 2015.

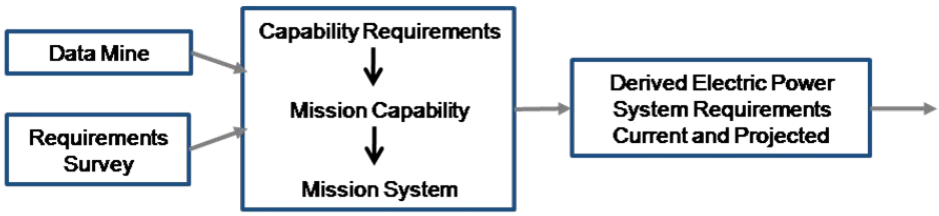


Figure 2: Capability Requirements Pull Approach

2.2 NPES Relevant Capability Requirements and Drivers

The capability requirement groupings, based on the UNTL, were evaluated for their overall impact on NPES. Table 3 summarizes the capabilities relevant to NPES and the major operational level tasks found in the UNTL. Meeting average power and pulse power requirements have the greatest impact on NPES. Therefore, **advanced sensors** and **advanced weapons**, aligned with operational tasks to **Develop Intelligence** and **Employ Firepower**, are identified as primary drivers for NPES.

Table 3: NPES Relevant Capabilities

Operational Task	Primary Drivers	Secondary Drivers	To Be Determined
Deploy/Conduct Maneuver		Advanced Propulsion	Flexible Ship Features
Develop Intelligence	Advanced Sensors	Arctic Operations Unmanned Systems	Mission Modules / Interfaces
Employ Firepower	Advanced Weapons	Active Protection	
Perform Logistics & Combat Service Support			
Exercise Command & Control	Communications & Information Security / Cybersecurity		
Protect the Force	Communications & Information Security / Cybersecurity		Low Observability

2.1.1 Primary Drivers

Capabilities required from **advanced sensors** and **advanced weapons** are seen in the latest guidance documents such as the *National Security Strategy.* These systems, currently under development will impose significant impacts on current NPES in both average and pulse power requirements in the near term. Due to these significant impacts, substantial investments are required in NPES. Future weapon systems are expected to continue to demand additional electric energy produced and stored on the ship resulting in increasing effects on NPES.

Communications & information security and issues related to **cybersecurity** are seen regularly in the latest guidance documents. Since the last revision of the NPS TDR where the driver was categorized as "to be determined," the Navy issued its *Information Dominance Roadmap 2013-2028*[11], the President published *Improving Critical Infrastructure Cybersecurity*,[12] and the National Institute of Standards and Technology (NIST) developed the *Framework for Improving Critical Infrastructure Cybersecurity.*[13] **Cybersecurity** is being included early during specification development and design of all new NPES products and

[11] United States Navy, "Information Dominance Roadmap 2013-2018", March 2013.
[12] The President of the United States. Executive Order 13636: Improving Critical Infrastructure Cybersecurity. *The Federal Register*, Vol.78 No.33, 19 FEB 2013.
[13] http://www.nist.gov/cyberframework/

systems. While requirements continue to evolve and solutions are developed, the potential for increased cost of information security requirements is a concern that must be addressed during NPES development. For these reasons, **communications & information security / cybersecurity** is classified as a primary driver for NPES. Due to the emerging nature of cybersecurity, a requirements traceability figure is not included in this section a detailed discussion of **cybersecurity** follows in Section 4.6.

2.1.2 Secondary Drivers

Secondary drivers associated with NPES include **advanced propulsion**, **arctic operations**, **unmanned systems** and **active protection**. These drivers generally have lesser impacts on NPES requirements than those listed as primary drivers.

For ships with electric propulsion, the requirement to provide large amounts of electric power to **Deploy and Conduct Maneuver** will remain, and the need to manage and reallocate power to mission systems will increase. The potential for an integrated power and energy system for propulsion, weapons, and ship service will be examined as part of early ship design evaluations and the ship acquisition process. Since the last revision of the NPS TDR, the President released the *National Strategy for the Arctic Region*,[14] the Department of Defense released the *Arctic Strategy*,[15] and the Navy subsequently updated the *US Navy Arctic Roadmap*[16] after its initial publication in 2009. It is expected that, as a minimum, **arctic operations** may result in additional requirements for electric shipboard heating that may increase electric plant loading.

Since the last revision of the NPS TDR, the DoD has released the *Unmanned Systems Integrated Roadmap 2013-2028*[17] and unmanned systems are a focus area in the *Naval S&T Strategic Plan*.[18] Increased utilization of unmanned systems has the potential to impact NPES requirements for ship to deployable mission system interfaces. Of note, increased power and energy density is mentioned as a mid-term (defined as 2018-2021 in their roadmap) capability goal.

The current overall utilization of alternative fuels and renewable energy by NPES is minimal. The Navy has tested engines to confirm compatibility with certain renewable and alternative fuels. The Navy will likely not invest in manufacturing alternative fuels for shipboard use but can use the fuels as doctrine or requirements dictate. The Navy has investigated the use of special fuels for some of its unmanned applications. The Navy is leveraging Department of Energy and industry investments in smart-grid and micro-grid efforts in controls methodologies and technologies for potential use in future Navy platforms. Commercial micro grids share similar characteristics to those desired in future NPES. They are reconfigurable, they utilize integrated energy storage, and their ability to manage stochastic generation may provide insight into how future NPES can handle stochastic loads.

2.1.3 Flexible Ship Features

Mission modules / interfaces cover a wide variety of capability requirements across multiple

[14] The President of the United States, “National Strategy for the Arctic Region”, May 2013.
[15] Department of Defense, “Arctic Strategy”, November 2013.
[16] United States Navy, “U.S. Navy Arctic Roadmap 2014-2030”, February 2014.
[17] Department of Defense, “Unmanned Systems Integrated Roadmap FY 2013-2038”, 2013.
[18] Office of Naval Research, “Naval S&T Strategy”, 20 January 2015.

naval mission systems and the definitive requirements for each platform or mission system are not yet known. These systems must be individually analyzed to determine the specific capability requirement they provide and the electric power requirements for each.

Requirements for platform flexibility, commonality, modularity, and open architecture began to take shape as PEO Ships released the *Flexible Ships Roadmap*[19] in 2014. The roadmap focuses on plans and opportunities to achieve wider integration of flexible payloads, technologies, and architectures with the four key attributes of adaptability, modularity, scalability, and commonality. While this roadmap lays out the plan for modular design, the system requirements and impacts of future mission modules on NPES are still under development at this time.
The National Security Strategy and the *Naval S&T Strategic Plan* contain the requirement to protect the force by developing systems that can provide low observability. These documents mention signature reduction leading to battle space dominance but offer limited system details. This capability will continue to be monitored to determine its impact on future NPES requirements.

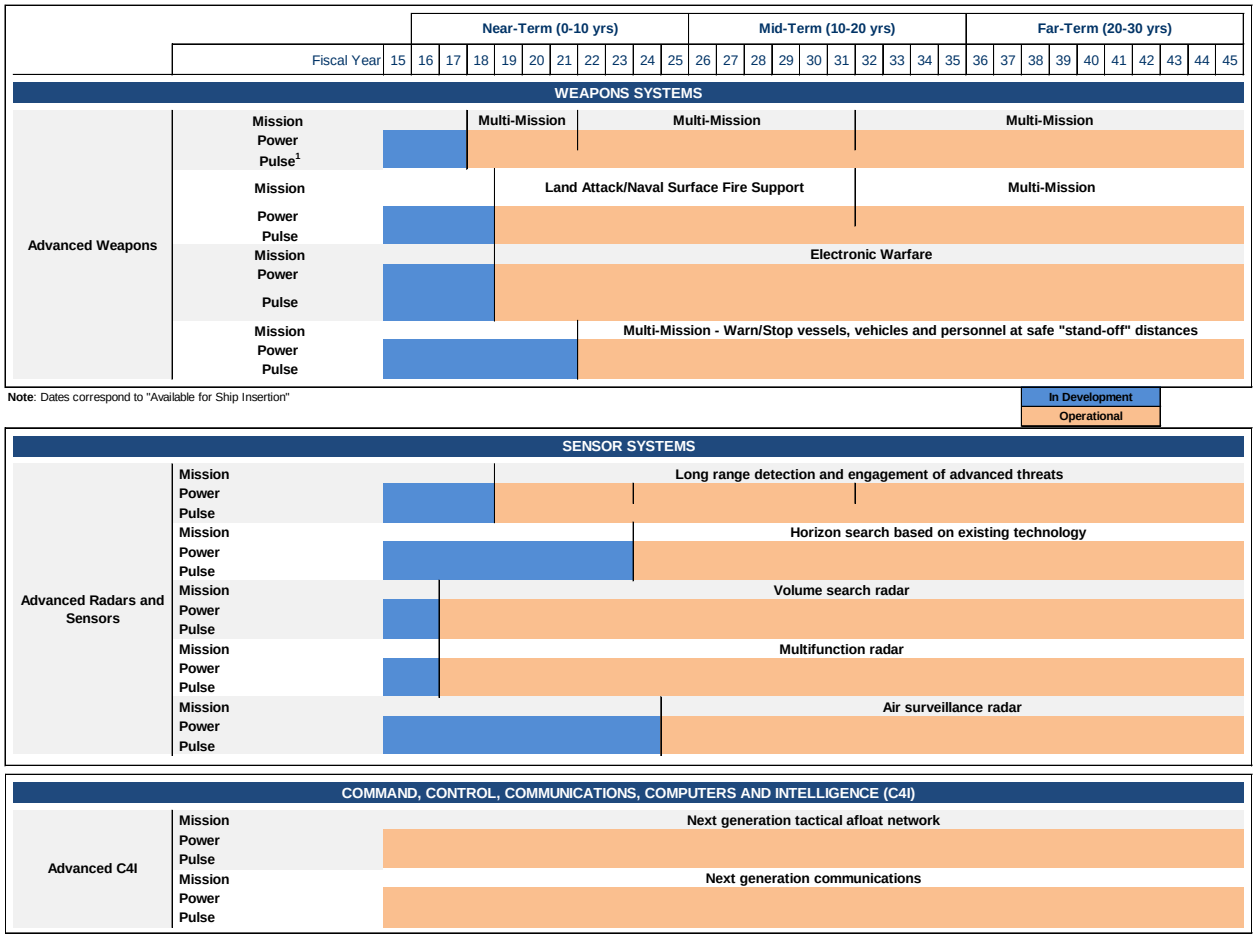
2.3 Derived Electric Power Requirements

The primary drivers described above contain the largest impact on NPES and will be the main focus of derived electric power requirements. Secondary drivers taken individually do not have substantial impacts on NPES requirements, but they will continue to be monitored as guidance is updated.

Increased average power and pulse requirements, along with required power to all other shipboard systems, will provide new challenges for the Navy in the near, mid, and far-term Naval Fleet. Advanced weapon systems also have increasing derived power requirements. These escalated power and pulse requirements occur in the near-term (5-10 years) and only increase in the future with additional capability developments. Table 4 shows derived electric requirements for anticipated future advanced sensor and weapons capabilities.

[19] Naval Sea Systems Command, “Flexible Ships Roadmap,” 30 May 2014.

Table 4: Derived Electric Power Requirements



2.4 Ubiquitous Requirements

In addition to derived electric requirements, other requirements were identified that are consistently described in the majority of sources and utilized by almost every stakeholder and subject matter expert. These requirements, which are referred to in this NPES TDR as ubiquitous requirements, are considered universally important to the Navy and generally apply to all systems. Ubiquitous requirements are used as “measures of goodness” to determine the best solution to meet a set of derived electric power requirements.

The NPES TDR identifies the following ubiquitous requirements:

- Improved Personnel and Ship Safety
- Reduced Operations and Sustainment Cost
- Reduced Acquisition Costs
- Reduced Manpower
- Improved Survivability, Maintainability, Reliability
- Reduced Environmental Impact
- Performance Improvements Above Threshold
- Commonality, Modularity, Open Architecture
- Operational Energy
- Alternative Fuels

- Renewable Energy

These ubiquitous requirements will evolve over time and will be updated accordingly in future NPES TDR iterations. The ubiquitous requirements were ranked in order of importance by the RWG as shown in Table 5.

Table 5: Ubiquitous Requirements

Rank	Ubiquitous Requirements		Justification
1	Improved Personnel and Ship Safety		Safety is paramount and government directives / mandates typically apply
2	Cost related requirements	• Reduced Operations and Sustainment Costs • Reduced Acquisition Costs • Reduced Manpower • Improved Survivability, Maintainability, Reliability, and Availability	Cost or cost related
		• Commonality, Modularity, Open Architecture	Total ownership cost related - must be shown to reduce cost or improve overall mission
	Operational Energy		Impact of high-power weapons, sensors, and other systems on platform operational energy use has implications for operational flexibility and operating cost.
3	Alternative Fuels		There are no plans at present to develop alternative fuels that would require new propulsion or energy conversion technology.
	Renewable Energy		Efforts involving other renewable energy sources are focused on increasing renewable energy use at shore installations.
	Lowered Environmental Impact		Possible government directive / mandate
	Performance Improvements Above Threshold		Important if above factors make sense - cost, etc.

3.0 NPES Technology Product Areas

This chapter addresses the state of technologies relevant to NPES. The targeted audience is technology developers in industry, academia, and government. This chapter's intent is to inform technology developers about NPES technologies and general technology advancements that are of interest to the Navy. These technologies fall into six technology product areas that comprise the main building blocks of NPES as determined by the TWG. The six technology product areas are listed below:

- Energy storage
- Electrical rotating machines
- Power conversion
- Prime movers
- Distribution
- Controls and autonomy

The six technology product areas are described in the six separate sections of this chapter. Each section is divided into three basic subsections designed to summarize what the product area is today, identify where industry is taking the product area, and discuss general evolution improvements that are of interest to the Navy. The first subsection discusses the current state of the art for the product area. It introduces relevant technical aspects of the product area, provides benchmarks, and in some cases summarizes product area use by industry. The second subsection provides a description of industry development trends in the product area. These trends present ongoing advancements in performance of equipment in the product area. They also summarize emerging industry needs that will likely drive investment for further improvements. The third subsection describes Navy needs that may not directly align with industry needs. These needs are presented from the technology push perspective; general advancements in and evolution of NPES technology product areas that align with generic Navy needs are desired even without a specific capability requirements pull.

Later, Chapter 4.0 describes ship implementation challenges that help the reader understand why Navy needs and industry needs do not necessarily align. Then, Chapter 5.0 and follow-on chapters complete the NPES TDR process by combining the RWG and TWG inputs, performing requirements analysis, identifying gaps, and providing development recommendations for near, mid-, and far-term Navy investment.

Establishing the current and projected technologies and product areas available was the responsibility of the TWG. The TWG consisted of members from various organizations throughout the Navy spanning a variety of technical areas. TWG members are listed in Table 1.

The TWG was responsible for:

- Categorizing naval power system technologies into product areas
- Determining the relevant metrics to track by category
- Baselining current metrics for each technology area
- Determining industry trends and metrics in each category for the next 30 years
- Identifying opportunities for commonality
- Identifying technology application opportunities and development timelines

Figure 3 below illustrates the general process followed by the TWG:

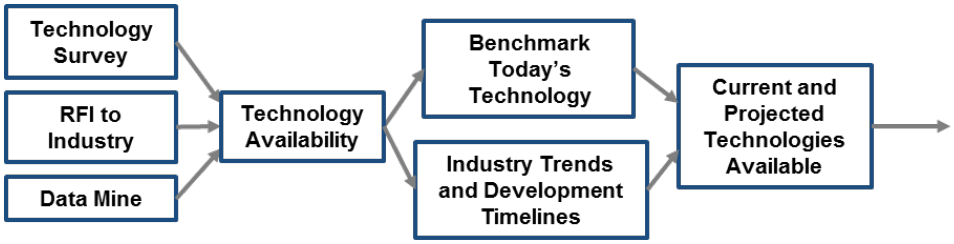


Figure 3: Technology Push Process

The products the Navy has developed or intends to develop in each product area constitute the Navy's product line. Metrics were developed to show how each category evolves over time as well as to compare products within each category. This comprehensive set of metrics was also used to baseline each product area. These metrics will be presented in Chapters 7.0 and 9.0. The TWG collected documents from sources that include but are not limited to the oil and gas, telecommunications, automotive, renewable energy, and power industries. This data set of industrial information was reviewed and used to establish baselines and determine trends.

It is important to note the six technology product area subsections report on industry technology benchmarks and trends without the injection of Navy investment. This industry centric perspective was adopted to understand what developments are ongoing now and will occur in the future without Navy intervention. Technology trends for each product area were developed by investigating selected metrics determined by the TWG to have the most effect on the future of NPES. This viewpoint provides an understanding of the areas where industry will develop technologies that can support Navy systems and the level of investment the Navy will have to make in areas where there is a gap between what the Navy needs and what industry is developing.

Where applicable, some of the key metrics to trend and benchmark each of the product areas are included. The goal of these descriptions is to highlight where industry is today and determine what the key drivers for industry will be going forward. Based on the knowledge of where industry is going, the Navy can determine how to apply those expected technological developments and begin to bridge gaps between what the Navy needs, what industry will be able to provide, and when industry will provide it. TWG action officer technology surveys, subject matter expert interviews, and an industry Request for Information (RFI) were used as additional sources of information for this TDR.

3.1 Naval Voltage Classification

Understanding how the Navy identifies voltage classes is important to scope the discussion of each product area. The Navy uses the term high voltage for any AC or DC voltage greater than or equal to 1000 volts,[20] low voltage for below 1000 volts, and does not use the term medium voltage in technical documentation. Because the majority of the NPES TDR technical audience is in industry and academia, commercial voltage classifications are used throughout this document and summarized in Table 6. What is classified commercially as high voltage is

[20] Naval Ships' Technical Manual Chapter 300, Electric Plant General, S9086-KC-STM-010, Chapter 300, section 2.1.1.3 Rev 9, May 2012.

typically used for long distance transmission and not applicable for Navy ships. *IEEE 141* identifies AC voltage classes by listing standard voltages for commercial and industrial applications; it does not specify precise dividing lines between voltage classifications. Relevant Navy AC voltages fall squarely within commercial voltage classes; 450VAC is low voltage while 4160VAC and 13.8kV are medium voltage. *IEEE 1709* defines medium voltage DC for ships.

Table 6: Voltage classifications for industry and the Navy

Voltage Class	***IEEE 141*** **AC voltages Used in NPES TDR**	***IEEE 1709*** **DC voltages Used in NPES TDR**	***NSTM 300*** **Navy Technical Documentation AC or DC voltages**
Low Voltage	Up to 600V	Up to 1kV	Below 1000V
Medium Voltage	2400V to 69kV	>1kV to 35kV	
High Voltage	115kV to 230kV		1000V and above

3.2 Energy Storage

An energy storage system is generally composed of energy storage media, power conversion or conditioning, and controls. The energy storage media is the actual repository of stored energy. Media of interest to this document include secondary batteries, capacitors, and flywheels. This section focuses on energy storage media along with their associated monitoring and management controls.

The following terms are often used to compare energy storage media: energy capacity, rate of charge and discharge, cycle life, and shelf life. Simple definitions of these terms are provided below as background. This list is not intended to be a complete list of relevant energy storage terms; additional terms specific to different energy storage media are discussed throughout this chapter. Further information is defined in specific vendor data sheets.

- Energy capacity is the total amount of energy that can be stored, measured in Joules (J), or equivalently as power for a duration of time, such as Watt-hour (1Wh = 3.6 kJ).
- Rate of charge and discharge represents how fast that energy can be transferred to and from the energy storage media. This is measured in Joules/second (J/s) or Watts (W). During operation these rates are determined by system demand and state-of-charge; maximum rates are driven by chemical, mechanical, and thermal limitations and design.
- Cycle life is the number of times an energy storage media can be charged and discharged. Cycle life varies by the use profile such as the relative depth of energy discharged with each cycle, the amount of charge, the energy transfer rate, temperature profile, age, etc.
- Shelf life is the length of time a product may be stored without becoming unsuitable for use.

<u>Batteries</u>
Batteries are devices that convert chemical energy contained in their active material directly into electric energy by means of an electrochemical oxidation-reduction reaction. They are classified as primary or secondary batteries. Primary batteries cannot be recharged. Secondary batteries can be electrically recharged and will be covered in this subsection.
The C-rate measures the rate at which a battery is discharged or charged relative to its maximum normalized capacity. A 1C discharge rate means that the battery will deliver the rated

current and fully discharge in 1 hour. A 0.2C discharge rate corresponds to the battery delivering 20% of its rated discharge current. Most batteries have lower maximum C-rates for charging than discharging. Battery voltage, current, and nominal capacity and cycle life will change based on different C-rates.

Capacitors

Capacitors are devices that store energy in an electric field. Capacitors generally have high and symmetrical charge and discharge rates. Typically capacitors have low equivalent series resistance (ESR), enabling them to deliver power efficiently. Most capacitors have a high cycle life and can be held at voltage without substantial concern of damage or significant electronics and controls. Capacitors are rated by voltage capability and capacitance, in units of farads (F), which describes the ability to store charge. Capacitive energy storage has been used predominantly in the role of power filtering and reactive power compensation.

Flywheels

Flywheels are devices that store kinetic energy in a rotating mass or rotor. The amount of stored energy is dependent on the mass of the rotor, the location of the mass on the rotor, and the rotational speed of the rotor. An accelerating torque causes a flywheel to speed up while storing energy, a decelerating torque causes a flywheel to slow down while providing energy. To function electrically, a flywheel system must include a generator to convert rotational kinetic energy to electrical energy. The generator may also serve as a motor to provide the accelerating torque for storage or the flywheel can be spun by a separate prime mover.

3.2.1 Industry Energy Storage Benchmark

The primary users of energy storage are consumer electronics, automobiles, and uninterruptible power markets. Applications are as diverse as smart phones, tablets, power tools, hybrid and electric cars, avionics, drones, data centers, and alternative energy systems. These applications have different energy and power requirements and different operating profiles. The energy storage requirements are met by different types of energy storage media, based upon their energy and power characteristics. Figure 4 is a general representation of the relative energy density vs. power density for various energy storage media. This graph is commonly called a Ragone plot.[21] Precise density comparisons require details of the specific system implementation.

[21] Named after David Ragone of Carnegie Mellon University.

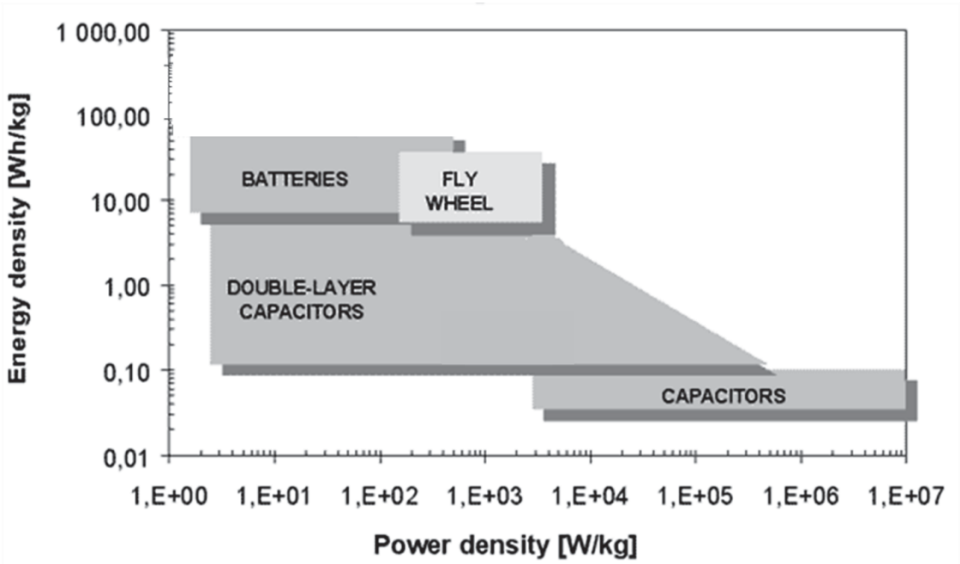


Figure 4: Logarithmic comparison of energy storage media energy and power densities[22]

Energy storage technologies can be inherently biased towards high power or high energy. In general, batteries have high energy density and low power density. Batteries are optimum for applications that require sustained operations. Flywheels and capacitors tend to work best for high power, short duration applications where fast charge and discharge are necessary.

3.2.1.1 Battery Benchmark

For many years, the lead acid battery was the most commonly used secondary battery in the market. They are used in automobiles primarily for engine start. They are also used to provide lighting and uninterruptable power for multiple systems. Lead acid batteries are robust, affordable, and have good service life characteristics.

Increases in power and energy demands from consumer electronics, portable tools, and hybrid or electric vehicles have driven consumer demand for batteries that have a higher energy density than the lead acid battery. Two of the leading secondary battery chemistries capable of meeting this need are the nickel metal hydride (NiMH) and lithium-ion (Li-Ion) chemistries. These chemistries provide improved energy density and power density, making them very attractive commercially despite their higher cost. Consumer demand is driving down the cost of batteries based on these chemistries. Some Li-Ion battery chemistries have demonstrated safety issues because of thermal failures. High demand continues to support safety improvements for Li-Ion batteries.

NiMH batteries are used in hybrid automobiles, low cost consumer applications such as cameras, mobile phones, and medical instruments, and in equipment and high power static applications such as telecommunications, uninterruptible power supplies (UPS), and smart grid.[23] Li-Ion batteries are the rechargeable battery of choice for portable consumer electronics equipment.[24] Li-ion batteries are displacing NiMH batteries in hybrid automobiles and are used

[22] *Alternative Energy Storage Methods* [Online]. Available: http://www.mpoweruk.com/alternatives.htm
[23] *Nickel Metal Hydride Batteries* [Online]. Available: http://www.mpoweruk.com/nimh.htm
[24] *Rechargeable Lithium Batteries* [Online]. Available: http://www.mpoweruk.com/lithiumS.htm

in plug-in hybrid and fully electric automotive applications.

Figure 5 shows relative gravimetric and volumetric energy densities for some battery chemistries and packaging.

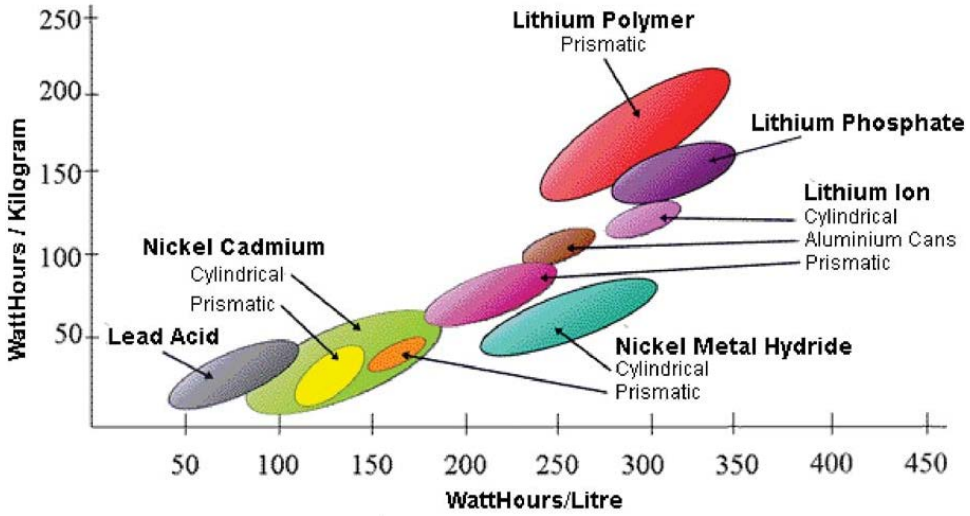


Figure 5: Energy densities of various battery chemistries and configurations[25]

Factors that may influence the selection of one battery chemistry and configuration over another for a particular application and operating environment include:

- The ability to maintain state of charge when not in use. Li-Ion batteries tend to maintain charge, NiMH batteries do not. Lead acid batteries require a floating charge.
- Change in voltage versus state of charge.
- Charge and discharge capability.
- The temporary or permanent loss of capacity due to repeated shallow discharges.
- The ability to shallow charge and discharge or partially charge intermittently during a discharge.
- Battery life considerations such as service life, cycle life, and shelf life.
- Off-gas properties which affect the level of ventilation and other associated auxiliary systems.
- The complexity of battery management systems and their effect on overall packaging and form factor.

A battery's cell type as well as its size can affect multiple factors including cell voltage, stored energy, thermal management, space utilization, and battery life. Some battery cell types include cylindrical, prismatic, and pouch. Cell sizes are not standardized across all cell types. Generally, larger cells are referred to as large format. The batteries specific application will determine which battery cell type or size is best.

The thermal characteristics of a battery are dependent on the internal resistance of the battery chemistry, cell type, and packaging. Charging and discharging a battery too quickly can generate excess heat leading to battery failure. Historically, Li-Ion batteries have issues with

[25] *Cell Chemistries – How Batteries Work* [Online] Available: http://www.mpoweruk.com/chemistries.htm

this phenomenon because of their extremely high energy density. Recent advances in Li-Ion battery cell technology have reduced their susceptibility to thermal failures.

Battery Management Systems (BMS) are used to address performance and safety issues. A BMS may be programmed or "tuned" for a specific battery chemistry, cell type, and application. The BMS monitors parameters such as voltage, temperature, and current. The BMS uses this information to determine state-of-charge, state-of-health, balance cell voltages, and initiate appropriate actions when abnormal conditions exist.

3.2.1.2 Capacitor Benchmark

Capacitors are used in cases where high power for short durations is required. Examples of capacitor applications include electronic camera flashes, bug zappers, electric filters, and reactive power compensation. Capacitance is a measure of the capacitor's ability to store charge. Capacitors are generally categorized either by their dielectric or by their electrode material. Though there are many types of capacitors, for the purposes of this section, they can be grouped into three general categories: electrostatic capacitors, electrolytic capacitors, and supercapacitors.

Electrostatic capacitors use a dry dielectric such as ceramic or mica. Their capacitance is in the picofarad to low microfarad range. Because of their low energy storage capability, they are predominantly used as filters. Electrolytic capacitors use a moist or polymeric electrolyte that increases the capacitor's ability to store energy. They generally have several thousand times the storage capacity of the electrostatic capacitor and are rated in microfarads. Electrolytic capacitors are commonly used in power filtering, buffering, and coupling.

Electrochemical capacitors are electric energy storage devices where electrical charge is typically stored as a result of non-Faradaic reactions at the electrodes. A subset of electrochemical capacitors referred to as an "asymmetric" type have non Faradaic reactions at one electrode and Faradaic reactions at the other electrode. The porous surface of the electrodes increases the surface area for holding charge resulting in much larger capacitance and energy density. Electrochemical capacitors differ from common electrolytic capacitors in that they employ a liquid rather than a solid dielectric with charge occurring at the liquid-solid interface of the electrodes when a potential is applied. Some other common names for an electrochemical capacitor are double layer capacitor, ultracapacitor, electrochemical double layer capacitor, and supercapacitor.[26] The term hybrid capacitor is used for supercapacitors that exhibit both significant double-layer capacitance and pseudocapacitance.

Electrochemical capacitors exhibit the following characteristics:[27,28,29]

- Fast charge and discharge in seconds or less due to low internal resistance
- Excellent cycle life when compared with batteries

[26] Underwriters Laboratory. (2013, December 11) *UL Standard for Safety for Batteries for Use In Light Electric Vehicle (LEV) Applications, UL 2271* [Online]. Available: http://ulstandards.ul.com/wp-content/uploads/2015/01/s2271_1.pdf)

[27] *BU-209: How does a Supercapacitor Work?* [Online]. Available: *http://batteryuniversity.com/learn/article/whats_the_role_of_the_supercapacitor*

[28] *What is an ultracapacitor?* [Online]. Available: *http://www.tecategroup.com/ultracapacitors-supercapacitors/ultracapacitor-FAQ.php*

[29] *Supercapacitors* [Online]. Available: *http://www.cellergycap.com/index.php?option=com_content&view=article&id=17&Itemid=3*

- Little to no risk of overcharging and no catastrophic failure
- Ability to charge and discharge at low-temperature
- High specific power in the range of 10kW/kg for the capacitor itself, which is approximately five to ten times that of Li-Ion batteries
- Low specific energy when compared to Li-Ion batteries
- Low voltage: Serial connections are needed to obtain higher voltages
- Linear discharge profile: Inability to use all of the stored energy
- Higher self-discharge than that of an electrochemical battery
- Higher cost per Watt-hour (Wh), up to 20 times that of Li-Ion batteries

3.2.1.3 Flywheel Benchmark

Most power system flywheels use a motor-generator to convert between kinetic and electrical energy. This provides a mechanism to fully control the charge and discharge of energy. Similar to capacitors, flywheels can have equal charge and discharge rates. The use of low loss bearings and vacuum enclosures to minimize frictional losses can increase the efficiency of flywheels. Some flywheel designs may lead to complex arrangements for support, cooling, vacuum, and protection. Flywheel systems must handle gyroscopic forces inherent with rotation and non-stationary applications. For most high speed flywheels, a safety enclosure is required to absorb the kinetic energy release during a failure. Modern flywheels are used to recoup power in vehicle regenerative braking in energy ranges below 1 kWh, in server farm UPS in the 1-3 kWh range, and in large scale utility frequency regulation systems over 100 kWh.[30] In stationary power applications, flywheels can provide facilities with a wide variety of services including serving as standby power sources, improving power quality, load leveling, peak shaving, and power factor correction.

3.2.2 Industry Energy Storage Trends

Industry trends are focused on improving energy and power density across the board. On a Ragone plot, see Figure 4, this means movement up and to the right for the various technologies.

3.2.2.1 Battery Trends

For batteries, the recent trend towards higher energy densities drives the need for improved safety. Safety improvements are being realized through manipulation of chemistry, electrode material selection, form factor optimization, and utilization of intelligent battery management systems. Additionally, commercial demand is driving industry to increase battery life particularly for lead acid and Li-Ion batteries. Battery manufacturers are exploring inclusion of innovative thermal management solutions into their designs to support increased service life and battery operational safety.[31] In applications above 20 kWh, sodium nickel batteries will gain market share for heavy transport, commercial vehicles as well as telecom and data center applications.[32]

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[30] *Power Storage Systems- Flywheel* [Online] Available: http://gtlcompany.com/power-storage-systems-flywheel/

[31] A. Pesaran et al., "Tools for Designing Thermal Management of Batteries in Electric Drive Vehicles," in Large Lithium Ion Battery Technology & Application Symposia, Advanced Automotive Battery Conference, Pasadena, CA, 2013.

[32] *"A Review of Battery Technologies for Automotive Applications,"* EUROBAT, ACEA, JAMA, KAMA, ILA. 2014.

3.2.2.2 Capacitor Trends

The high capacitances of electrochemical capacitors have created new opportunities for use such as energy storage for electric cars, regenerative braking, and larger UPS. Electrochemical capacitor improvements continue to focus on improving energy density while maintaining inherently high power density. Design improvements include development and integration of higher temperature films, advanced electrolytes, advanced electrode materials, and minimizing ESR. A lower ESR allows a capacitor to charge and discharge quicker because of a lower time constant, enabling less capacitance to meet fast discharge needs.[33] Performance benefits include reducing self-discharge, improving service life while maintaining safety. Renewable energy applications are looking to supercapacitive energy storage, arrays and where applicable, advanced thermal management systems.

3.2.2.3 Flywheel Trends

Flywheel designs are continuing to focus on high-rate charge and discharge cycles, overall system efficiency, improved service life, and design improvements that can minimize safety containment requirements.

3.2.3 Industrial Energy Storage in relation to Naval Power and Energy Systems

Traditionally, NPES have used energy storage to provide point of use dedicated uninterruptible power. Hence, short duration UPS providing power for a few seconds used capacitors while long duration UPS applications providing power for minutes relied on lead acid batteries. More recently, the Navy has employed high energy battery systems such as those with Li-Ion chemistries in unmanned vehicles and the Joint Strike Fighter. As discussed in Chapter 2.0, the Navy plans to introduce advanced pulsed weapons and sensors into existing and future ships. Energy storage can be used to integrate high power pulsed loads, thus minimizing deleterious effects of pulsating loads on a ship's power system.

Energy storage system improvements important to NPES include the ability to operate while experiencing motion in all three axis due to ship's motion, an increase in system volumetric and gravimetric power and energy density including storage media and power conversion, providing electrical isolation to ground, shock hardening of the energy storage system, high temperature stability, and increased cycle and service life to support decreased total ownership cost.

Shared energy storage presents a number of naval power system benefits compared to dedicated energy storage. The Navy is exploring the possibility of transitioning some of its dedicated energy storage functions to a multifunction, shared energy storage approach. This paradigm shift could mitigate pulse load effects on component service life and support flexibility for future upgrades. It could also provide a load leveling capability for the ship's power system, emergency ship wide power, and energy storage system commonality and modularity. Any shared energy approach must perform similar to dedicated energy storage in terms of survivability, system integrity, and power quality.

NPES are diverse systems encompassing many interrelated systems. As such, there may exist a need to combine multiple energy storage media in a hybrid system such that together they

[33] D. Evans and S. Rackey, *Hybrid® Capacitor Applications* [Online]. Available: http://www.evanscap.com/pdf/98SW.pdf

provide both high energy and power densities. The Navy is currently participating in a joint DoD and Advanced Research Projects Agency-Energy (ARPA-e) program to develop a prototype hybrid energy storage system. The system is scheduled to be demonstrated in early 2016.

The Navy has introduced safety qualifications for high energy storage systems with the NAVSEA SG270-BV-SAF-010[34] Additionally, Li-Ion batteries are such a promising technology that the Navy has introduced a rigorous Li-Ion battery qualification process governed by NAVSEA S9310-AQ-SAF-010.[35] These two documents govern system qualification from the cell level up to full system integration within a ship compartment. The Navy is qualifying multiple Li-Ion battery chemistries and configurations using these processes. Currently, the Navy is working on an adaptation of the Li-Ion safety process for use in qualifying other high energy systems.

3.3 Electrical Rotating Machines

Electrical rotating machines (ERMs) are prevalent throughout all segments of industry worldwide as both motors and generators. Of the many machine types available today, this TDR considers AC induction, AC synchronous, permanent magnet (PM), and High Temperature Superconducting (HTS) machines. In this section, ERMs are categorized as standard and large machines. Machine ratings in industry vary from fractional to hundreds of kilowatts for standards machines and up to hundreds of megawatts for large machines such as utility power generators.

3.3.1 Industry Electrical Rotating Machine Benchmarks

Despite their significant differences, the market for standard and large machines is best classified as stable; ERMs have consistent demand. Incremental, evolutionary technology improvements are being incorporated into new product releases.

3.3.1.1 Standard Machines

Standard machines (i.e., fractional and integral) are commodities, have a well-established market, come in standard frame sizes, and are built to industry or military specifications. Today, standard machines are used in industry for applications such as pumps, fans and conveyors. The vast majority of standard motors are air cooled AC induction motors. PM motors are used where improved efficiency and precise control are desired.

3.3.1.2 Large Machines

Large machines tend to be custom designs based on commercial practices ranging from hundreds of kW to tens of MW for motors and hundreds of kW to hundreds of MW for generators. In general, they are ordered in small quantities for specific applications.

3.3.1.2.1 Large Motors

Large motors are typically used in industry for pumping fluids, such as water, oil or natural gas, or for process manufacturing in paper, steel, and mining industries. Induction motors range in power up to tens of MW and are used over a wide speed range from less than 200 RPM for

[34] *High-Energy Storage System Safety Manual,* SG270-BV-SAF-010, Naval Sea Systems Command, April 27, 2011.
[35] *Technical Manual for Batteries, Navy Lithium Safety Program Responsibilities and Procedures*, S9310-AQ-SAF-010, Naval Sea Systems Command, August 19, 2014.

direct drive rolling mills and low speed pumps, to high speed machines in compressor applications that operate at up to approximately 6000 rpm or higher. Wound field synchronous motors are often used in the low speed range as well, depending upon the customer's specific requirements. Recently, PM synchronous machines are seeing increasing use, especially at the higher RPM ranges. Air cooling or totally enclosed water to air cooled (TEWAC) is normally used for large motors to minimize cost since space is not a major design driver for land applications. Minimal cost and high reliability with existing or established technologies are the primary design drivers for large industrial motors.

Affordability and excellent reliability with established technologies are the key design drivers for ship propulsion motors. Commercial ships have primarily used wound field synchronous motors up to 25 MW[36] per motor for ship propulsion, although in recent years, squirrel cage induction machines are starting to appear at the higher power levels. These large motors are typically slow speed (< 200 rpm) and are TEWAC machines. The cruise ship industry was one of the early adopters of electric propulsion with most cruise ships today featuring electric propulsion. Electric podded propulsion first appeared in approximately 1991. The shift towards podded propulsors has been driven by a desire to increase hydrodynamic efficiency, increase maneuverability, reduce ship construction time, and increased demand for ship volume dedicated to non-machinery spaces. By 1999, lessons learned from the cruise ship industry regarding pods were available to inform Navy ship design concept studies. Some pods in small propulsion applications use PM machines.

3.3.1.2.2 Large Generators

The largest generators employed in industry today are those in the electric utility industry. Electric utilities use 3000 or 3600 rpm wound field synchronous generators to produce high voltage at 50 or 60 Hz in the tens to hundreds of MW ratings. Direct cooling of generator armature windings, which improves power density, is the standard for these very large, turbine driven generators. Cooling is normally accomplished with deionized water or hydrogen for stator windings and hydrogen for rotor windings. Medium speed diesel generators (500-1800 rpm) in the hundreds of kW to ten MW range also use wound field synchronous machines; they are often used as emergency or local standby power sources for utilities, industrial facilities, hospitals, and other users demanding high reliability.

The offshore and on shore oil and gas industry, commercial ships, and process industries, such as paper, steel, mining, and refining industries use medium to high speed wound field synchronous generators in the hundreds of kilowatts to tens of megawatts range for localized power generation. Capital cost and reliability and maintainability are the primary metrics, with efficiency and power density also being important in continuous use mobile applications such as ship or off shore power generation. These generators typically use TEWAC for cooling.

The wind power industry is a relatively recent large user of many thousands of medium to very low speed generators in the 15 to 1800 rpm range, at 1 to 8 MW,[37,38,39] with the majority of units

[36] ABB. (2010, January). *Azipod XO* [Online]. Available: http://www.abb.com/abblibrary/downloadcenter/?View=Result
[37] *The 10 Biggest Turbines in the World* [Online]. Available: http://www.windpowermonthly.com/10-biggest-turbines
[38] D. Snieckus. (2015, Jan. 12). *2015 Outlook: Wind turbines get bigger and smarter* [Online]. Available: http://www.rechargenews.com/wind/1387372/2015-OUTLOOK-Wind-turbines-get-bigger-and-smarter
[39] J.S. Hill. (2014, Feb. 19). *UK Offshore Wind Farm Will Field Vestas' 8 MW Behemoths* [Online].

in the 1 to 3 MW size. Most wind turbines are gear-driven, high-speed generators, although low speed direct drive units have been built and tested in some locations. The torque level of these direct drive units is very similar to that of direct-drive ship propulsion motors. Size, weight, and reliability are the driving metrics of interest.

3.3.2 Industry Rotating Electrical Machine Trends

3.3.2.1 Standard Machines

The primary trend identified for standard machines is efficiency because of government regulations requiring higher efficiency.[40] While some premium efficiency synchronous motors incorporate PM rotors, research and development in higher efficiency induction motors is leading to lower resistance rotor bars. A consequence of the lower resistance rotor is that there are higher starting currents for cross-the-line starts. Hence, these high efficiency induction motors are best suited for soft-starting and having Variable Speed Drives (VSDs) to preserve their high efficiency while not impacting the power system with extremely high starting currents. VSDs also offer the opportunity for higher efficiency operations by matching the motor speed to the operational requirements of the systems.

3.3.2.2 Large Machines

Industry trends for large machines involve improvements in basic machine construction materials that improve overall efficiency or power/torque density. Industry is focusing their development efforts on the following areas:

- Increased magnetic material flux carrying or flux generation capacity
- Increased electrical insulation material and insulation system dielectric strength
- Increased mechanical strength, increased thermal conductivity, and reduced sensitivity to temperature
- Improved structural materials and design concepts that accept higher torsional and electromagnetically induced stress
- Innovative and aggressive cooling to allow improved thermal management and increased current loading
- Increased electrical conductor current carrying capacity and loss reduction

3.3.2.3 Large Advanced Technology Machines

Large sized advanced technology machines in the megawatt range offer several advantages over traditional machines. In the wind power industry, weight minimization in the nacelle[41] at the top of the wind tower is a design driver which is fostering commercial investment into both permanent magnet and superconducting generators. PM and HTS rotors have higher power density than their induction and synchronous rotor counterparts. Wind power PM generators eliminate excitation losses which can account for 30% of total generator losses.[42] PM machines use rare earth elements in their magnets; these elements are used in many applications and currently have limited availability from US sources. It is estimated that a 6MW PM direct drive

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Available: http://cleantechnica.com/2014/02/19/uk-offshore-wind-farm-will-field-vestas-8-mw-behemoths/

[40] 10 CFR 431, The Integral Motor rule, takes effect June 1, 2016 and The Small Motor Rule, which is already in effect.

[41] A nacelle is the enclosure at the top of the tower that houses all of the generating components in a wind turbine, including the generator, gearbox, drive train, etc.

[42] ABB. *New high speed PMG series for 1.5-3.6 MW full converter concept* [Online]. Available: http://www.abb.com/product/ap/seitp322/ec5d4e40e6becf9b4425779e001cf9e4.aspx

wind turbine uses 5 tons of permanent magnets, roughly the equivalent of what is used in 2,500 hybrid electric cars.[43] The offshore wind power industry is moving to larger power wind tower generators in the 10MW class.[44,45] HTS shows promise for these higher power levels because of low excitation losses and low weight due to reduction in stator and rotor iron. HTS motors may be up to 50% smaller and lighter than traditional iron-core and copper machines.[46] They have reduced harmonic vibrations due to minimization of flux path iron and have mitigated thermal cycling failures due to precision control of temperature. HTS machines use rare earth elements, though significantly less than PM machines use. There is evidence that with technology advances, wound field synchronous and PM machine volumetric power density could be reduced to rival HTS density.[47]

A prototype commercial 8.0 Mega Volt Ampere Reactive (MVAR) HTS Generator was operated on the Tennessee Valley Authority (TVA) electric grid for one year. Of note, the generator fed a steel mill and repeated arc strikes from the arc furnaces cycled the machine from zero to 100% torque. Approximately 30,000 load cycles were achieved in the one year approximating three times what would be seen in a normal service 30 year lifetime.

3.3.3 Industrial Electrical Rotating Machines in Relation to Naval Power and Energy Systems

In terms of relative quantities, one Navy platform will typically have hundreds of standard militarized motors, a few generators, and in the case of electric propulsion one or more large custom motors as required. The challenge for machine development will be to maintain or improve efficiency while increasing power density to meet Navy performance. Standard motors aboard Navy ships are in the few kW to a few hundred kW range and dominated by AC induction motors, closely mirroring industry. General improvements that increase efficiency and/or reduce cost are expected to continue for standard motors. Given their commodity nature, the Navy will benefit from these industrial improvements by purchasing new machines as needed.

Large motors, greater than a few hundred KW, used by the Navy tend to require custom design for applications such as propulsion from hybrid electric or electric drive systems. The U.S. Navy has explored warship application of pods, but power density, shock requirements, signature requirements, and concerns over directional stability have prevented podded propulsion adoption.

Currently, industry is investing in the following areas, and advancements in these areas are

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[43] B. Jensen et al., "Advantages and Challenges of Superconducting Wind Turbine Generators," in *2nd International Conference E/E Systems for Wind Turbines*, Bremen, Germany, 2012.
[44] P. Smith. (2014, June 09). *Question of the week: Do we need a 10 MW turbine?* [Online]. Available: http://www.windpowermonthly.com/article/1297819/question-week-need-10mw-turbine
[45] AMSC. *Wind Turbine Designs* [Online]. Available: http://www.amsc.com/documents/wind-turbines-designs-brochure/
[46] R. Calfo and B. Eckels, "An Evaluation of High Torque Density Electric Motor Topologies and their Application for Ship Propulsion," in *Electric Machine Technology Symposium (EMTS)*, Philadelphia, PA, 2004.
[47] R. Calfo and B. Eckels, "An Evaluation of High Torque Density Electric Motor Topologies and their Application for Ship Propulsion," in Electric Machine Technology Symposium (EMTS), Philadelphia, PA, 2004.

applicable to all electrical rotating machines in general.

ERM design considerations:

- Accurate 3-D modeling of machines for static dynamic and transients behaviors
- Use of amorphous and low iron loss high saturation flux density core materials
- Low form-factor designs for reduced active mass and cost

Harmonics:

- Refined stator and rotor design for reduced harmonics
- Active harmonics control by injecting controlled distorted excitation

Reliability:

- Embedded sensing for improved reliability
- Improved insulation systems for use with variable speed drives and higher voltages
- Condition Based Maintenance (CBM) and prognostics

Some recent machines developed specifically for Navy applications are listed below:

- Advanced induction propulsion motors ~ 20-35 MW (DDG 1000 and UK Type 45 Destroyers)
- TEWAC synchronous generator ~40MVA (DDG 1000)
- Ruggedized commercial off the shelf (COTS) induction propulsion motor ~ 4 MW (in service in LHD 8)
- Propulsion induction motor for Hybrid Electric Drive ~ 1.9 MW (DDG 51)
- Propulsion PM motor for Hybrid Electric Drive ~ 1.5 MW (prototype)
- High speed synchronous generator with water cooled rotor ~14MW (Advanced Development Model)
- PM submarine propulsion motor with integrated power electronics ~ 4 MW (in production overseas)
- Synchronous PM motor ~ 36 MW (prototype)
- Synchronous HTS motor ~36 MW (prototype)
- COTS wound field synchronous propulsion motor ~ 20 MW (T-AKE 1, MLP)

Navy generators tend to fall into the range of hundreds of kW for emergency generators, a few MW for most ship power generation, and tens of MW for ships with very high electric demands such as IPS ships. As with motors, power density improvements are desirable; these may be achieved by higher rotational speeds and use of newer technologies including thermal management improvements. Industry is pursuing investments in advanced high speed generator designs including actively controlled magnetic bearings and refined stator and rotor windings for lower slot harmonics. Reducing the length of large generators enables shorter generator sets which are more desirable for Navy ships.

The Navy will increasingly desire ERM advances that do not align with market demands; these advances may be implemented by industry given consistent Navy intended targets. One example of a Navy specific interest for specific platforms is reduced acoustic signature of the electrical rotating machines for increased stealth and mine warfare concerns. Another area of Navy specific interest is increased power density that can be afforded by generators with higher rotational speeds, the use of high energy product PM materials, and/or advanced cooling techniques such as liquid cooled rotors.

3.4 Power Conversion

Power conversion equipment changes voltage and/or frequency to a different voltage and/or frequency. In power systems, power conversion exists to meet the demands of the electric transmission/distribution system or to meet the demand of a load or loads that require something other than what the electric distribution system naturally provides. Power converters of interest include two basic categories: power electronics based converters and transformers. The technologies are vastly different, though both perform a power conversion function. The following subsections are split into power electronic power converters and transformers.

General categories include conversion from/to AC/DC (rectifier), DC/DC (converter), DC/AC (inverter), and AC/AC (transformer or cycloconverter). In general, a power converter may incorporate more than one stage of power conversion. For example, an AC to DC power converter may incorporate a transformer (AC/AC) connected to a power electronic rectifier (AC/DC).

3.4.1 Industry Power Conversion Benchmarks

3.4.1.1 Power Electronic Power Converters

Power electronic converter output is determined by switching of component devices in different topologies or configurations. Diodes are switching devices that are not controlled. Transistors and thyristors are controllable switching devices that require gate drivers and control schemes. These devices switch between “on” (pass current, minimum voltage drop) or “off” (block current, voltage drop determined by topology). The converter delivers the desired output voltage and frequency waveforms when the devices are combined with inductors and capacitors that act as energy storage and filters. Multiple topologies exist, and as devices and controls have advanced some topologies have gained wide favor. For example, the three level neutral point clamped inverter is the dominant pulse width modulation topology found in industry today. In motor drive applications, converters are readily available up to 6.6kVAC.[48] Soft switching topologies which use zero-voltage and/or zero-current switching are used in niche applications to reduce switching losses at the cost of additional components and more complex control.

Power electronic power converters have a wide variety of applications. Variable speed drives (VSDs) for motors can enable soft starting, which reduces inrush current, and supports continuously variable speeds for many motor applications. VSDs typically vary voltage and frequency to maintain a constant volts/Hz ratio for most efficient drive/motor operation. Applications for VSDs vary from ventilation systems to heavy equipment to ship propulsion motors.

Hybrid electric drive automobiles have bidirectional power converters that combine the functionality of a VSD with charging the vehicle’s energy storage battery. Extremely high power versions of power converters have enabled high voltage DC transmission for electric utilities. An example is the 2000 MW Sandy Pond, Massachusetts load station which takes high voltage DC and converts it to high voltage AC to feed the New England power pool section of the grid. Renewable sources such as wind power and photovoltaics require power conversion to change variable frequency (wind power) or DC (photovoltaic) to alternating current at the required grid frequency and voltage. Power converters are also prevalent in low power applications such as

[48] S. Fazel, “Investigation and Comparison of Multi-Level Converters for Medium Voltage Applications,” Dr.-Ing. dissertation, Berlin University, Berlin, Germany, 2007.

consumer electronics such as, computers, microprocessor controlled appliances, and in industrial applications such as UPS, data centers, telecommunications, and building HVAC. The automotive industry, including trucks, and buses, is currently considered a major driver today for device ratings because of the emerging electric vehicle market.

A plethora of power electronic devices has evolved over the last 30 to 40 years. Insulated gate bipolar transistors (IGBTs) coupled with antiparallel diodes are currently the main devices used in medium power, medium voltage applications. Integrated gate commutated thyristors (IGCTs) are also used in medium voltage drive and grid applications. Metal-oxide-semiconductor field-effect-transistors (MOSFETs) are used in low power, low voltage applications. Utility high voltage applications use thyristors which can handle higher voltages. Devices used today are mostly silicon based.

All power electronic devices have losses. When on and conducting, devices have a small on-state resistance producing I^2R losses in MOSFETs and losses due to voltage drop in IGBTs and diodes. When off, devices allow small reverse leakage currents; thus, power electronic devices do not provide galvanic isolation. Galvanic isolation refers to the prevention of electric conduction between two electric circuits intended to exchange power and/or signals.[49] Galvanic separation can be provided by an isolating transformer or an opto-coupler. During switching transitions, including on to off, and off to on, the instantaneous losses are much greater than on-state losses. Thus, higher switching frequencies which enable better power quality also create more heat. Soft switching designs can mitigate losses during switching. To remove heat, devices are mounted on heat sinks which reject heat to air or other cooling media, such as water, ethylene glycol. Because power electronic devices have limited operating temperature ranges, increases in the power and/or switching frequency increase the importance of a proper thermal management system for converters due to these increased switching losses.
Benchmarks for power electronic devices and power converters are difficult to define in a rapidly changing and evolving product area. Devices are predominantly silicon (Si) based because they are affordable, easily manufactured, operate efficiently, and have proven dependability. Commercial drive power density is typically in the 200-400 kVA/m^3 range. There are several other device metrics of interest for power applications, they include:

- Voltage rating
- Current rating
- Switching frequency
- Operating temperature range

[49] Galvanic isolation definition retrieved from International Electrotechnical Committee's International Electrotechnical Vocabulary – www.electropedia.org

A plot of Si devices and their commonly realized voltage, current and frequency characteristics is shown below in Figure 6. Figure 6 is outdated with respect to present device ratings, but it illustrates the ability of IGBTs to handle relatively high switching frequencies which allows tighter control of power converter output.

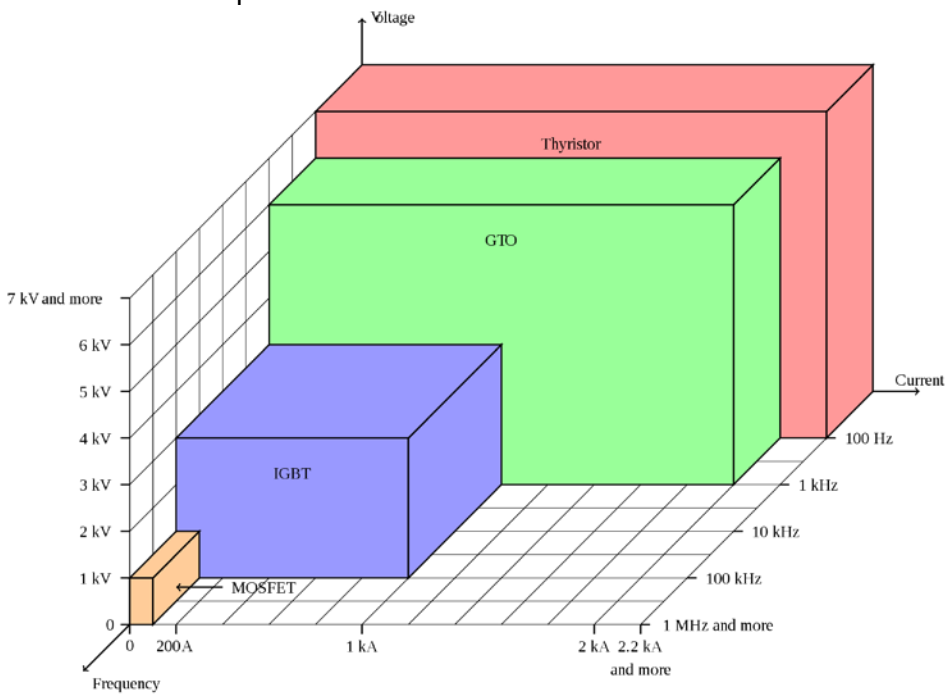

Figure 6: Si-Based Device Power vs. Switching Frequency[50]

Device voltage and current ratings drive the number of devices in a converter as well as the power circuit topology. Generally, the more devices a converter has, the less efficient it is because of switching and conduction losses. Having more devices also increases control complexity. IGBTs are well suited for higher power, higher voltage applications because of their saturation characteristics and low on-state losses. In low voltage applications, single IGBT devices have ranges from 300 to 1700V and currents up to 100A[51]. When combined into modules to act as a single device, the ratings increase significantly. Some IGBT module ratings of interest for MV applications:[52]

- Voltage rating: Up to 6500V (other standard ratings 4500V, 3300V, 1700V) for medium voltage applications
- Voltage rating: Up to 1700V (other standard ratings 1200V, 600V, and lower) for low voltage applications
- Current rating: Up to 750A for 6500V, up to 1200A for 4500V, up to 3600A for 1700V (generally higher current rating at lower voltages)
- Switching frequency: 1-100 kHz inversely related to switch voltage rating
- Temperature limit: 125 degrees C

Another metric of interest is efficiency. Efficiencies in drive applications are consistently above 96% at full load. Even at low loading, power conversion equipment has over 90% efficiency due

[50] "Switches domain" by Cyril Buttay. CC BY-NC-SA 2.0
[51] *IGBT Applications Handbook*, Rev 3, ON Semiconductor, Denver, CO, 2013.
[52] Values are from a market survey. Voltage rating refers to off-state voltage; the current rating refers to on-state current. Devices are not capable of handling both at the same time.

to the nature of the power electronic devices. This is important because certain applications, such as motors, do not always operate at high percentages of total loading during normal operations. Commercial power converter systems are designed to maximize efficiency and avoid modes of operation where efficiencies will be less than 95%. Sustained operation in modes below 95% efficiency is discouraged because of the adverse economic impacts.[53]

3.4.1.2 Transformers

Transformers are AC/AC voltage converters that do not change frequency. Transformers are generally more efficient (>98%) than power electronic converters, and used extensively throughout industry. Transformers have three main constituent parts associated with them: the core (steel with desirable magnetic properties), insulation, and windings (copper). A fourth component may be associated with cooling. Dry type transformers, up to a few thousand kVA, use convective cooling with air or sometimes forced air. Larger HV transformers use mineral oil for cooling, with heat rejected via an oil to air or water heat exchanger. Utility, industrial and commercial oil-cooled transformers are physically isolated, either by distance or location in a vault inside a facility, to contain damage in the event of failure.

Initial energization of a transformer creates an inrush of current which can be several times higher than the nominal operating current. To mitigate this inrush, transformers can be integrated with soft start circuits.

For equivalent power levels, transformers are heavier and smaller than power electronic converters. Higher frequency transformers are used in the airline industry and other applications that require higher gravimetric power density. The cross sectional area of a magnetic core of a transformer is approximately inversely proportional to the frequency of operation. Thus, the weight of the transformer core, not including the windings, of a 240 Hz. transformer would be expected to be about one quarter the weight of a 60 Hz transformer. 400 Hz is a common frequency for aircraft power systems where weight is a critical design driver. Transformers inherently provide galvanic isolation with separate primary and secondary windings.

3.4.2 Industry Power Conversion Trends

Advances in power electronics are expected to dominate improvements in the power conversion market. As capabilities of power electronics increase and their prices fall, some transformer functionality will likely be incorporated into power electronic converters. In applications where galvanic isolation is required, more substantial improvements can be had by combining solid state power conversion with high frequency transformers. Transformer and power converter trends are presented in the subsections below.

[53] Values are from a market survey.

3.4.2.1 Power Electronic Power Converter Trends

Continuous improvement in both capability and efficiency continues to be the most notable industry trend in the power electronic power conversion market. Increasing efficiency is critical for power systems and thus more efficient power conversion is constantly in demand. Devices will continue to drive towards increased power density, increased efficiency, higher switching frequencies, and refined topologies with associated control schemes.

As mentioned in the benchmark sub-section above, the automotive, utility, renewable, consumer electronics and industrial applications such as data centers, telecommunications, etc. all drive power electronic trends. Lower voltage applications such as automotive, both electric and hybrid vehicle, drive investments in improving device ratings and operating temperatures in that range. The key innovations are in wide-bandgap devices, which are discussed at length below.

Silicon device designs are approaching their physical material limitations. Power electronic device manufacturers are introducing new semiconductor materials to enable a leap in performance. Wide bandgap semiconductors can perform better than Si because they have higher material limits for off-state voltage, on-state current, and operating temperature combined with higher thermal conductivity. Wide bandgap semiconductor materials with ongoing development include Silicon Carbide (SiC), Gallium Nitride (GaN), and diamond. They are generally expected to at least double the power density of a power system and cut switching losses in half, with commensurate increases in efficiency. For example, SiC can operate at 350 degrees C (junction temp) while current Silicon based IGBTs and MOSFETs can operate at up to 175 degrees C (junction temp).[54] Power converters using wide band gap semiconductors can take advantage of the minimized switching losses by operating at higher switching frequencies. This will lead to better power quality with less filtering including fewer and/or smaller capacitors and inductors.

Higher switching frequency improvements will contribute to smaller converter sizes. Major areas of focus for developing new wide bandgap devices include developing device packaging to withstand higher operating temperatures, reducing radiated noise at the higher switching frequencies, and the durability of the die architecture. Advanced cooling, better packaging, and wide bandgap devices will all contribute to improved converter power densities.

Wide bandgap devices are beginning to transition from development to market with expected sales in excess of a billion dollars by the end of the decade. SiC Schottky diodes are commercially available either as stand-alone devices or packaged as antiparallel diodes for Si IGBTs. Higher power diodes up to 3300V are being developed, but still have some manufacturing challenges. SiC MOSFET's are now available in discrete packages up to 1700V, 225A[55] with higher rated devices on the horizon, with manufacturability of these devices being the biggest hurdle.

GaN is better suited for low voltage applications such as automotive, general lighting, solar and industrial power systems. GaN devices up to 600V have already been produced and the trends show that up to 1200V operation is possible.[56] There is the possibility that GaN devices could

[54] "Electrical and Electronics Technical Team Roadmap," U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability), Washington, D.C., June 2013.
[55] http://www.cree.com/Power/Products/SiC-Power-Modules/SiC-Modules/CAS300M17BM2
[56] Venture-Q, LLC. *The commercialization of GaN-on-Si technology for power conversion applications* [Online]. Available: http://www.venture-q.com/

overlap SiC applications up to 1kV. This overlap could slow down SiC's market penetration because consumers may opt for a more affordable GaN on Silicon substrate option in the overlapping range. Reliability of GaN devices is an issue that still needs to be worked out before more widespread use can occur.

SiC based devices will most likely remain preferred in higher power applications due to its improved thermal management properties when compared to GaN devices. Diamond has the widest bandgap but is the least mature of the three. Looking further into the future, aluminum nitride and advanced thin-film magnetic materials have the potential to emerge as potential technologies that can compete with or improve upon the properties of wide band gap devices. The U.S. Department of Energy has already started to invest in this area and the potential for improvement in power density can be as much as ten times over the current state of the art.

Device yield is a manufacturing challenge for wide bandgap devices. Yields for wide bandgap devices over 10kV continue to be a challenge. It is anticipated that the manufacturing challenges will be overcome over the next 10 years, leading to further industry adoption of wide bandgap devices in higher voltage, higher power conversion applications where power density is required. Devices that are more affordable, more power dense, and more efficient are expected to continue to enter the market.

In addition to improvements in devices, cooling advancements also improve the efficiency of power conversion equipment and advances in cooling methods will be required to handle larger heat loads at higher power levels. Techniques such as double sided cold plates are being developed for use with IGBTs and are being driven by the renewable industry.[57] Another advanced cooling method that has potential to increase power density is spray cooling.

3.4.2.2 Transformer Trends

Transformers have been in use for more than 100 years. Electric utilities will drive high power transformer development. As power electronics and DC distribution start to enter the utility market, existing transformers can be replaced with power electronic based converters that may include high frequency transformers in the 100 kW to 10 MW range. The use of high frequency transformers can provide galvanic isolation with reduced size and weight impacts compared to traditional transformers for applications that require it. Other applications include traction, mass transit and microgrid converters. Issues with using transformers in these types of applications include the need to design and match a transformer to each specific application, which drives overall cost of a system. Important factors in the design of transformers are leakage inductance, permeability and saturation inductance.

Other research areas include core materials. Nanocrystalline materials and amorphous metals can provide a higher flux density and lower loss, thus improving overall power density and efficiency. Other benefits that can be made to improve efficiency include reducing hysteresis losses and eddy currents.

Additional industry transformer trends include:

- Improved insulation
- Increased voltage and power ratings

[57] Semikron. (April, 2013) *MiniSKiiP® Half Bridge Modules and High Power PCBs* [Online]. Available: www.Semikron.com

- Alternative cooling media which are environmentally friendly and non-flammable
- Cooling improvements
- Prognostic failure diagnosis
- Higher frequency which results in reduced size

3.4.3 Industrial Power Conversion in Relation to Naval Power and Energy Systems (NPES)

Currently, the Navy predominantly uses transformers for power distribution. Most Navy transformers are convection dry type, with a few large water cooled transformer applications. NPES have begun to incorporate more solid state power conversion. DDG 1000 has a distribution system that has multiple levels of solid state power conversion that perform AC/DC, DC/DC, and DC/AC power conversion.

Moving forward, NPES will need to support higher power and energy loads. Power conversion will be required to interface these loads with the power system and any associated energy storage. Combining power electronics with transformers allows loads to be decoupled from a distribution system. This combination provides galvanic isolation and the ability to convert between multiple voltages and frequencies. Point-of-use (POU) converters can replace separate distributed power systems such as 400Hz. POU converters are called out in the LHA 8 shipbuilding specifications and an RFP has been issued for a production buy for DDG 51 ships. Any future DC distribution systems will also require the use of power conversion to interface with existing prime movers and electric machines.

Space is limited on current and planned future ships. Any additional power conversion equipment will need to be power dense and efficient. The power density at the power levels required for future Navy applications and the shock and vibration requirements will drive the Navy to either repackage commercial converters or develop Navy-unique power conversion equipment.

Navy equipment operates with duty cycles that are not common in commercial applications, such as extended periods of low power operation for propulsion. This introduces a design challenge to achieve part power efficiency while maintaining the capability to operate at high power levels. In addition to duty cycle, additional design challenges are introduced by Navy unique and/or critical load requirements. Pulsed power with high and low frequency repetition as well as ride through capabilities can have huge impacts on hardware and control requirements.

The concepts and underlying converter technologies described in Subsection 3.4.2 above that are being developed by industry will provide the basis for naval power conversion equipment. These improvements and developments should be leveraged by NPES designers in the selection of interfaces.

Wide bandgap devices and technologies continue to mature. These emerging wide bandgap technologies, along with control philosophies and new topologies, have the potential to be game changing for future NPES. However; commercial markets, not the Navy, will drive the production and cost of switching devices, circuit topologies, and power converter development. Most device improvements will focus on operating voltages below 1000V because they are heavily driven by the consumer electronics and automotive industries. An exception is the commercial photovoltaic industry where the current European practice is 1000VDC and the U.S.

is moving towards this operating voltage as well.[58] Still, improvements in higher voltage devices desired for future NPES may not be provided by industry at the rate desired. The Navy has invested in high power wide-band gap devices and will continue to do so, including SiC and GaN devices. In addition, the Navy has and will continue to invest in increasing the power density and efficiency of converters, which leverage industry improvements made at the device level, but incorporate Navy specific packaging concepts.

The Navy will follow industry improvements in transformers. Mineral oil filled transformers are not used in Navy applications because of the fire hazard. Commercial propulsion and hybrid electric motor drives already use a synthetic ester for cooling because of the high power levels. Exploration of using similar techniques for cooling magnetics to increase power density in converters may have naval benefits.

Modular, scalable power converter technologies and standardized advanced load interfaces may become the foundations for enabling these advanced loads on future platforms. Establishing these types of interfaces and common building blocks will result in the distribution and power conversion technology areas becoming more intertwined. It will be important to consider system wide, rather than component level, power density and efficiency. The Navy needs to keep apprised of industry lessons learned from the expansion of power conversion equipment in commercial system architectures.

3.5 Prime Movers

A prime mover is the source of motive power for a given system. The prime mover product area for NPES focuses primarily on diesel engines and gas turbines. Energy recovery and fuel cells are also discussed. Steam turbine prime movers for naval nuclear propulsion applications are not within this roadmap's purview.

3.5.1 Industry Prime Mover Benchmark

The prime mover market is well established and stable. Incremental innovations and new technology are emerging and continuously entering the market. Compared to other technologies discussed in this NPES TDR, there are significant barriers to entry for completely new engine designs, notably the costs of designing, developing and manufacturing a completely new engine. Thus, new diesel and gas turbine designs enter the market on an infrequent basis.

Diesel and gas turbine engines are used in a variety of commercial transportation, power generation, and industrial applications. In the transportation industry, gas turbines are the primary source of propulsion and power for aviation applications. Gas turbines have application in commercial marine propulsion where power density and/or emissions are important; examples include fast ferries and cruise ships. A majority of marine turbines are aero derivatives rather than industrial frame gas turbines. In commercial large and medium scale power generation, gas turbines are increasingly used as alternatives to coal-fired steam plants due in large part to environmental laws, availability of natural gas, lower capital costs, and industry deregulation encouraging independent power producers. In these applications, the gas

[58] G. Ball *et al*. (2013). *1,000 VDC Utilization Voltages in Nonresidential PV Applications* (Issue 6.3) [Online]. Available: http://solarprofessional.com/articles/design-installation/1000-vdc-utilization-voltages?v=disable_pagination

turbine is often operated in a combined thermodynamic cycle configuration with a waste heat recovery system, based typically on steam as the working fluid. This significantly increases system efficiency, with engine waste heat converted for a variety of uses, including steam for process and building heating or electric power, depending on the application requirements.

Gas turbines are also used extensively in the oil and gas industry. They are the primary power source for natural gas pipeline compression stations with over 80% of that market whereas electric motors make up the other 20%. Gas turbines are also being used more often to provide electric power to offshore oil rigs where very high power is required and deck space is at a premium.

Diesel engines are the primary source of propulsion and power where efficiency is important and power density is not a primary design consideration. They are prevalent in overland transportation applications such as trucking and locomotives, as well as the vast majority of commercial marine applications. In small scale or emergency power generation applications, diesel engines are the primary source of power. Diesel and gas turbines share common attributes of quick starting from cold iron to full power, good transient performance to load changes in power generation applications, and good efficiency. Primary discriminators for applications include power density and efficiency. The increased power density of gas turbines may be offset by the large airflow requirements in some applications. Diesel engine efficiency is fairly uniform across the operating range of the engine while gas turbine efficiency decreases at part power operation.

3.5.2 Industry Prime Mover Trends

Primary Industries driving prime mover trends for gas turbines are:

- Transportation – aviation
- Commercial Marine – fast ferries and cruise ships
- Oil and Gas – offshore and remote location power
- Electric Utilities – primary or peaking power generation

Primary Industries driving prime mover trends for diesels are:

- Transportation – rail and truck
- Commercial marine – ship propulsion and power generation
- Heavy equipment – construction and mining
- Electric utilities – distributed or backup electric power generation

Commercial research is focused primarily on improving engine efficiency, reducing emissions to meet regulations, increasing maintainability, and lowering life cycle cost. This is common to both gas turbine and diesel applications. Developments for commercial marine engines address operation in a more corrosive atmosphere, as well as the use of less expensive fuels. Advances in combustion technology address environmental compliance, efficiency, and transient performance, as well as accommodating and leveraging the effects of fuel variability.

MARPOL[59] Annex VI sets limits on sulfur oxide and nitrogen oxide emissions from ship

[59] The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes.

exhausts and prohibits deliberate emissions of ozone depleting substances. These regulations were developed under the aegis of the International Maritime Organization (IMO) and apply to all commercial marine diesel engines above 130 kW. Gas turbine driven ships generally comply with the international rule because they tend to have emission rates below the Tier II emission standards. More stringent Tier III standards go into effect on 01 January 2016. Annex VI compliance has forced the commercial shipping industry to evaluate emissions from their prime movers and is a driving force behind the adoption of alternative fuels such as Liquefied Natural Gas (LNG).

Some general trends apply to both diesels and gas turbines. Others are specific to one or the other. In addition to improvements related to cleaner emissions, prime mover improvements are predominantly focused on reducing operating cost in two areas. These areas are increased efficiency and the combination of reduced maintenance and increased reliability. Below is a list of technical thrusts in each of these areas.

Advanced controls for increased efficiency, reduced maintenance and increased reliability:

- Implementation of digital controls
- Enhanced engine monitoring, diagnostics and prognostics
- Distributed controls

Advanced designs for increased efficiency:

- New applications of thermodynamic cycles such as Humphrey, Atkinson cycles[60] for gas turbines and diesels and Miller cycle for diesel
- Enhanced fuel injection and combustion
- Intercooling and recuperation
- Higher operating temperatures and pressures
- Optimized thermal management

Advanced materials for reduced maintenance and increased reliability:

- Composite structures and enclosures
- High temperature, corrosion resistant alloys and coatings

3.5.2.1 Technical Thrusts Specific to Diesel Engines

For diesel engines, technologies tend to be implemented first for the smaller engines, such as automobile, truck, and emergency generators, then to the medium sized engines such as locomotive and heavy equipment, and then finally large propulsion diesels featured in commercial marine applications. Specific diesel engine trends include:

Advanced controls:

- In-line continuous oil condition monitoring
- Stress wave bearing monitoring on crosshead, connecting rod, or main bearings
- Variable valve timing and actuation
- Variable area turbine nozzles for turbocharging

[60] National Energy Technology Laboratory. *Advanced Combustion Turbines* [Online]. Available: http://www.netl.doe.gov/research/coal/energy-systems/turbines/advanced-combustion-turbines

- Low temperature combustion modes such as Homogenous Charge Compression Ignition (HCCI), Pre-Mixed Charge Compression Ignition (PCCI), Reactivity Controller Compression Ignition (RCCI), stratified combustion

Advanced designs:
- Turbo-compounding
- Common rail fuel injection
- Rotary valves
- Low speed diesel engines without camshafts
- Exhaust gas recirculation

3.5.2.2 Technical Thrusts Specific to Gas Turbines

For gas turbines, new core engine technologies tend to be implemented first in military and commercial aviation applications. Advanced complex or combined cycles tend to be implemented in commercial power generation. Gas turbine performance and efficiency improvements are driven by increases in overall pressure ratio and firing temperature enabled in large part by improved high temperature materials, high strength materials, coatings, advanced component designs, and implementation of complex/variable thermodynamic cycles. Specific gas turbine engine trends include:

Advanced controls:
- Active clearance control between rotating and fixed components for increased efficiency
- Variable cycle engines
- Model based controls

Advanced designs:
- Technologies to reduce airflow such as reheat combustion
- Technologies to increase power such as inlet cooling
- Variable area turbine nozzle and variable free power turbine
- Compact power turbines
- Integration with waste heat recovery and recuperation
- High temperature working fluids
- Trapped vortex combustion

There is a separate trend in industry toward alternatives to existing prime movers. One such alternative is the fuel cell. Fuel cells exist commercially and they primarily use hydrogen and / or methane for fuel. Fuel cells are currently used to generate power for hotel complexes and remote communities (up to 1 MW), in the automotive industry to enable clean fossil fuel free transportation (approximately 50–100 kW), and for small backup power (approximately 5-10 kW). Research continues in developing more robust fuel cells that can use a variety of fuels and reduce the dependence on rare commodities for advanced catalysts.

Energy and waste heat recovery is being incorporated into existing industrial plants and with commercial marine applications to increase overall fuel efficiency. Generally, waste heat can be used to improve engine performance by contributing heat or electric energy to reduce prime mover load. Areas pursued commercially include topping and bottoming cycles, cogeneration, and combined cycles. Today, steam is the typical working fluid in waste heat recovery systems. Recent trends include other working fluids such as organics and supercritical CO_2. Another trend is recovery using thermal-to-electric materials.

3.5.3 Industrial Prime Movers in Relation to Naval Power and Energy Systems (NPES)

Today, the US Navy uses both diesel and gas turbine prime movers in the surface fleet. Most surface combatants use gas turbines for propulsion and ship service generation. Most amphibious ships use diesels propulsion and ship service generation. FFG 7 Class, LHD 8, and LHA 6 use gas turbine propulsion and diesel ship service generation. Recently, the LCS 1 variant introduced combined diesel and gas turbine propulsion systems (CODAG) to the Fleet.[61] Foreign navies use combined propulsion systems in many ship classes. Today's worldwide commercial and military market demand is sufficient enough that marinized diesel generator sets are available in the size ranges envisaged for U.S. surface combatants.

The Navy's need for more efficient, lower cost, more maintainable prime mover designs is consistent with industry needs. For diesel engines, the Navy relies primarily on commercial developments. Carryover technologies implemented in naval diesel applications are typically first introduced commercially and subsequently qualified for military use. For gas turbine engines, a similar relationship with commercial developments equipment exists but it should be noted that many commercial gas turbine developments are supported by robust engine development activities for military aviation applications, especially at the engine core level. Consequently, many new commercial gas turbine engine designs introduced into commercial applications are rooted in military core engine technology development efforts. Twin spool gas turbines are becoming more prevalent in the oil and gas and aerospace industry. Research indicates that marine use of a twin spool gas turbine may improve fuel efficiency up to 12-15% over current single spool gas turbines. The Navy has been investigating marinizing these engines for naval platform use.

Navy unique requirements are associated with shock, operating environment, operational profiles, and signatures. Compliance with Navy shock requirements can require redesign to provide the necessary robustness. Operating in the marine environment may require the incorporation of special materials and/or coatings to provide the necessary life and durability. Naval engines typically operate with relatively high intake and uptake duct losses, which may impact steady state and transient performance. The Navy uses a constant gas turbine engine rating across the range of ambient temperatures while commercial practice decreases engine rating with increasing temperature. Navy fuel is much higher grade than commercial marine fuel but naval prime movers may be required to operate on lower quality fuels if constrained by availability in the operational theater. The Navy generally operates engines very differently than the commercial sector. Navy prime movers typically experience large accelerations/transients and long times at part load.

3.5.3.1 Prime Movers for Future NPES

For future NPES, the demands for significant and repetitive transient loading on prime movers may exceed the mechanical response limitations of the prime mover and/or the transients allowed under current Navy electric interface standards. Solutions to these problems range from augmenting the system with energy storage as a buffer between the load and prime mover to revisions of currently accepted electric interface standards. Accurately determining and validating a prime mover's ability to tolerate pulse loading levels may reduce the requirements for energy storage, thereby minimizing ship's prime mover system size and supporting ship

[61] http://www.public.navy.mil/surfor/documents/freedomfactsheet.pdf

equipment.

For future ship power system architectures as described in NAVSEA's *Flexible Ships Roadmap* where adaptability, scalability, modularity, and commonality are emphasized, the availability of a complete range of gas turbine and diesel candidates which represent a wide range of power ratings is desired. Although there are a reasonable number of diesel engines in a wide range of power ratings their size and weight relative to gas turbines can limit their use on small or medium combatants. Gas turbines offer size and weight advantages compared to diesels. The Navy's inventory of marinized gas turbines is limited to two general size ranges: small, nominally 2-4 MW and large, nominally 20-40 MW. A notable gap exists in marinized gas turbines in the 9-14 MW range. The Navy has conducted several investigations into options to fill this gap, but existing industrial gas turbines in this mid power range do not meet Navy unique shock, vibration and marinization requirements. The anticipated Navy demand does not provide sufficient sales volume for the OEM to modify the engine to meet Navy specifications.

A Navy development effort would be necessary to design, build, test, and qualify a 9-14 MW GTG. Such an engine may provide a flexible, scalable, standard medium sized GTG across multiple ship classes and improve future Navy ship design options.
Energy and waste heat recovery technology also shows promise for Navy ships. The highly transient operation of US Navy engines and the shipboard space constraints will limit the application of commercially available systems. Highly transient prime mover operations can cause high thermo-mechanical stresses resulting in fatigue and material failures of traditional heat exchangers. Modular energy recovery systems have potential application on board Navy ships. These systems should interact with engine, either diesel or gas turbine, exhaust and cooling systems by extracting energy from the exhaust stream and converting it to useful electric power. This electric power can be used for ship service hotel loads or charging of energy storage units. It is critical that such systems be simple, robust and low maintenance. Additionally, energy recovery systems should be sized so that they maximize their benefits to the overall NPES.

Fuel cell systems show promise, as a method of providing quiet, distributed power generation on board future Navy ships. In order to convert the Navy standard logistics fuels to hydrogen or methane a process called reformation is required. These fuels contain impurities including sulfur that even at low levels can be harmful to fuel cells. The Navy and other military services have invested in processes that can clean logistics fuels of their impurities and convert them to fuels useful to fuel cells. The DoD has also invested in fuel cells that can use logistics fuel directly as well as fuel cells that have increased tolerance to impurities. Although there have been significant advances in these areas, multiple challenges still exist before fuel cells can be used as a practical shipboard power generation option. The Navy is exploring using fuel cells to provide shore power for ships.

3.6 Distribution

In power systems, the distribution equipment exists to transmit power, to configure a power system via connecting/disconnecting equipment, and to provide protection of the connected equipment from electric faults. Distribution equipment includes circuit breakers, fuses, protective relays, switchboards, cables, and other equipment. Power converters can be considered a subset of distribution systems and are covered in Section 3.4. This section addresses low voltage DC, medium voltage AC, and medium voltage DC distribution systems. Low voltage AC distribution is mature, well understood, and not addressed in this section.

3.6.1 Industry Distribution Benchmark

3.6.1.1 Circuit Isolation and Fault Interruption

In medium voltage applications vacuum breakers have replaced air, SF_6, and oil based circuit breakers.[62,63] Typically, medium voltage breakers utilize external protective relays. Vacuum circuit breakers (VCBs), fused vacuum contactors, and fused disconnects dominate the medium voltage AC circuit isolation and fault interruption market.[64] Presently, American National Standards Institute (ANSI) or International Electrotechnical Commission (IEC) certified VCBs provide superior control and protection of medium voltage power equipment. Typical VCBs handle continuous currents of approximately 3-4kA and fault currents of approximately 40-60kA. VCBs are applicable to medium voltages in the range of 1-35kVAC. Industry use of medium voltage, medium frequency distribution is not common, but VCBs appear applicable with appropriate deratings. VCBs used in AC systems are not directly applicable to DC systems because VCBs rely on the zero crossing of the alternating current waveform. DC fault isolation is typically accomplished using large air circuit breakers or employing a power converter in combination with an upstream AC circuit breaker. IEC standards for DC air circuit breakers are generally applicable up to 3000VDC, but breakers are available up to 3600VDC at 4000A with interrupting ratings of 100kA for locomotive and industrial applications.[65]

3.6.1.2 Protection and Control Logic

Relays are the industry standard for providing protection and control logic in power systems. Their functions include metering, protection, automation, control, digital fault recording, reporting, and Human Machine Interface (HMI). Multi-function relays use sensors and logic for control and are easily tailored, and dependable. The fastest algorithms that have no intentional delay (i.e. differential or instantaneous overcurrent) respond to faults in about one electric cycle or approximately 16 msecs. Arc fault protection systems can detect the visible light emissions from arcing faults in several milliseconds. When combined together, the circuit protection and relay total response time, from fault initiation to isolation, are typically in the sub-second range, with fastest responses in approximately 100 msecs. On-line partial discharge systems are available for electric insulation systems for fault risk analysis and condition based maintenance.

3.6.1.3 Switchboards

The protection relays and breakers are integrated into switchboards that are typically naturally or forced air cooled. ANSI standards define metal enclosed and metal clad construction for switchboard enclosures. These are large enclosures and tailored based on various driving requirements including: enclosure tightness (National Electrical Manufacturers Association [NEMA] or IEC ingress protection), degree of electrical isolation and compartmentalization (metal clad versus enclosed construction), and arc fault resistance. Typically, up to two breakers can be stacked within a single vertical section unit when the continuous currents are below 1-2kA per breaker. Above this level, only a single breaker can be installed per vertical

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[62] Csanyigroup. *Comparison Between Vacuum and SF6 Circuit Breaker* [Online]. Available: http://www.csanyigroup.com/comparison-between-vacuum-and-sf6-circuit-breaker

[63] M.L. Flack, L.T. Conner, "Replacement of hydro plant generator oil circuit breakers with modern vacuum technology," EATON, Cleveland, OH, WP083001EN, Sept. 2012.

[64] Edvard, *Circuit breakers classified by interrupting medium* [Online]. Available: http://electrical-engineering-portal.com/circuit-breakers-classified-by-interrupting-medium

[65] Secheron. *DC circuit-breakers* [Online]. Available: http://www.secheron.com/Products/DC-circuit-breakers

section based on thermal limitations.

DC switchgear is typically available in ratings up to 3000-4000VDC. IEC series specifies requirements for DC switchgear and control gear and is intended to be used in fixed electrical installations with nominal voltage not exceeding 3000VDC. The breakers cannot be vertically stacked as significant vertical space is necessary for arc chutes.

3.6.1.4 Cables

Cables are the most common method for interconnection of components in a distribution system. They are widely used because of their low cost and flexibility. Most medium voltage cable insulations use cross-linked polyethylene (XLPE), Tree-Retardant XLPE (TR-XLPE), or ethylene propylene rubber (EPR). Overall, the lifespan of existing cable (aluminum or copper) technology is quite good as long as it is installed per its design specifications. Cables in service in most industrial applications have shown lifespans of 30-40 years.[66]

Where higher power density, modular installation capability, higher mechanical and environmental protection, or tight bend radius is required, then bus duct or insulated bus pipe (IBP) may be selected. Bus pipe is an extruded tubular product used to conduct electricity. Bus duct is an electric conduit prefabricated in sections and containing heavy conductors for transmission of large currents. Bus duct typically uses a combination of air and insulation to provide medium voltage rating. IBP uses solid insulation materials and can be encased in a stainless steel pipe. These technologies are installed in sections and bolted together. Bus pipe and bus duct are being installed in commercial ships for both AC and DC systems.

Copper and aluminum are the industry standards for conductors and which one is used depends on the application. Design considerations for selection of copper vs. aluminum include rated current, operating environment, cost, power density, etc. In weight sensitive applications, aluminum often provides a better solution because it is lighter than copper; however, when more power density is needed, the higher conductivity, and thus smaller size, of a copper cable is selected.

3.6.2 Industry Distribution Trends

Developments in power distribution are primarily driven by the following:

- Safety - Recent recognition of the dangers of arc faults based on updates to National Fire Protection Association (NFPA) 70e and IEEE 1584 have led to the increased use of fault current limiters, multifunction relays, arc fault detectors, remote racking systems, and arc resistant switchboards.
- Reliability - Reducing the scope and frequency of outages is a key driver for electric distribution systems. The primary trends that enable this goal are:
    - System networking - Connecting distribution systems together to provide greater power handling and redundancy
    - Additional isolation - Divides the distribution system into smaller sections and reduces the interrupted area
- Power demands - Consumer power demands are continuing to increase while the grid is aging, spurring the development of power distribution and control alternatives to meet

[66] S. Bushong. (2012, June 01). *2012: Trends in cables* [Online]. Available: http://www.windpowerengineering.com/design/electrical/cables/2012-trends-in-cables/

demand. Advanced distribution enables the integration of renewable energy to meet increasing power demand.

The subsections below describe specific trends for evolving industries and for distribution components:

3.6.2.1 Smartgrids and Microgrids

Early microgrid efforts were largely focused on AC so as to line up with the existing power system infrastructure. Because of this, significant efforts focusing on improvement of current sharing, power quality, stability, energy management, and smooth mode transitions have been undertaken to perfect and standardize the operation of inverter-based AC microgrids.

3.6.2.2 Utilities/Residential, Data Centers, Telecommunications, and Renewables

DC distribution is being implemented in industry as more electric loads and renewable sources come on line. This can be attributed to the desire to decrease conversion steps, increase efficiency and increase power quality. 380VDC is a voltage adopted widely in Europe and used by data centers, telecommunications and commercial buildings. There is also discussion on having multiple DC buses as part of distribution systems, one for distribution and high power loads, and another for lower power loads.[67] 1000VDC is emerging as a candidate voltage aboard commercial ships [68] and in the commercial photovoltaic market.[69]

3.6.2.3 Railway

The railway industry is also starting to employ more DC distribution. The European Union is interested in developing technologies to increase interoperability of the railway, which can be done through voltage standardization. Currently different areas of Europe use different voltages, which range from 600V to 3000VDC and 15 to 25kVAC. A high voltage DC link is being considered between Spain and France. One of the main challenges to this interoperability and DC distribution is the lack of a suitable DC circuit breaker.[70]

3.6.2.4 Circuit Isolation and Fault Interruption

For AC systems, the circuit isolation and fault interruption trends appear to be evolutionary improvements in size and reliability of VCBs. Developments will continue in fault current limiters, including the development of solid-state and high temperature superconducting solutions. Fault current limiters support the introduction of distributed generation and increased system networking without experiencing fault current issues. There is little development effort underway on technologies specific to medium voltage, medium frequency.

DC air circuit breakers will continue evolutionary developments. Ongoing research for medium voltage DC circuit isolation and protection includes islanded inverters for powering AC loads off a DC bus. Islanded inverters, in conjunction with fuses and isolation switches, provide circuit

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[67] Dragicevic, Tomislav *et al*. "Advanced LVDC Electrical Power Architectures and Microgrids," *IEEE Electrification Magazine*, pp. 54-65, March, 2014.

[68] J. Rasanen. "Onboard DC-Grid and Energy Management Tools, Energy Efficient Solutions," in *37th Annual Interferry Conference*, 2012.

[69] G. Ball *et al*. (2013). *1,000 VDC Utilization Voltages in Nonresidential PV Applications* (Issue 6.3) [Online]. Available: http://solarprofessional.com/articles/design-installation/1000-vdc-utilization-voltages?v=disable_pagination

[70] Gomez-Exposito, Antonio et al. "VSC-Based MVDC Railway Electrification System," *IEEE Transactions on Power Delivery*, vol. 29, no 1, pp. 422-431, Feb. 2014.

protection functionality.[71] Additional advanced DC protection research includes solid state circuit protection, hybrid circuit protection, and other advanced DC breaker technologies.[72,73]

3.6.2.5 Protection Logic

The networking of systems, increased number of isolation points, and increased use of distributed generation have driven the need for more comprehensive and complex protective relaying. Protective digital relays continue to incorporate an increasing number of functions within a single relaying unit at reasonable costs. Increased communication between relays enables a system view for better overall coordination response. The adoption of advanced communication and adaptable settings leads to increased automation and improved service restoration, thereby increasing safety and power reliability.[74] Additionally, these multifunction digital protective relays are being adopted into lower power and voltage systems, further increasing reliability, safety and control granularity for larger systems with multiple voltages.

3.6.2.6 Cables

Traditional copper and aluminum cables are considered very mature. Alternatives to traditional cabling are being explored. HTS cables are being explored and tested throughout the world as a means to efficiently address increased power demands. These cables can be employed at various 50/60 Hz AC voltages at both distribution and transmission power levels and are planned to be installed at DC voltages. HTS cables have negligible resistance and therefore can increase overall system efficiency by reducing the cable losses and can increase the current density[75] by up to nine times. HTS cables change from no resistance when superconducting to a discrete resistance governed by cable material properties when not superconducting. This feature can be used by system designers as a way to provide fault current limitation. HTS cables[76] require cryogenic cooling to 77 Kelvin, the temperature range required for superconducting. An operational demonstration in New York City is planned to connect two 13.8kV Con Edison substations with HTS cables and preliminary testing indicates up to 50% fault current reduction. Additional applications are also being explored.[77,78]

Preliminary research has been conducted on using carbon nanotubes in distribution systems. This research indicates that carbon nanotubes present a promising conductor technology with greater conductivity than copper at room temperature. Covetics is a new hybrid made from high-strength carbon and metal, and is the first bonded nanocarbon-metal material with significantly enhanced properties that can survive repeated melting cycles. Covetics can

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[71] J. Rasanen. "Onboard DC-Grid and Energy Management Tools, Energy Efficient Solutions," in *37th Annual Interferry Conference*, 2012.

[72] V.A. Centeno *et al.*, "Southern California Edison's Advanced Distribution Protection Demonstrations," *IEEE Transactions on Smart Grid*, vol. 3, no. 2, pp.1012-1019, June, 2012.

[73] Yang, J., "Protection issue discussion of DC network development: Circuit breaker or fault-tolerant converter," Developments in Power Systems Protection, 2012. DPSP 2012. vol., no., pp.1,6, 23-26 April 2012.

[74] Jecu, C.; Raison, B.; Caire, R.; Chilard, O.; Grenard, S.; Deschamps, P.; Alibert, P., "MV distribution protection schemes to reduce customers and DGs interruptions," PowerTech, 2011 IEEE Trondheim , vol., no., pp.1,7, 19-23 June 2011

[75] H. Masayuki *et al*. "Study on Commercialization of a Superconductor". SEI Technical Review No. 62, June, 2006.

[76] STI. *Conductus Superconducting Cables* [Online]. Available: http://www.suptech.com/Cables_final.pdf

[77] 11th EPRI Superconductivity Conference. 28-30 October, 2013.

[78] D. Haught, "Recent HTS Activities in the US," in *IEA HTS Executive Committee Meeting,* Milan, Italy, 2014.

improve thermal and electric conductivity, increase yield strength, and resist corrosion and oxidation.[79]

3.6.3 Industrial Distribution in Relation to Naval Power and Energy Systems

Navy surface ship distribution varies based on the ship class. Voltages include 450 VAC and 4160VAC, 60 Hz, for primary distribution. Certain applications also use higher frequencies and DC voltages for distribution. Increases in electric power demand by evolving loads are driving Navy distribution systems to implement higher AC and DC voltages. The Navy adopted NFPA 70e guidelines for personal protective equipment (PPE) during maintenance of these higher voltage systems. Chapter 4.0 addresses Navy ship implementation challenges associated with the selection of a distribution system.

3.6.3.1 Circuit Isolation and Fault Interruption

For medium voltage, the 4160VAC air circuit breakers (ACBs) and 13.8kVAC VCBs and their associated protection relays and switchboards are currently deployed in the fleet. In the near-term, the Navy will continue to adopt commercial VCBs and protection relays where possible and work with industry to develop modified off the shelf (MOTS) VCBs appropriate for Navy use. VCBs have cost, weight and maintenance advantages compared to air circuit breakers. The Navy employs a conservative approach and derating of circuit breaker ampacity is typical. This derating is based on the Navy's operating environment and testing requirements. Present design best practices suggest that circuit ampacities should be kept below approximately 3000-4000A to leverage commercial devices and limit weight since additional cabling is required for higher ampacities.

Certain Navy ships use shock mounted commercial switchboards. Future Navy ships may not be able to accommodate the physical size of typical commercial marine switchboards. The Navy continues to develop militarized switchboards accommodating state-of-the-art commercial or MOTS VCBs and protection relays for 4160VAC. Future ships may require similar hardware at voltages greater than 4160VAC. These switchboards will need to address the naval operating environment for shock, vibration, EMI, high ambient temperatures, confined maintenance space, and possibly water-mist fire suppression systems. Space constraints on Navy platforms mean that size must be an important consideration for any new switchboards. The switchboards should also incorporate newer safety capabilities where possible, such as closed door test position, novel grounding methods, continuous thermal monitoring, arc fault detection, arc resistance, and so forth. Based upon available switchboards and efforts taken by vendors on previous breaker and switchboard development efforts, the physical size limitations may drive ampacity rating limits to approximately 1200-2000A.

Based on the TWG industry survey conducted, industry is not investing in equipment that enables advanced power systems to clear faults faster and eliminate power interruptions to high power loads with high power continuity and survivability requirements. The Navy is investigating MVDC solid state circuit protection methods and monitoring commercial MVDC distribution efforts.

[79] Graphene-info. *Covetics - a new hybrid that fuses carbon and metal in strong bonds* [Online] Available: *http://www.graphene-info.com/covetics-hybrids-fuse-carbon-and-metal-strong-bonds*

3.6.3.2 Cables

Navy medium voltage cabling must pass gas-flame circuit integrity and water-tightness testing necessary to ensure survivability. Another important test for naval shipboard cabling is the low smoke / zero halogen generation under fire conditions. Overall, Navy testing is far more rigorous than commercial applications would require. For many Naval applications cabling is a mature, relatively low risk component with specifications and characteristics defined by MIL-DTL 24643, MIL-DTL 24640, MIL-DTL 915, and characterized in MIL-HDBK 299. The Navy uses copper conductors and silicon glass insulation (up to 4160VAC) for its cables. As voltages increase above 4160VAC the silicon glass insulation system is no longer viable and the Navy has opted to use ethylene propylene rubber. Voltage spikes and pulsed power demands may also drive future cable design changes.

To be incorporated into the fleet, new technologies for cabling or bus systems must demonstrate a compelling cost and or performance improvement and pass the rigorous testing that existing cabling systems already comply with. Due to the anticipated higher power loads and potential move towards IPS, future NPES will require cable or bus systems that can support medium voltage, high current capacity, tight bend radius, and high volumetric density. While it has not passed Navy testing to date, IBP may prove advantageous[80] to meet these requirements. IBP would introduce new integration challenges. Long IBP runs, connections between IBP sections, and interfaces through watertight boundaries present challenges associated with hull flexure, survivability, electric continuity, and electromagnetic considerations. Carbon nanotubes, metals infused with carbon nano-tubes, and Covetics have been invested in by both Navy and industry and have the potential to provide significant improvements, but presently these technologies are immature and are heavily focused on material science.

HTS will also be a potential option for future power distribution. While the Navy can leverage technology developments used in commercial HTS power systems, these commercial HTS systems focus on liquid nitrogen cooling at 77 degrees Kelvin. Use of liquid nitrogen is prohibited in most Navy applications due to boil-off and expansion in emergency conditions. For these reasons, the Navy's HTS degaussing system development effort used gaseous helium based cooling systems. Similar gaseous helium cooling methods are expected for development in Navy HTS power cable systems. Navy investments will continue to push towards higher voltages, improved terminations, and improved cooling methods to ensure cables are suitable to be used aboard Navy ships.

Power converters may emerge in future distribution systems. At a minimum, any DC distribution system will have power conversion equipment to rectify the AC generation and provide power to legacy loads. Another implementation of power converters could include power conversion as part of a protection scheme to provide current limiting, circuit interruption and other functionality currently provided by distribution equipment. The distribution and power conversion areas will be more and more intertwined moving forward. In addition, UPS are expected to be increasingly integrated into commercial distribution systems. Different concepts are being implemented across various industries and many aspects could be leveraged for future NPES.

3.6.3.3 Naval Power System Stability Requirements

Stability of a system ensures that the system operates as intended without power oscillations,

[80] D. Burley. (2011, October 05). *Ship Installation of Insulated Bus Pipe* [Online]. Available: http://www.nsrp.org/6-Presentations/Joint/100411_Ship_Installation_of_Insulated_Bus_Pipe_Burley.pdf

which can degrade or damage the electric power system components and loads. If stability is not maintained then the power system and mission loads will not function as designed. Traditionally, the electric source was at least one order of magnitude larger than the largest loads and the percentage of power converter loads were relatively small; therefore, the power source transient dynamics dominated the system response. As individual electric load power demands increase and approach the magnitude of the power source, additional integration considerations are required to ensure stability.

As large power converters are incorporated into the distribution systems, their impacts must be fully understood. Power converters can have their own transient response. They can appear as an incrementally negative impedance, consume/inject power at various frequencies, and have various resonance points from their controls and filters. When integrated together into an NPES, end user equipment and electric system stability issues can arise.

The Navy has matured broadband frequency stability analysis techniques, requirements, and verification methods for several systems. Broadband frequency stability requirements such as phase/gain margins have been imposed at the system level and on individual components and interfaces. Electric impedance magnitude and phase requirements have been levied. As power systems employ more and larger power converters, broad-band stability requirements are increasingly needed in both AC and DC power system designs.

For the reasons discussed above, NPES require toolsets to assess stability. Existing techniques are inadequate to help define requirements for open architecture stability as well as component and system designs. Improved verification methods are also needed to ensure that the individual components and then the system meet stability requirements. These requirements and verification methods need to better address the wide range of operating points of the individual components. Lastly, this body of knowledge needs to be incorporated into end user stability requirements specifications and standards.

Grounding methods are also of interest. The power system grounding method is integral to the system architecture and interfaces. Traditional 450VAC power systems are ungrounded. MVAC power systems use high resistance grounding. Grounding methods for MVDC systems are not yet standardized.[81,82] Some of the competing factors include: common mode current, power loss, system power continuity, circuit protection impact, and insulation requirements.

3.7 Controls and Autonomy

A control system is defined as a device or set of devices that manages, commands, directs or regulates the behavior of other devices or systems. One objective of a control system is to improve or optimize the performance of a given dynamic system. Industrial Control Systems (ICS), which include Supervisory Control and Data Acquisition (SCADA) Systems, Programmable Logic Controllers (PLCs), and Distributed Control Systems (DCS) are utilized in numerous industries and provide control in an autonomous manner. These systems provide a hardware platform for processing automation and control functions. These hardware platforms execute the algorithms and communication protocols that control the process or plant.

[81] "Grounding of Shipboard Power Systems – Results from Research and Preliminary Guidelines for the Shipbuilding Industry." Graber, Pekarek, Massola. ESRDC. February 2014
[82] "Grounding Study for Mixed AC/DC Systems." Reichl, Belkayat.

An ICS may consist of workstations, controllers, drives, high level control software, databases, sensors, and graphical user interfaces to provide supervisory control. Supervisory functions provide the ability to set configuration of the plant, calculate set points, execute high level decision processes for the machinery plant, and optimize managed processes. Depending on the architecture, an ICS may also provide device level control, which consists of local devices with microprocessors integrated into the machinery or equipment. The device level control provides the ability to determine process states and interfaces to the supervisory control. In many cases the devices are networked and communicate real time data and control signals.

At the highest level, a control system, such as an ICS, can be broken down into three main areas. These areas are not mutually exclusive; however, they serve to allow one to decompose a particular control system implementation and to compare it to other designs. They also allow for decomposition of the technology development problems one is faced with when attempting to characterize the types of research investments that are required to advance our capability to perform the control function. The three areas are architectures, algorithms, and communications.

3.7.1 Control System Areas

3.7.1.1 Architectures

Architectures refer to several aspects of the control system. In centralized control architectures, all the control decisions are made at a centralized location and communicated to the actuators. Centralized control architectures have the advantage that all information upon which control decisions are based is processed at a single location. SCADA systems tend to have centralized architectures. Distributed control architectures distribute system intelligence from the enterprise or plant level down to individual systems and components, enabling encapsulation of the consequences of failures. Other control architectures of interest include hierarchical, heterarchical, and hybrid structures.

3.7.1.2 Algorithms

Algorithms refer to the policies by which control decisions are made. At the lowest level, feedback control algorithms such as proportional, integral, derivative (PID) or full state feedback methods are used to stabilize and control individual elements in the system. For example, a PID controller may be used to control the speed of a motor or the behavior of a power converter. Monitoring algorithms refer to the ways in which data, typically from sensors, are utilized and turned into information. Human Systems Integration (HSI) algorithms refer to ways in which data is manipulated to make it appropriate for human interface with the control system, as well as methods which enable the human and the autonomy in the control system to interact and provide inputs to the system in a synergistic manner. Optimization algorithms are a class of algorithms which are used to determine the most appropriate allocation of system resources.

3.7.1.3 Communications

Communications refers to the host of technologies that are employed to transfer data and information across the control system. This includes field bus technologies that allow for communications at the lowest level of the control system, communication protocols which standardize communications and allow for the development of interfaces, and networked control system communication methods such as agent communication languages.

3.7.2 Industry Controls Benchmark

Industrial Control Systems (ICS) provide supervisory and device-level control in the electric, water, oil, chemical, transportation, and manufacturing industries among others. Typical ICS control approaches are open loop, closed loop, PID, discrete processes, and system state control. PID controllers are fairly common and utilized in many applications across industries. These controls are utilized to improve safety, process management, product quality and repeatability. Power utilities use centralized and distributed control to perform functions, such as voltage and volt-ampere reactive (VAR) optimization (VVO), load management, and communications throughout the grid infrastructure to enable bi-directional communication, including to individual devices. This is primarily accomplished using SCADA systems.

SCADA systems are typically used where a centralized monitoring and control architecture is necessary for data acquisition and supervisory commands over significant distances. A DCS has an architecture where a supervisory control system provides high level commands to subsystems and where local controllers provide control of a portion of the process. PLCs have a similar architecture to a DCS and are generally programmed using ladder logic.

Architectures are currently a mix of centralized and distributed, depending on the application. Control is also moving toward the device-level. Industrial control systems take advantage of many benefits resulting from the use of fieldbus technology. Initially, the primary advantage was savings in the installation in wiring. More recently, the devices have enough computational capability to provide real time data to plant operators. The open nature of many of these devices allows interoperability between devices of different manufacturers.

There are currently no standardized methods to compare the performance of different control algorithms. In industry, PID controllers are widely used as the algorithm of choice. When tuned correctly, the PID control algorithm provides satisfactory performance. Other control methodologies exist and may also provide satisfactory performance.

In ICS communications there are a variety of different protocols and communication methods. In many instances, these protocols were developed by a specific company and later adopted into a standard. One such protocol, fieldbus, has numerous protocol types within its standard. Additionally, a number of Ethernet-based communication formats are being utilized. For device level communications there are numerous other protocols. Communication between ICS devices can be via wired network connection or via wireless network, adding to the complexity of protocols.

3.7.3 Industry Controls Trends

There is no trend toward establishing performance benchmarks for control systems.[83] Benchmarks require further definition and quantification because they are not standardized across industries; measures tend to be application and industry specific. General areas of interest for this TDR fall into the three control system areas of algorithms, architectures and communications and are generically outlined below:

Algorithms:

[83] Automation.com, “Automation & Control Trends in 2013,” January 2013.

- Decision and response time
- Quality of response
- Usability, including operator training requirements, and operator intervention required
    - Appropriate autonomy
    - Intuitive, user optimized human machine interface (HMI)
- Stability

Architectures:
- Location of control intelligence - local, central, or distributed
- Degree of openness

Communications:
- Expressiveness - communicate correct information
- Succinctness - ability to communicate quickly enough
- Bandwidth and efficiency - throughput
- Interfaces and protocols
- Security - information assurance, anti-tamper, cybersecurity

The general sequence of events in each industry example has been that the availability of microcomputers has led to the replacement of analog systems, which were difficult or impossible to reconfigure, with digital systems. The digital systems allow for more precise control of process variables generally increasing performance. Next, the availability of communication networks allows for sharing of information across a system and eventually across the enterprise.

Communication trends include more wireless devices and increased use of device-level protocols. Cybersecurity will garner significant attention in the communication area.
In summary, industrial automation and control needs are:
- To continue production through equipment failure
- To optimize product quality, quantity & cost
- To reduce human labor and assoc. cost
- To embed machinery diagnostics
- To use open, standards-based hardware & software
- To support equipment commonality over multiple plants
- To ensure life cycle cost over 30-50 year plant life

The following industries drive controls technology improvements:

<u>Automotive - Production, vehicle maintenance and control</u>
The prominent trends in automotive control appear to be in the areas of pre-crash safety systems, collision avoidance systems, parking support systems, engine and brake control with information from roadside infrastructure and vehicle radar.

<u>Aviation</u>
The prominent trends in aviation control appear to be in the areas of software growth enabling more automation, craft to craft communication for drones, and handling large quantities of data for analysis.

<u>Computing</u>

The prominent trends in computing appear to be data analytics - tools that enable companies to analyze massive amount of data, no touch interfaces, more devices connected to the internet, near field wireless communication and energy harvesting.

Oil and Gas

The prominent trends in controls for the oil and gas industry appear to be the integration and continuous communication with sensors, equipment, and systems distributed in an oilfield.[84] Data analytics will be used to fine tune flow and optimize production.

Smart Grids, Renewables, and Utility Interface

The prominent trends in smart grids appear to be development of advanced control and communication technology.[85] In addition to smart grid implementation of smart meters and user programmable technologies (e.g. programmable thermostats, energy management systems), advanced communication and control technologies can reduce outages due to faults, dynamically optimize power levels, and monitor system health. Complexity from the addition of renewable energy sources with variable output power, devices with two way power flow (e.g. energy storage devices), and integration of cybersecurity technology will drive the current trend toward advanced communication and control approaches. Lastly, a trend toward increasing resilience due to weather related events and concerns will result in more sophisticated, intelligent systems with advanced control technologies.

Utility companies will need advanced controls combined with sophisticated communications to enable stable, reliable, and optimal balance of supply and demand. Effectively integrating these resources requires a more sophisticated, intelligent grid that can dynamically manage power flows between highly distributed energy sources and loads—while maintaining a high standard of reliability and resilience. A transactive energy framework may be needed.[86]

Telecommunications

The prominent trends in telecommunications appear to be enterprise mobile applications and cybersecurity.

Process Control Industries

The prominent trends in process control are data analytics for predictive maintenance, cybersecurity, increased embedded functionality at lower control levels, such as at the device level, and remote monitoring by subject matter experts.

Industry advances in architecture will include open architecture, resilient controls, and embedded controls. Algorithm trends which are more difficult to evaluate include use of data analytics for preventative maintenance, resilient control, agent based control, optimal control/model predictive control, and mixed initiative systems. Open architecture will provide the ability to integrate various control systems moving toward an enterprise automation and control system. Resilient controls provide a means for operating through a casualty or cyberattack. The embedded controls trend is programming higher order functions at the device level. While industry has shown interest in some of the advanced control topics that follow, most of the effort

[84] Automation World. (2014, October 01) *Role of Advanced Software in the Refinery of the Future* [Online]. Available: http://www.automationworld.com/role-advanced-software-refinery-future
[85] ABB. "Smart grid Beyond smart meters," Whitepaper. 2012.
[86] U.S. Department of Energy. *2014 Smart Grid System Report* [Online] Available: http://energy.gov/oe/downloads/2014-smart-grid-system-report-august-2014

in these areas lies in academia.

3.7.3.1 Control Trends in Academia

3.7.3.1.1 Agent Based Control Architectures

The desire for more distributed controls structures has led to the development of control architectures that rely on the concept of intelligent agents which reason about system state and enact control policies. A simple example of these agents in a control system is the use of autonomous software coupled with smart meters in a smart grid implementation. The agents, smart meters in this example, can temporarily shut off air conditioning but not the refrigerator in residences during grid peak power usage times when the cost per watt is highest on hot days. The agent software acts autonomously within its authority to comply with programmed customer desires.

3.7.3.1.2 Resilient Control Systems

Resilient control systems are those control systems that maintain operational normalcy and state awareness when subjected to large disturbances, which may be malicious in nature. These disturbances may also be physical (e.g. network communication faults caused by battle damage or otherwise) or cyber (e.g. network intrusion or malicious code) in nature. Resilient control systems provide defense in depth to casualty situations, errant sensors, and cyberattacks, allowing the control system to continue to function successfully.

3.7.3.1.3 Mixed-initiative Systems

As the level of autonomy in our systems increases, the role of the human operator and autonomy begin to interact. Ideally, computer based autonomy is used to perform functions where computers are more efficient at performing the task than humans and vice versa. An example of where this can work effectively is the state awareness problem. The state awareness problem is to determine the state of the system with enough accuracy and in a short enough period of time that an appropriate control action can be employed. With no human input, it is difficult or in some cases impossible for a control system to determine the state of complex systems in a reasonable amount of time. Typically, software agents use search algorithms coupled with sensed data in the system to solve the state awareness problem. However, there are a number of conditions which may exist that humans can process very quickly, but machines cannot. A simple example is a failed valve position sensor which indicates a valve is shut after being commanded to shut, yet the valve is actually open; a human may be able to look at the valve stem to determine valve position, reconcile inconsistent information, and manually shut the valve. By allowing collaboration between humans and machines, large portions of the search space can be pruned from the search space by the human operator. This coupling of human and machine intelligence can enable the solution to problems that neither humans nor machines can solve on their own in a reasonable amount of time.

3.7.3.1.4 Optimal Control and Model Predictive Control

Optimal control is a method by which the control system optimizes the method or configuration utilized to perform a given action and be computed to be optimal in the sense that the control policy causes a cost function to be minimized. The cost function is typically a function of the state and control variables. Optimal control methods allow for the utilization of control resources to be considered in devising a control policy. If we consider that the energy available in our power system represents our actuation, the optimal utilization of that scarce resource is important.

Model Predictive Control (MPC) uses a dynamic model of the system under control combined with an optimization algorithm to optimize the state trajectory of the system for some time into the future. MPC allows us to go one step further than optimal control. Mathematically, the formulations are similar in that the cost functions are weighted sums of control and state variables. MPC incorporates a model of the system that allows the impact of control actions to be predicted forward for some finite amount of time so that the future impacts of control decisions are considered as part of the optimization. MPC has been used extensively in the process control industry and is beginning to find application in power systems as a result advances in available computational power.

3.7.4 Industrial Controls in Relation to Naval Power and Energy Systems (NPES)

In Navy ships, the Machinery Control System (MCS), provides supervisory control and monitoring of machinery systems including the propulsion plant, electric power plant, auxiliary systems, and damage control systems. The MCS is comprised of the hardware and software, including the user interface, required to enable monitoring and control of the machinery plant. MCS, sometimes referred to as an engineering control system, may consist of PLCs, a DCS, network switches, user workstations, software, distributed I/O, signal conditioning, and device level networks.

Most current machinery control systems are distributed with the capability to control the ship's machinery systems from numerous workstations throughout the ship. The distributed control system relies on a network to allow communication between workstations, control equipment, and controlled and monitored devices. The Navy may be able to leverage current trends and collaborations in the areas of data analytics, wireless devices, communication protocols, and smarter devices with more embedded controls. The Navy will also continue to leverage the gains in processors and computer hardware.
The lag in industry integrating resilient control, agent based control, optimal control/model predictive control, and mixed initiative systems may result in these algorithms not being at the necessary technology readiness level when they would be beneficial. These control strategies are emerging in the basic and applied research communities of control theory, optimization theory, resilience, and computational intelligence. They are rich areas of research applicable to both the smart grid industry and the Navy. The results of this research hold a promise of additional gains that address both emerging architectural and algorithmic challenges for control system design and implementation. Opportunities to transition emerging work will affect the projected challenges the Navy will face on future platforms.

Microgrids and smart grids are of interest due to their similarities with shipboard electric plants. There is a significant research thrust into technologies that will enable the Smart Grid that are relevant to naval shipboard control systems. Technologies that provide demand side control methods and enable the integration of stochastic energy sources such as wind and solar generation will provide some of the algorithmic capability that the Navy needs as it works to integrate energy storage, high energy weapons and sensors into naval platforms. Advanced algorithms and communication technologies will also be developed for microgrid resilience and cybersecurity.

Navy control systems must be architected in a manner that supports survivability and recoverability. For this reason, the trend in R&D for shipboard controls has been with an eye toward more distributed intelligence and decision making. This trend is not seen in most other

types of industrial control systems and gives rise to some Navy unique problems. An IPES ship with electric propulsion, multiple high power sensors, and high energy/power electric weapons, presents a series of additional unique control challenges that are Navy specific. Such an IPES future surface combatants are the assumed basis for the "will" statements about future Navy control system trends and requirements in this section. Controls advancements and trends to support IPES on future combatants also apply to non-IPS ships in less complex control system instantiations.

3.7.4.1 Future Design Space for NPES Control Systems

The trends toward advances in the areas of architectures, algorithms, and communications, driven by both basic and applied research efforts and by market forces, will alter the available design space for naval shipboard control systems. One possibility is to design systems that give more capability in terms of combat effectiveness than we are capable of designing today. Another possibility is to use the technology to deliver the same relative combat effectiveness at a reduced cost. For example, using today's control technology to deploy a fully electric ship with a full suite of electric weapons may require some amount of energy storage in order to support all the loads and stabilize the distribution bus. Basic research results indicate that through the implementation of model predictive control methods and optimization of the design of the energy storage system, a significant reduction in the required amount of storage is possible. This reduced requirement can be used to reduce the installed energy storage, holding combat effectiveness constant and avoid acquisition and life cycle costs of the additional energy storage. Alternatively, if the amount of storage is held constant, the platform would realize an increase in combat effectiveness because the additional energy storage represents increased capabilities for mobility, sensing, and the delivery of ordnance.

In addition to distributed intelligence, the number of power system nodes and associated input and output signals and control functions will continue to increase to support future electric plant architectures. Power systems will be more complex and require more autonomous system management, a major function of a combat power control system. An interface is expected to be implemented between the MCS and combat systems to communicate information as the two systems become interdependent. Autonomic control, executed faster than a human operator, will be a requirement of the combat power control system's power management system as the complexity of control decisions is increased to optimize electric plant configurations for a mission or scenario.

Additionally, advances in controls will be required for thermal management systems, considering their interdependency with the electric power system. For thermal management, high energy pulse loads may require additional cooling during firing events which will increase the amount of actuation in the cooling system. Advanced methods to coordinate the delivery of cooling resources and power resources to the weapon systems will require that the control system behave in a predictive manner. Future power management systems will need to autonomously configure and actuate electric power and thermal management systems, such that:

- The optimal amount of power is available for mission and user systems
- Power is controlled in a resilient and robust way, able to operate through a cyberattack
- Computation and communication occurs rapidly enough to maintain power during steady state and transient operation
- Systems are capable of physical plant recognition for optimal reconfiguration during casualty events, using local or zone control as necessary to operate

The tight coupling anticipated between the weapon and sensor systems, propulsion system, power system, and thermal management system require that the control solutions for these systems be complementary and sufficiently nuanced to address the complex interactions and difference in response times and behaviors between these systems. This coupling and coordination will require a total ship systems approach to a ship-wide combat power control system. These challenges are Navy unique and are not likely to be solved as result of trends emerging in industry. The Navy is currently engaging with the Department of Energy National Laboratories to leverage their advanced controls experience gained from terrestrial power systems and microgrids.

4.0 Navy Ship Implementation Challenges

The previous chapter presented a general analysis of industry benchmarks, trends, and potential naval applicability. Follow on chapters describe the systems engineering analysis process, review the requirements analysis, and provide development recommendations for the next 30 years. This section describes some of the challenges associated with the Navy shipboard environment and general considerations that developers should address. The intent is to give the developer an understanding that will inform innovation decisions at all stages of the NPES technology development process.

4.1 Shipboard Environment

Power system technologies of interest to the Navy are ones that are relevant to Navy needs, are improvements over previous technologies (e.g. less expensive, more reliable, smaller or lighter), and provide an increase in capability. Relevant means the technologies must be compatible with the Navy shipboard environment. Physical size constraints are dictated by ship missions and naval architecture considerations, such as space, weight, and intact and damaged stability. Navy ships tend to be more maneuverable, faster, and have a more variable operational profile when compared to oceangoing commercial marine vessels. They have payloads such as weapons systems and advanced sensors which don't have commercial equivalents. These payloads generally have more demanding electric power requirements than commercial vessels. Large power demand drives the physical size of power generation and power system equipment to become a major consideration in the overall ship design. For smaller warships, compact power systems may be required to meet mission requirements. Power system elements must physically fit within a space and weight limited ship design. For larger warships, increasing power density of the electrical system has value, but only if affordable.

Navy warships have unique military performance requirements. They are expected to have service lives of 40 years or more. This service life requirement creates challenges for the power system designers as the infrastructure installed at delivery of the ship is expected to remain relevant over its entire service life. Allowances for Space, Weight, Power and Cooling (SWaP-C) must be incorporated early in the design cycle. Additionally, as missions and threats evolve over a ship's service life, the NPES must be able to support future mission systems affordably. Essential ship systems must be designed to survive and continue to operate following a casualty. Most NPES are designed for a shock, vibration, and ship motion environment that ranges from calm peacetime transits to rough seas and battle damage conditions. System redundancy combined with physical separation of components and multiple system distribution paths are inherently required to continue ship operation with flooding, fire, and/or battle damage. Navy ships are inherently sustainable by ships force for up to nine months without original equipment manufacturer (OEM) or depot level support. These long deployment cycles drive many NPES support considerations including providing the crew with the ability to rapidly repair systems, incorporation of line replaceable units into designs, and provision of technical documentation.

Navy ships generally require equipment to operate in a wider range of ambient temperatures than commercial equipment. Future electrical loads are likely to be more power dense, which increases local heat loads in selected ship compartments, and overall require higher power which increases total ship heat load. Advances in thermal management capability and capacity will be required to complement these future loads. Electromagnetic interference and electromagnetic compatibility (EMI/EMC), airborne noise, structureborne noise, and signatures

are additional design considerations for Navy ships, with naval systems required to meet much more stringent requirements than commercial ships. Another major design consideration is that all projected improvements must be critically evaluated for cost effectiveness and contribute to overall system/ship affordability.

4.2 Ship Electric Power Systems

Ship electric power systems can be globally defined by key electric parameters. Design tradeoffs include these technical design parameters, budget constraints, allowance for growth, and naval architecture considerations discussed above. The following specific electric parameters and issues are discussed in more detail in the following paragraphs:

- Frequency
- Voltage
- Load characterizations
- Distributed system layout
- System integration

Frequency measured in Hertz (Hz) is a basic electric parameter. The US commercial standard and the standard Navy ship frequency is 60 Hz. Worldwide, the standard is either 50 Hz or 60 Hz. Navy ships predominantly generate and distribute power at 60 Hz (three phase), with the majority of loads directly powered at 60 Hz. All ships generate power using AC generators. DDG 1000 is unique with its generation at 60 Hz and a DC electric distribution system fed by transformer-rectifiers. Frequency selection for future ships will be determined based on a variety of considerations. Higher frequencies enable smaller transformers and filter components which mitigate naval architecture space and weight issues, and also allow smaller, higher speed rotating electrical machines. Physics based concerns mandate derating some equipment at higher frequencies, such as cables for skin effect, and circuit breakers for arc extinguishing time before restrike voltage. While DC distribution uses fewer cables and removes phase matching complications, conversion from AC generated power, the current norm, to DC for distribution introduces losses. This TDR invites innovation to determine what shipboard frequency, or combination of frequency alternatives, best meets the needs of future platforms.

Voltage level for generation and distribution is primarily determined by a platform's design power requirements. The Navy's predominant generation and distribution voltage has been 450VAC while more recent designs have used 13.8kVAC (CVN 78), 6.6kVAC (T-AKE 1) and 4160VAC (CVN 68-77, LHA 6, LHD 8, DDG 1000). Commercial and foreign navy ships use all of these voltages as well as some others, notably: 480VAC, 690VAC, 3.3kVAC, and 11kVAC. Selection of voltage level is driven by limitations of the electric distribution system.[87] Higher voltages result in lower currents to deliver the same amount of power. There are natural breakpoints where engineering and naval architecture considerations dictate higher voltages. Available circuit breakers have limited continuous current ratings, and commercial design practice is to use a higher voltage rather than develop breakers to handle higher continuous currents. Higher voltages impose additional considerations for cable insulation and physical separation requirements, such as creepage and clearance. Ship distribution cables are heavy (approximately 6 lbs./foot for 400 MCM three phase cable), and lower current means fewer cables thereby reducing distributed system weight. Fewer cables also reduce the cost of pulling and terminating the cables – reducing ship acquisition cost. In general, it is expected that future

[87] See IEC 60038 for a complete listing of standard voltage levels.

Navy ships will use industry standard voltages and current ranges to take advantage of available product lines as long as they can meet military performance demands.

Shipboard loads can be characterized in terms of application, magnitude of the load, transient and power interruption tolerance, and desired input such as voltage and frequency. Major applications include motors (pumps, fans, propulsion, etc.), heating and lighting, computers and electronics, and combat systems loads (radars, sensors, weapons). Tolerance to power interruptions is covered under Quality of Service (QoS) and described in detail in *NAVSEA DDS 310-1 Rev.1*[88]. Quality of Service is invoked in the IEEE 1709 and IEEE 1826 standards. Different loads also have different inherent power needs that result in a preference for AC or DC power. Fan and pump motors are predominantly AC induction motors. These loads are relatively insensitive to momentary fluctuations in frequency or voltage or short term disruptions in power. Heating and lighting are traditionally AC fed because ship distribution systems are AC, and they are also tolerant of momentary to longer term power interruptions.

Computers, other electronics, and combat systems loads require some or all power to be DC, and incorporate conversion from the distribution input (required for AC, may be required for DC) to the specific load DC voltage level. These loads are very intolerant to transients and power interruptions, especially COTS based equipment, and they often incorporate an UPS to maintain power continuity. Equipment level UPS result in increased cost and maintenance. System reboots due to power quality problems are inconvenient commercially and unacceptable in a combat situation. A major shipboard implementation challenge is to provide loads the power they need, most efficiently, with appropriate QoS for different loads, while minimizing the number of UPS and dedicated load power converters.

The ship electric power system is a distributed system, with multiple generators and sometimes emergency generators, multiple switchboards, and redundant paths to power vital loads. Improvements in components that distribute power such as switchboards, circuit breakers within switchboards, cables or alternative distributed transmission means are of interest, as well as better methods to distribute power to loads that demand different types of power.

Other ship implementation challenges are grouped here as system integration challenges. Navy warships must be able to continue to fight under adverse circumstances. This imparts a systems design philosophy that requires a means to ensure power continuity through fault isolation, through load shedding operation to account for generator casualties, and through the use of an alternate source to maintain vital loads. Generators and associated equipment must be robust enough to ride through overloads, provide fault current to enable automatic circuit protection actions such as tripping circuit breakers, handle large step load changes, and return to providing specified power as soon as possible following emergency transients. Several ship implementation challenges and opportunities exist since the Navy is interested in faster fault identification and clearing, smarter and better circuit protection schemes, more robust machines and controls, and components that improve existing responses to casualties and emergencies. Power system recoverability is required in order to restore power to critical loads in parts of the ship where the installed power distribution system has suffered weapons induced damage. All solutions must respond during the worst cases of shock, vibration and environmental conditions as the warship goes into harm's way.

[88] NAVSEA DDS 310-1 Rev 1, "Design Data Sheet: Electric Power Load Analysis (EPLA) for Surface Ships," 17 September 2012.

4.3 Power System Architectures

Shipboard power system architectures are enabled by their supporting technology and associated developments to meet future ship integration challenges. Historically, the power demands of most naval ships were modest enough such that most power was generated as 450VAC three phase power and most loads employed the same type of power. A radial architecture simplified circuit breaker coordination, but required additional cabling for those few vital loads requiring a high degree of power continuity.

As electronic mission systems became more numerous onboard ship, many of these loads were designated as vital and required considerable cabling to provide redundant power. In the 1990s, the radial power system was replaced by a zonal power system on destroyers, primarily to reduce the cost and weight of the distribution system. This zonal power system improved power system survivability and maintained the same level of power quality and power continuity. The overall evolution of Navy primary distribution and power to ship and mission ship systems is illustrated in Figure 7 below.

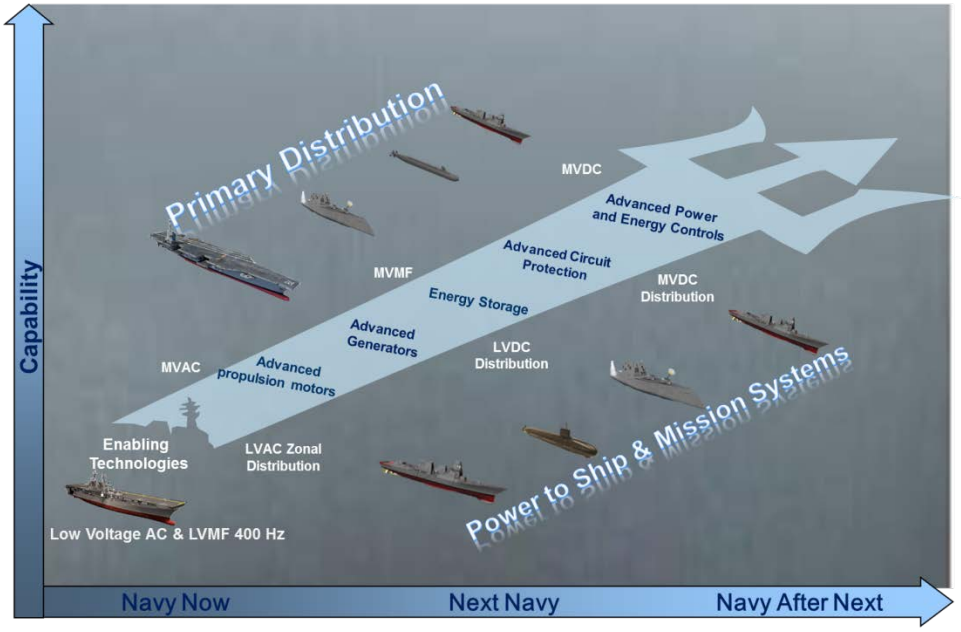

Figure 7: Directing the Future of Ship's Power

The total electric load onboard ships grew substantially during the 1990s. LHD 8 is a good example of this trend. Chilled water loads grew to satisfy the cooling needs of numerous electronic mission systems while the replacement of steam heating increased electric heating loads. As these loads increased, generating and distributing medium voltage AC power via zonal transformers became more affordable and lighter than employing a 450VAC only system. This trend not only applies to auxiliary systems such as heating and cooling loads but mission loads as well. Increased mission loads have led to the adoption of 4160VAC distribution in the DDG 51 Flight III.

In this emerging paradigm, increased electric load power demands can rival the power demands of propulsion during many operational scenarios. The ability of IPS' to more affordably meet

these power demands was an important driver for its introduction into the T-AKE 1 Class and DDG 1000 Class. IPS enables the installation of fewer prime movers on a ship, and enables the more efficient use of those prime movers. Some key technologies that enabled IPS were the development of propulsion motors, their drives, harmonic filters, and advanced machinery control systems. More recently, hybrid electric drive on LHD 8 provides significant operational fuel economy, but did not enable a reduction in the number of prime movers.

The growth in sensitive electronic loads that cannot tolerate power interruptions has led to the proliferation of UPSs onboard ship. Until the introduction of electronic systems, service interruptions on the order of one second were tolerable. The response to the introduction of sensitive electronics into naval ships, driven by MIL-STD 1399 requirements was to require these loads to provide their own UPS. Centralizing this function and incorporating the capability to service uninterruptible loads directly from the power system or from more centralized energy storage would reduce the number and variety of individual UPS configurations. Medium voltage DC zonal distribution similar to that designed into the ship service distribution system for DDG 1000 (1000VDC) is also capable of providing uninterrupted power from multiple sources to sensitive equipment. The recent development of QoS and its incorporation into standards will assist the design of future power systems in affordably meeting the power continuity needs of the loads.

Developing technologies, components, and systems offer further opportunities to provide more affordable shipboard power systems that meet the needs of ship systems. Energy storage technologies are rapidly improving and offer the opportunity to introduce more affordable components such as twin-spool gas turbines, enable single generator or reduced generator operations to decrease fuel consumption, provide a source of power for uninterruptible loads, eliminate the need for dedicated harmonic filters, provide load leveling, and perform power factor correction in AC systems.

Within electrical zones, the development and standardization of low voltage power conversion will enable elimination of low power distribution system layers. Many loads will be powered directly from these standardized converters with other loads separated from a standardized converter by only a single power panel. The additional ability of the power system to manage overall power consumption by large loads will enable improved load shedding for QoS and mission prioritization, reduced need for energy storage, and at potentially lower cost than currently possible.

The specific architectures and technologies that will be employed by a particular ship design will be chosen by the responsible ship design team. Typically, the ship design team will use the *Design Criteria and Practices Manual* for electrical systems to develop its power system options. The goal of this TDR is to ensure technologies are sufficiently mature for the ship designers to have affordable and effective power system alternatives to choose from.

Gaining the potential improvements in cost and performance of the technologies described in this document will require incorporating evolutionary or even revolutionary change to accepted specifications, standards, handbooks, design data sheets, and design criteria and practices manuals. It also requires ensuring the workforce and industry can affordably implement the technology into NPES and eliminate obsolete technologies and methods from consideration for new power system designs. Supporting these institutionalization efforts is implicit in the proposed technology development efforts described in this TDR.

4.4 Thermal Management

Naval power systems require cooling to operate. Similarly, thermal management systems which encompass ship heating and cooling (air conditioning plants, HVAC, associated pumps and fans, electric heaters, etc.) require electric power to operate. Simultaneous operation of ship power and thermal management systems is necessary to achieve military performance. As ship power demands and associated thermal loads increase, thermal management and power systems will become more intertwined and potentially require intelligently linked controls. Because the power system relies on the thermal management system for proper operation and in recognition of this important linkage, this section provides general background on the thermal management challenges on board US Navy ships and discusses the advancements required to meet the emerging increase in cooling demands.

The thermal management system is the largest and most complex auxiliary system on a ship. Its function is to maintain living spaces, equipment, and systems at specific operational temperatures and ventilation rates. Assessing and optimizing the effectiveness of a thermal management system requires the analysis of heat transfer mechanisms, energy sources, and energy sinks. Sources can be simply defined as anything that generates heat, and sinks are ultimately the ocean and atmosphere. Ideally, the thermal management system should transfer the heat generated at the sources to the sinks in the most efficient manner. On Navy ships, the principal heat transfer media are water, including seawater, chilled water, and fresh water, and air for HVAC systems on the ship. Some systems' equipment use secondary fluids such as propylene glycol or deionized water for intermediate heat transfer.

The Navy is interested in thermal management technologies and systems that provide improvement over current capabilities (e.g. less expensive, more reliable, more survivable, more efficient, smaller, lighter, etc.). The systems/technologies must be compatible with the Navy shipboard environment; the naval architecture considerations discussed in Section 4.1 apply. Military specific electric weapons systems and advanced sensors are less efficient than traditional electric loads, approximately 25% as opposed to 90% or more, and therefore generate a significant amount of heat. Large electric power demands and inefficient operation lead to increasing demands on thermal management systems.

Today's shipboard thermal management systems have changed little over the past 60 years. The design/architecture reflects the thinking of that era, which emphasized simplicity and dependability with no manpower constraints nor need for energy conservation. Thermal management of cooling is an interlinked mix of several subsystems including ambient air, HVAC recirculation air, chilled water, A/C[89] plants, deionized water, freshwater, propylene glycol, and seawater, as shown in Figure 8. Using the ventilation system to remove large amounts of equipment heat tends to be inefficient due to the number of steps required to finally transfer heat to sea water.

Thermal management requirements vary with each piece of equipment and are dependent on two parameters: operational temperature and total heat load. For equipment with high heat loads, heat is typically transferred directly to cooling water pumped through the system. The decision between chilled water and seawater depends on operating temperature and operating

[89] For clarity, "A/C" is used in this TDR to denote air conditioning and "AC" is used to denote alternating current.

temperature range. Chilled water provides a constant inlet temperature while seawater provides a wide range of temperatures between Arctic and Persian Gulf conditions. Other considerations are weight of cooling hardware, fouling, corrosion, location in the ship, reliability, sustainability, and maintainability. For equipment with small loads, heat is typically transferred from the system to air and removed through cooling coils using chilled water which eventually rejects heat to sea water or through ventilation to air. These small loads together can add up to a significant heat load for the HVAC system. Typical ship loads are depicted in Figure 8.

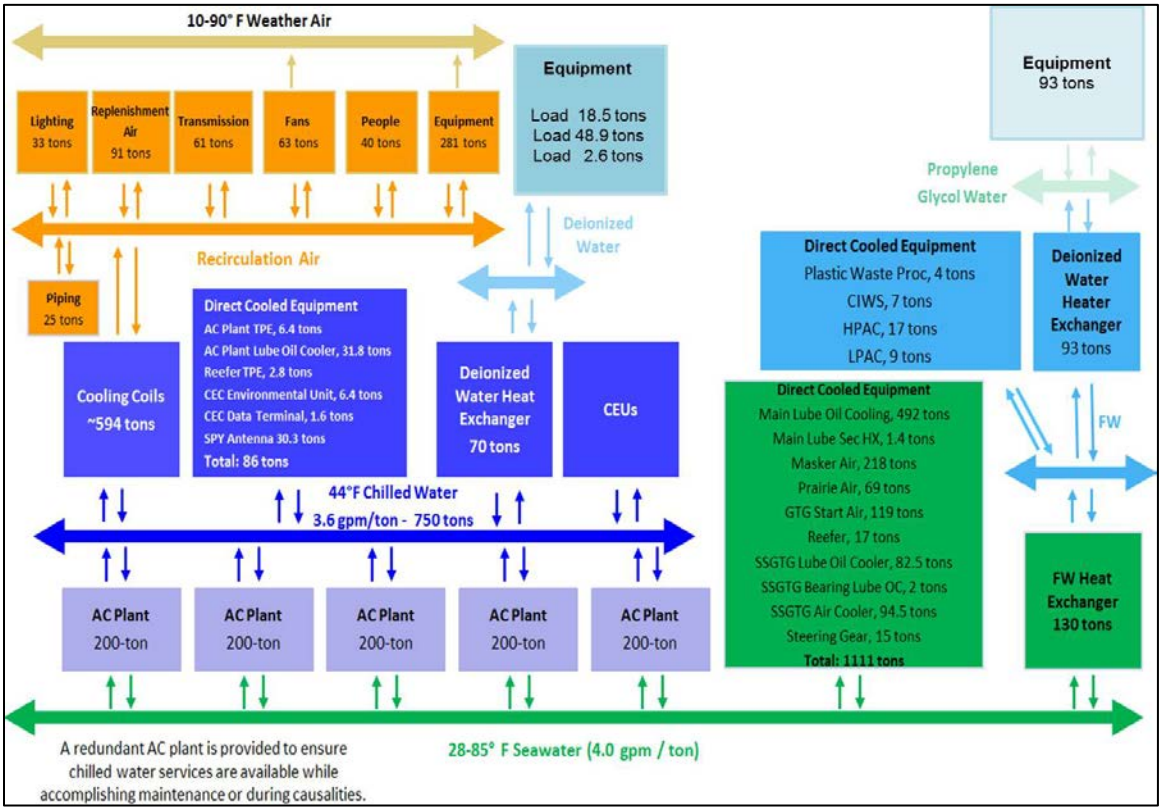

Figure 8: Notional Shipboard Thermal Management System Diagram

Navy warships have unique military performance requirements. The ship's thermal management system is mission critical and must continue to operate under adverse conditions. System redundancy combined with physical separation of components and multiple system distribution paths will be critical to continue ship operation with flooding, fire, and/or battle damage. Ideally, the ship's thermal architecture should be compatible with the ship's electric zonal architecture to maximize survivability.

Developing technologies, components, controls methodologies, and systems offer opportunities to provide a thermal management system that meets the needs of future ships. The high efficiency small capacity (HES-C) chiller is about to enter service and has 1.75 times the capacity in a smaller footprint than legacy chillers.

Additional technologies capable of transforming shipboard thermal management include:

- Thermal management system controls
- Advanced fan technologies
- Compact cooling coils designed to utilize less water

- Intermediate temperature chillers
- Scalable liquid cooling design methodologies
- Cooling and heat pump cycles
- Direct refrigerant cooling / two-phase cooling
- Magnetic refrigeration
- Thermal-to-electric
- Advanced thermal energy storage
- Improved efficiency heaters

4.5 Specifications and Design Rules

Specifications, standards, handbooks, design data sheets, and design criteria and practices manuals are essential to institutionalizing new technologies, architectures, and interfaces. These documents are all related but have different functions in the design, development and procurement of NPES.

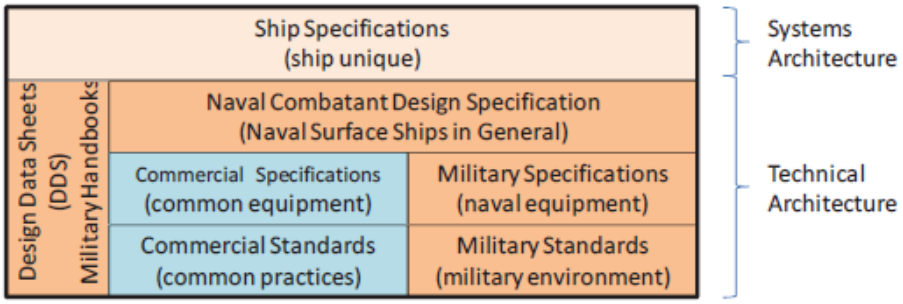

Figure 9: Technical Documentation Relationships

Figure 9 shows the relationships of the various technical documents. At the lowest level are commercial and military standards that provide rules, test requirements, best practices, and interface requirements. These standards are usually invoked through commercial and military specifications which collect all the requirements from the commercial and military standards in addition to equipment requirements into a document that can, along with owner preferences, be directly employed to buy power system components or equipment. These specifications can either be performance specifications which describe the equipment in terms of the performance, interfaces, and testing requirements, or detail specifications which specify the precise design for the equipment along with manufacturing methods and acceptance test procedures.
While the specifications are used to describe the requirements for procuring equipment, the processes for design and design verification are described in military handbooks and design data sheets.

Specifications and standards should be viewed as one of the primary transition products resulting from technology development. The key source documents for electric plant design and development include: MIL-STD-1399 300/680 (Electrical Interface Standard), MIL-STD-1399 377 (Electrical Plant Security), MIL-STD-XXX (Electric Plant Control System), NCDS Section 300 (Naval Combatant Design Specification), DPCM Section 300 (Design Practices and Criteria Manual), and DDS 310.1 (Electric Plant Load Analysis. These documents are the primary enablers for ship and system designers to incorporate and procure products and provide them to the Fleet. Through maturation efforts, a specification or standard evolves from a generalized

specification or standard (either commercial or military) to a formal specification, standard, or Project Peculiar Document (PPD) developed for incorporation into the ship specification. Specifications and standards also enable industry to produce product lines in anticipation of Navy needs.

The *NAVSEA Technical Standards Procedures*[90] provides the details for developing, revising, reviewing, approving, issuing, maintaining, canceling, and adopting technical standards within NAVSEA. The Command is currently reviewing and updating many military specifications, standards, and handbooks, and employing commercial standards and specifications in an effort to reduce cost while maintaining military effectiveness.

Specifications and standards play a vital role in realizing next generation NPES. Updates to standards and specifications cannot occur in a vacuum and should proceed in lockstep with the technology development process. Some of the major Navy specifications and standards that are anticipated to be developed or updated in parallel with the recommended technology developments are listed below:

System Design and Engineering:
- MIL-STD-1399 sections for MVDC and LVDC
- Military or commercial standard for MVDC protection systems
- Design data sheet for stability analysis
- Electric Plant Installation Standard Methods for surface ships and submarines for MVDC
- Electrical Systems Design Criteria and Practices Manual (Surface Ships) for Preliminary and Contract Design

Power Generation:
- Updates to various generator set specifications to incorporate MVDC, electronic governors, voltage regulation, power sharing, and allowance for magnetic bearings

Energy Storage:
- Performance specification (either commercial or military) for energy storage

Power Distribution:
- Updates to various specifications to incorporate controllable bus transfer, medium voltage cables up to 20 kV, cables for propulsion motors with high harmonic currents, marine Insulated Bus Pipe (IBP), medium voltage transformers, MV shore power connections
- Design data sheet for MV cable design so it is clear when drain or grounding wires and shielding is necessary

Power Conversion:
- Extend MIL-PRF-32272 Integrated Power Node Center (IPNC) to include medium voltage input and higher power levels

Propulsion Motors and Drives:
- Specification (either commercial or military) for propulsion motor and drives

Power Control:
- MIL-STD-1399 section for machinery control system interface to loads
- Handbook for describing the architecture and integration method for power control

A more complete listing is provided in Appendix A - Naval Power Systems Specifications and

[90] Naval Sea Systems Command, "NAVSEA TECHNICAL STANDARDS PROCEDURES," 30 Aug 2006.

Standards.

4.6 Cybersecurity

Cybersecurity, as defined in *National Security Presidential Directive (NSPD)-54* issued in 2008, is "the prevention of damage to, protection of, and restoration of computers, electronic communications systems, electronic communication services, wire communication, and electronic communication, including information contained therein, to ensure its availability, integrity, authentication, confidentiality, and non-repudiation." DoD and the Navy recognize the importance of Cybersecurity against cyber-attack due to the relatively low level of effort needed to cause high impact effects on mission capabilities. NAVSEA'S *Strategic Business Plan 2013-2018*[91] states, "we exist under a continuous state of cyber-attack. Our goal is to ensure both our shore networks and shipboard systems will withstand these attacks, or recover quickly when failures occur." Cybersecurity has been elevated to one of NAVSEA's four mission priorities for the design, build, delivery, and maintenance of ships and systems for the Navy, with commensurate attention throughout the Navy's Systems Commands (SYSCOMs) and PEOs.

4.6.1 Cybersecurity Impact to Naval Power and Energy Systems (NPES)

Naval power systems include the machinery controls, systems controls, and networked communications required to generate and deliver power to ship systems. All the technology product areas described in Chapter 3.0 involve some level of control and communication at the system level, and often include local and internal control functions at the component level. As these technologies continue to evolve, there is increasing pressure and desire to leverage increased sophistication in control systems to improve capability, reduce maintenance, and integrate with other Navy systems, for example communications between power systems and combat systems.

Many of the cybersecurity challenges faced by Navy power systems are similar to the challenges faced by electric utilities. Much of the infrastructure which serves the US grid is aging, and as components of the system are retired, they are replaced with newer components often linked to communications or automated systems. The electric power grid has a preponderance of Supervisory Control and Data Acquisition (SCADA) systems for many functions including health and status monitoring. General vulnerabilities of a smarter power grid include control systems, connections through other systems (wireless, telephone, etc.), communications and internet access, combined cyber and physical attacks, and component supply chain management (smart meters, microprocessors, etc.). The National Institute of Standards and Technology (NIST) has the role of coordinating the development of a framework to enable the development of the smart grid in a safe and secure manner, with the first guidelines for smart grid cybersecurity issued in 2010.[92] The Navy must understand and address these vulnerabilities as part of the development and deployment of any modern Navy power system.

4.6.1.1 Cybersecurity Guidance

In March 2014, the Office of the Secretary of Defense (OSD) issued *Department of Defense*

[91]USA. Department of the Navy. NAVSEA. NAVSEA Strategic Business Plan 2013 - 2018. 2nd ed. Washington, DC: NAVAL SEA SYSTEMS COMMAND, 2013. Web. 02 Dec. 2014.
[92]Campbell, Richard J. "The Smart Grid and Cybersecurity - Regulatory Policy and Issues." Fas.org. Congressional Research Service, 15 June 2011. Web. 2 Dec. 2014

Instruction (DoDI) 8500.01 Cybersecurity, replacing the 2007 *Department of Defense Directive* (*DoDD) 8500.01E Information Assurance (IA)*. This instruction codified the DoD Cybersecurity Program – a set of policies and procedures based heavily upon the *NIST Risk Management Framework* (RMF) – and established the term cybersecurity to take the place of IA in DoD guidance and operations. DoD also issued DoDI 8510.01 *RMF for DoD Information Technology (IT).* RMF replaces the DoD IA Certification and Accreditation Process (DIACAP) and manages the lifecycle cybersecurity risk to DoD IT. The Navy follows DoD guidance for cybersecurity, and is developing the supporting layers of guidance necessary to realize effective cybersecurity. The Department of the Navy (DON) Chief Information Officer (CIO) provided additional guidance with the issuance of the *DON Implementation of the RMF for DoD Information Technology* memorandum in May 2014, which established requirements and guidance for the adoption of DoDI 8500.01 and DoDI 8510.01E for Navy systems acquisition and operation. Additionally, DoD created a separate command to address cybersecurity issues. In 2010, US Cyber Command achieved full operational capability as a sub-unified command; the Navy service element is Fleet Cyber Command (FLTCYBERCOM).[93]

The Space and Naval Warfare Systems Command (SPAWAR), acting as the Navy's Information Assurance Technical Authority (IATA), is developing the Defense in Depth Functional Implementation Architecture (DFIA) which will provide specific guidance on how and what is needed to effectively design cybersecurity technologies into systems and networks aboard afloat platforms. NAVSEA is participating with the other SYSCOMs in developing uniform guidance for program managers to use as they develop cybersecurity solutions. NAVSEA is in the process of updating *NAVSEA 9400* series documents to align with these new processes and implement current cyber security, certification, and accreditation.

In response to a recent evaluation of the increasing challenges faced by the Navy, the Chief of Naval Operations established Task Force - Cyber Awakening (TFCA) in August 2014 to devise an integrated approach for improving cybersecurity capabilities throughout the Fleet. The Task Force has been charged with aligning and strengthening the authority, accountability, and rigor in Navy cybersecurity by delivering fundamental change to the Navy's cyber organization, resourcing, acquisition, and readiness capabilities. It is anticipated that cybersecurity guidance and requirements will continue to rapidly evolve to adapt to the cyber threat. Such evolving requirements create challenges for new technology development projects thus close coordination and alignment with targeted ship platforms is essential.

4.6.2 Technology Development Cybersecurity Considerations

The cyber threat necessitates designing cybersecurity into systems from the beginning and that cybersecurity be part of the systems engineering process. New technologies will require cybersecurity certification, assessment, and authorization. Cybersecurity is a complex problem with growing impact on technology development, specifications, standards, interfaces, architectures, systems engineering, acquisition, operations, and support. Cybersecurity considerations will also drive requirements for new approaches and documentation such as a cybersecurity strategy, cyber CONOPs, and Information Support Plans (ISPs). The Navy has to deal with cybersecurity for forward fit and new construction applications as well as back fit of new technologies into in-service platforms. Some considerations are provided below as

[93] U.S. Strategic Command. (2015, March). *Cyber Command factsheet* [Online]. Available: http://www.stratcom.mil/factsheets/2/Cyber_Command/

examples of incorporating cybersecurity into designs:

- Control systems networks shall be logically and physically separated from other shipboard networks.
- Prevent unauthorized changes to control system data such as instructions, commands, configuration settings, and alarm thresholds that could damage, disable, or shut down equipment.
- Restrict logical and physical access to control system components at the control layer, network layer, and the application and information layer.
- Detect and prevent control system data disruptions, which delay or block information flow necessary to prevent loss of control functionality or loss of control system situational awareness.
- Detect and manage false information sent to the control system operators intended to disguise unauthorized changes or initiate inappropriate actions by control system operators
- Disable unused ports and services on control system components at the control layer, network layer, and the application and information layer.
- Deploy required security patches on control system components at the control layer, network layer, and the application, operating system, and information layer.
- Control systems networks or devices shall not be allowed access to the internet.
- Security controls shall be implemented such as intrusion detection software, error handling routines, defensive code, antivirus software, and file integrity checking software to detect, prevent and mitigate the impact of malicious software to the control system.
- Security techniques such as encryption or cryptographic hashes shall be applied to stored data in order to maintain data integrity, confidentiality, and availability.

This chapter presented Navy ship implementation challenges that impact NPES. Understanding the unique design considerations and performance requirements that are invoked for NPES provides some insight into the level of engineering rigor that is required to develop an NPES. The next chapter will discuss how systems engineering is applied to NPES development.

5.0 Systems Engineering Approach to Aligning Requirements and Technologies

The final steps of the NPES TDR process include aligning technologies with requirements and identifying gaps as shown in Figure 10. Chapter 5.0 presents the systems engineering analysis approach used to align requirements with technologies and identify gaps. The cumulative results of these two steps are presented in two chapters each for the near-, mid-, and far-term. Chapters 6.0, 8.0, and 10.0 present the analysis results, and identify gaps and drivers and notional time phasing of requirements that merit NPES development in each term. Chapters 7.0, 9.0, and 11.0 present specific development recommendations and relevant target metrics.

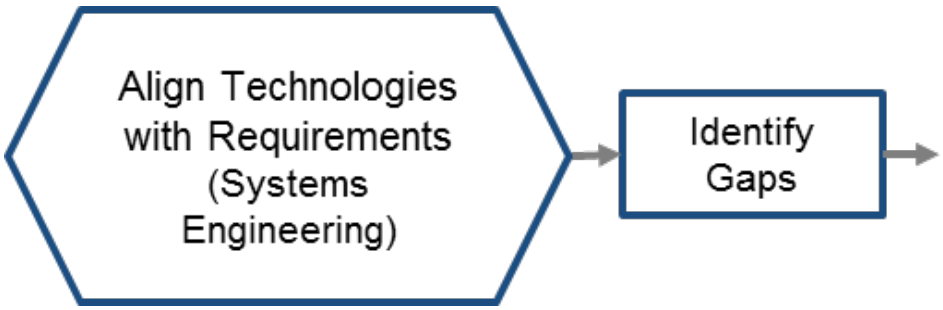

Figure 10: Final steps in TDR process - Systems Engineering and Gap Identification

The primary objective of aligning derived electric requirements with available technologies is to determine if available technologies can satisfy the derived electric requirements in the timeframe required. If technologies are not or will not be available, then a gap exists which must be filled by a development effort. Given the long lead time between identification of a gap and when a functioning system is installed onboard a ship, this roadmap seeks to identify future gaps via a systematic and disciplined technical approach.

5.1 Systems Engineering Process Overview

Figure 11 below shows an overview of the process used to align derived electric requirements with available technologies. Based on this process, the following information is required in order to determine if a gap exists:

- The derived electric requirements
- The projected platforms and timeline
- The available, or projected to be available, electric power system configurations
- The technologies, products, and systems that are available, or projected to be available, when the solution is required
- The relevant specifications or standards that affect the solution
- A prioritization of the ubiquitous requirements

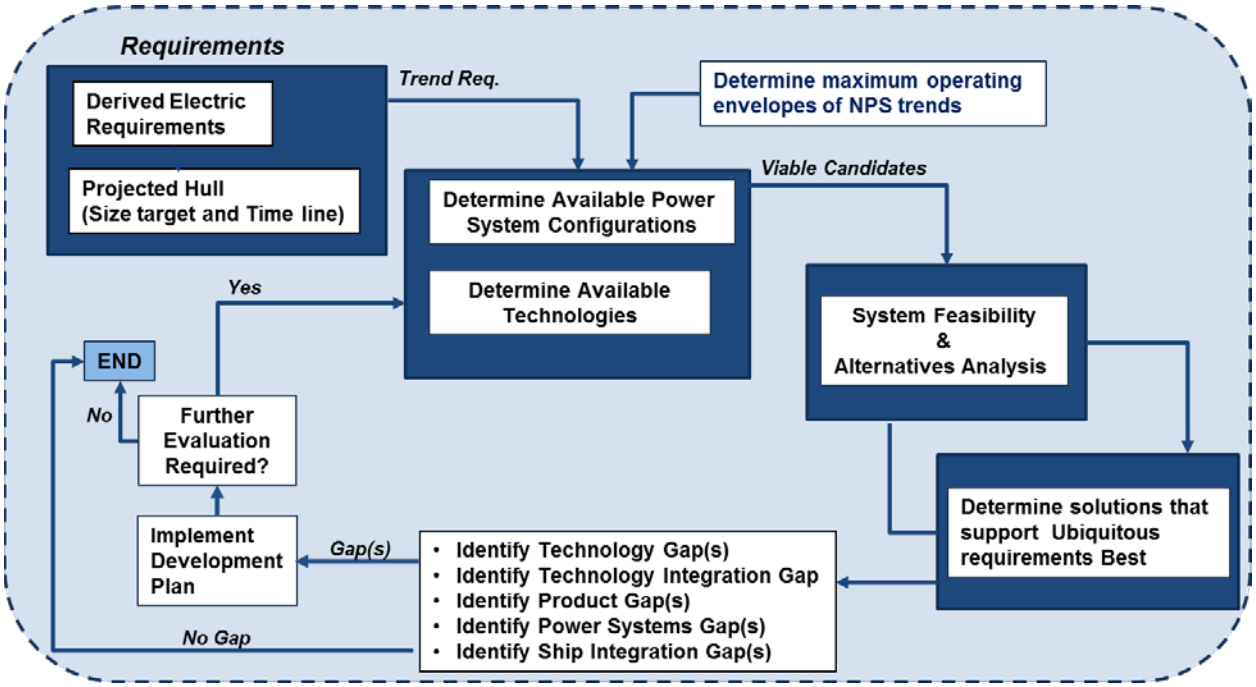

Figure 11: Systems Engineering Analysis Approach

When a gap exists, the Navy must initiate the appropriate S&T, engineering and or systems integration development efforts to meet the requirement. The activities associated with increasing the maturity of technologies, products, and systems at varying levels will differ. Figure 12 provides an overview of the Navy's approach to NPES development. There is a logical progression where individual technologies mature into products which mature further and then are integrated into the NPES to provide the final capability on the ship.

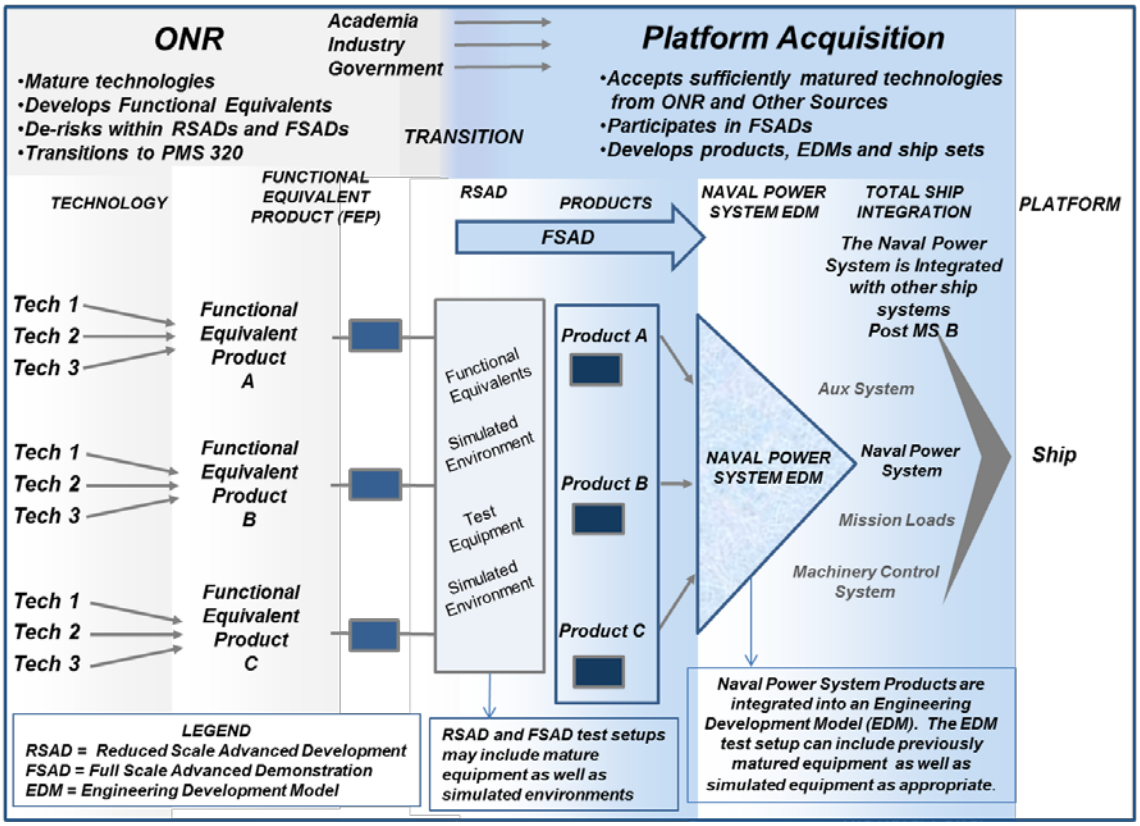

Figure 12: Naval Power and Energy Systems (NPES) Development

5.1.1 Identification of Gaps

The gaps identified by the systems engineering analysis approach can exist at any point in the NPES development process depending on the maturity of the product or system. A brief description of the types of gaps is provided below:

- Technology gap - the fundamental knowledge has not been realized to create a technology capable of meeting an emerging requirement
- Technology integration gap - the enabling technologies have not been integrated into a functional equivalent product
- Product gap - the functional equivalent product has not been further matured into a product suitable for use on a Navy platform
- Electric system integration gap - the products that make up the NPES have not been integrated to operate as an electric power system
- Total ship integration gap - the NPES has not been integrated into the total ship system, including physical integration of components as well as integration into the ship's control system and auxiliary systems

5.1.2 NPES Systems Engineering Stakeholders

The NPES development process involves many organizations including the Office of Naval Research (ONR), other S&T focused agencies, the platform program offices, the appropriate technical authorities, various PEOs as required, resource sponsors, OSD, other government departments/agencies, commercial industry, and academia. A critical consideration that will be

discussed in the subsection that follows is that stakeholders must be aware that NPES development requires a significant amount of time. The NPES must be considered well in advance of the formal DoD ship acquisition process.

ONR is generally responsible for developing new technologies and their integration into a functional equivalent product. A functional equivalent product meets the performance requirements sufficiently enough that TRL 6 will be attained when successfully tested. It may not have the appropriate physical dimensions, packaging or other design features required for shipboard use. The functional equivalent is tested via a Reduced Scale Advanced Development (RSAD) or Full Scale Advanced Development (FSAD). The result of testing the functional equivalent enables the development of initial performance specifications. Utilizing the knowledge attained through the functional equivalent development process (hardware and initial performance specifications), Platform Acquisition organizations develop a product consisting of Navy ready hardware and software that can be procured either by the Navy or prime contractors. This product is tested in a Land Based Test Site. Several products may be integrated into an Engineering Development Model (EDM) of a ship electrical system. Products are developed with the intention that either subcomponents or the entire product may have multiple applications to enable commonality across the fleet as often as is practical.

5.1.3 NPES Development Timelines

Figure 13 shows the NPES development timeline and its relationship to the ship acquisition timeline. Overlaying this NPES development approach onto a new ship acquisition timeline is complex. The development timeline includes a number of simulated environments in order to adequately build, integrate, and test developmental products and systems. These environments are the result of electric system M&S efforts which are critical to determining system requirements and examining potential solutions in the early stages of development and in providing realistic, relevant environments for integration and testing in later phases of development.

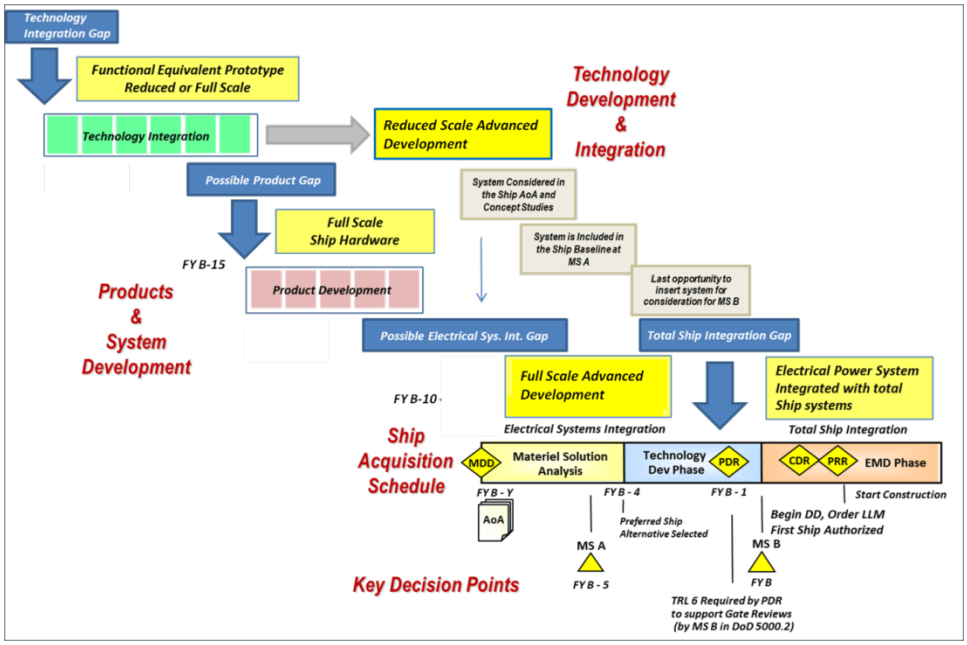

Figure 13: Notional NPES Development Timeline Overlay

The key take away from this overlay is that the candidate electric technology, systems, and overall electric power system options must be considered years before the formal DoD ship acquisition process begins. The Navy selects a preferred alternative ship, usually from the Analysis of Alternatives (AoA) conducted prior to milestone A. This preferred alternative ship is based on a naval power system also selected from a variety of options. In order to be considered as a viable alternative suitable for inclusion in the AoA, any major upgrade or new system must be developed at least to the point where full scale hardware has been demonstrated and integrated and considered low risk prior to milestone B. The total time required for technology development and integration from S&T to milestone B historically has been approximately 15 to 18 years.

Timelines vary for all DoD programs but to provide some perspective, DDG 51, DDG 1000, LPD 17 and CVN 21 took on average, 4.5 years[94] to proceed from milestone A to milestone B. DDG 51 reached milestone B in 2.5 years and DDG 1000 required 8 years to achieve milestone B. Even though milestone A is considered the start of the technology development phase, the pre-milestone A science and technology investigations and technology development efforts can be quite lengthy and may take 3 to 4 times as long as the time between milestone A and milestone B.

5.1.3.1 NPES Forward Fit Timeline

Forward fit refers to the process of introducing a change into an ongoing new ship construction program. The development timeline for a forward fit insertion would be similar to that shown in Figure 13, where the authorization year of the first ship to receive the change corresponding to MS B. Additionally, a parallel timeline would be added for development of the engineering change proposal beginning approximately four years prior to the year of ship authorization.

5.1.3.2 NPES Back Fit Timeline

Back fit refers to the process of introducing change to ships already in service, and follows a different, but similar process, in which the ship change document for fleet modernization is developed in parallel with the ongoing technology development. In fleet modernization, all ship installation drawings must be completed and all long lead-time material must be ordered one year prior to the start of the industrial availability for installation. Therefore, the initial product factory testing and all associated system testing at a Land Based Engineering Site must also be completed at that time. It is also critical that maintenance requirements for new equipment added to in service platforms be developed and updated as part of the modernization effort.

In this chapter, the systems engineering analysis approach used to align requirements with technologies and identify gaps was presented. Timelines, stakeholder roles, and key development considerations that impact NPES were also discussed. A critical takeaway from this chapter is that the total time required for technology development and integration from S&T to milestone B historically has been approximately 15 to 18 years. This must be incorporated in the planning horizon for NPES. Products from the systems engineering analysis discussed in this chapter are discussed in Chapters 6.0, 8.0, and 10.0. Chapters 7.0, 9.0, and 11.0 present specific development recommendations and relevant target metrics.

[94] J. Drezner *et al*., "Are Ships Different? Policies and Procedures for the Acquisition of Ship Programs," RAND Corporation., Santa Monica, CA, 2011.

6.0 Near-term (2016-2025) Requirements Analysis

This chapter builds upon the systems engineering process discussed in the previous chapter by conducting requirements analysis. A critical focus is analysis of the mission systems that will impact NPES in the near-term and understanding what platforms those mission systems will be installed on.

6.1 Addressing Near-Term Mission System Requirements

The following mission systems are expected to impact NPES in the near-term:

- Advanced radars and sensors
- Directed and pulse energy weapons

These mission systems operate at various power levels from hundreds of kilowatts to multiple megawatts and can present a pulse power draw on the power source. In order to meet MIL-STD-1399 sections 300 and 680 electrical interface requirements, the mission load to ship interface may require an intermediate power and energy system consisting of power conversion, advanced controls, and likely energy storage. A variety of technical solutions could satisfy the derived electric system requirements and meet MIL-STD 1399 interface requirements.

In order to determine the best technical approaches for providing appropriate power and energy to the weapon and sensor loads, the load's inherent behavior must be understood. The load's power draw, ramp rate, and constant or variable operating voltage are an abridged list of behavior characteristics necessary to determine a ship integration strategy. Characteristics such as whether the load is continuously pulsing or durations between pulse events can determine whether a load will meet or exceed MIL-STD 1399 interface requirements. It is possible that in the case of advanced pulse loads the electrical characteristics identified in the MIL-STD 1399 are inadequate to properly determine whether or not a load may be incompatible with the existing power system.

Next, a Design Reference Mission/CONOPS for individual and combinations of weapons and sensors (loads), and platforms must be developed. Understanding the CONOPS of these loads, individually, and in combinations is necessary to acquire a complete understanding of the effects of these loads on the ships power system.

6.2 Integrating Mission Systems with Existing Power Systems

Radars use power conversion, capacitive energy storage and power controls to meet MIL-STD 1399 requirements. They are currently the only pulsed loads onboard ships. DEW, electronic warfare and active denial, pulsed loads are anticipated to transition to Navy platforms during the next 10 years. The traditional approach to integrating these loads onto a ship platform is to have each load provide the necessary equipment required to meet MIL-STD 1399. Each load provides a point integration solution per platform. This means that:

- Each load has dedicated power conversion and dedicated capacitive, electro chemical, or kinetic energy storage
- Each load has its own controls philosophy
- Each load has additional equipment to enable survivability and quality of service

Space is a scarce commodity on board Navy ships. Surface combatants are generally smaller than amphibious vessels and aircraft carriers. Having each mission load bring its own support

systems to meet MIL-STD 1399 will tax already limited space constraints. Developing and transitioning multiple unique mission load support systems can also lead to increased acquisition and support cost, overstretching technical resources, increased integration complexity, and the possible need to test and qualify multiple dedicated energy storage systems.

Recent studies have investigated the possibility of creating an intermediate power system that behaves as a buffer, conditioning and controlling load demands, so that MIL-STD 1399 is not violated. Computational models of ships 450VAC, 4160VAC and 1000VDC electric power systems were created. The 13.8KVAC voltage architecture on CVN 78 has not been modeled for this purpose to date. Computational electrical models representing notional versions of advanced weapons and sensors were also created. These power systems and notional load models were exercised to determine whether a multi-function, intermediate power system could be designed and built to act as a buffer, conditioning and controlling load demands, so that MIL-STD 1399 is not violated. Results showed that an intermediate power system could be designed to perform these functions.

The 2013 NPS TDR introduced the concept of an intermediate power and energy system and named it the Energy Magazine (EM). The EM concept can be utilized in back fit and forward fit applications with existing ship power systems. The EM is envisioned to be modular, scalable and made of common building blocks. Traditionally, magazines are the specific spaces which are designated for the stowage of ammunition, explosives and ordnance, and are equipped with detection, protection, and security devices and systems.[95] EM is a term that recognizes the emerging role of capacitive, kinetic, and chemical stored energy in the readiness kill chain where energy may physically take the place of ammunition, explosives, and/or ordnance. An EM may require detection, protection, and security analogous to traditional magazine requirements depending on its design and implementation.

6.3 Next Generation Navy Platforms

The Navy's 30 year shipbuilding includes the transition to future flexible, modular ships. In support of this effort, the Navy has issued a *Flexible Ships Roadmap*[96] that articulates the following major principles:

- Flexible Infrastructure - a physical open system consisting of 6 key elements: open structure, open power, open HVAC, open data cabling, open lighting, and open outfitting to provide affordability, re-configurability, and upgradability
- Module Access Routes/Rapid Removal Routes - Routes designed to enable modular equipment and pre-engineered elements (PrEEs) to be installed later in the production process, and to be easily removed/swapped-out during maintenance or modernization without major ship structural modifications
- Payload Zones / Module Stations - Volume of the ship that provides space, structural support, power and cooling for a major function located therein, includes one or more module stations
- SWaP-C Service Life Allowances - Strategically defining and controlling space, weight, power and cooling (SWaP-C) service life allowance (SLA) is key to achieving a more

[95] Naval Sea Systems Command, NAVSEA OP 4, Seventh revision, "Ammunition and Explosives Safety Afloat" of 15 November 2002.
[96] Naval Sea Systems Command. "Flexible Ships Roadmap," 30 May 2014.

flexible warship over its life. Clearly defined and controlled SLA can allow the flexibility for a ship to grow smartly in zones where technology or threat change is anticipated

- IPS' - use electricity for both propulsion and ship's service power requirements, and are completely integrated on the electrical side
- Energy Storage Modules – Comprised of both energy storage media and any power conversion components for interfacing with the electrical power system/load
- Flexible Ship-wide Data Transport Infrastructure – Refers to shared, permanent data infrastructure that supports the exchange of digital information between systems. The ship networks "ride" on this shared infrastructure.
- Common Computing and Networks (CS, C4I, HM&E) - Implementation and delivery of Open Architecture Computing Environment (OACE) hardware and software in a common configuration that provides computer processing and memory, data storage and extraction, and input/output (I/O) interfaces to support hosting C4ISR and Combat System software applications.
- Common Modular Hull Sections – Common hull, mechanical and electrical equipment design elements can enable a common fleet architecture across ship classes. This ability to achieve this capability transcends requirements for a single ship class and will involve cross platform agreements where commonality is possible.

The *Flexible Ship Roadmap* advocates that: "Flexible warship designs must incorporate defined payload-to-platform interfaces, communicated via an interface control document (ICD). 'Design-to-interface' is a fundamental principle of modular design and should be expected to be part of any serious flexible-modular ship acquisition strategy. Interfaces should be standardized to permit the use of common payloads across multiple ship classes/types. All stakeholders, including industry partners, should be involved in the definition of the interfaces. The evolution of interface definitions should be carefully managed so as to balance the ability for payloads to keep pace with threats or needs against the impacts of changing the interfaces."

As discussed earlier, Navy warships are expected to have service lives of up to 40 years. Studies have shown that the design/implementation cycle for threats and counter threats has shortened over the last 50 years[97]. This finding and the replacement of traditional mission systems with electric power based mission systems may mean that standard design margins and lifecycle growth allowances may no longer be sufficient to maintain naval power and energy system viability. Naval power and energy system designers face the simultaneous challenge of creating a power and energy system to meet increasing load demands, the dynamic nature of the anticipated loads, and the demand profile of the loads required to meet emergent unanticipated threats.

6.4 Integrating Mission Systems with New Power Systems

A LX(R) and a new design future surface combatant are discussed in the 30 year shipbuilding plan with the first future surface combatant targeted to begin construction in 2030. The previous chapter describes the systems engineering approach to aligning requirements and technologies and the 15-18 year timeline required for major technology development and final transition of products to platforms. Development efforts necessary to meet anticipated requirements for the

[97] R. Neches, (2012). *Engineered Resilient Systems (ERS): Insights and Achievements within the ERS Secretary of Defense Science and Technology (S&T) Priority* [Online] Available: http://www.acq.osd.mil/se/briefs/14773-2012_10_24-NDIA-SEC-Neches-ERS%20Insights.pdf

future surface combatant will be required in the near-term. The 30 year shipbuilding plan describes the future surface combatant as "…an affordable follow-on, multi-mission, mid-sized future surface combatant to replace the Flight IIA DDG 51s that will begin reaching their ESLs [expected service lives] in FY 2040. The requirements of this ship are in the early stages of development. These ships will incorporate space, weight, power and cooling margins into their designs and have the flexibility and modularity to host new technologies…"

When designing and implementing the power systems for future platforms, it is necessary to strike a balance between the services provided by the platform and those provided by the mission system. It may be advantageous for naval power and energy systems to provide some of the electric support equipment traditionally supplied by each load for each load. This approach can help minimize duplication of mission support equipment, thereby enabling mission systems to only provide unique mission system features such as pulse forming networks or other dedicated resources not shared by other loads on the ship. This vision/concept/capability could be implemented through developing module station[98] technology and standardized through the introduction of a new interface specification. Developing module station technology allows for the fielding of future capabilities that otherwise may not be accommodated or be cost-effective on a platform.

Leveraging EM lessons learned will assist in the development of this advanced load interface specification. In new power system designs, the buffer function of the EM is expected to be fully integrated into the future ship's advanced power system thereby integrating energy storage into the ships power distribution. This advanced power architecture is anticipated to incorporate multi-use distributed energy storage as well as advanced controls and energy management within an IPS, and result in a fully IPES. A notional IPES philosophy is illustrated in Figure 14 as described in *IEEE 1709 – IEEE Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships.*

[98] A module station is the volume of the ship that provides space, structural support, power and cooling for a major function located therein.

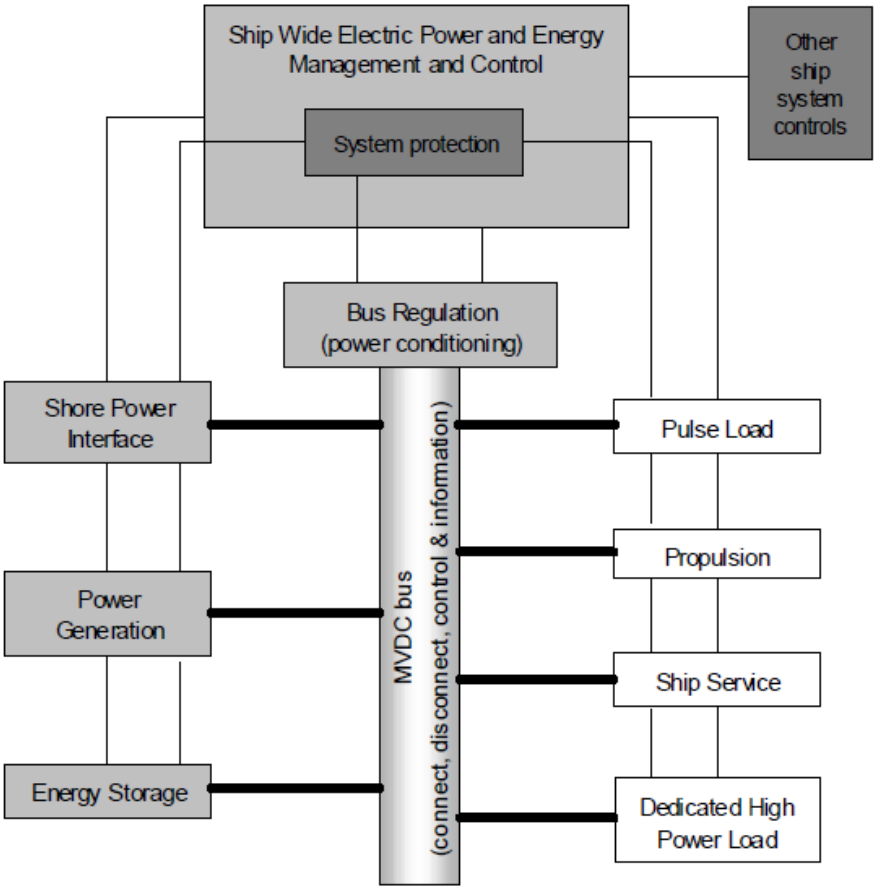

Figure 14: Functional MVDC block diagram

Early concept studies are underway to determine the feasibility of incorporating an IPES type system on a future surface combatant. The Navy has invested in developing IPS solutions for DDG 1000 and other platforms and intends to leverage those developments and lessons learned wherever possible. A Capabilities Based Assessment (CBA) for future surface combatants is expected in the near term to examine ship and major system concept designs at the feasibility level.

The primary challenge of installing an IPES type system on a future surface combatant is expected to be power density in order to meet eventual warfighting requirements, fit within available space, and meet ship speed requirements. Additional studies and developments are required to determine if more advanced power system technologies or advanced architectures such as MVMF or MVDC could provide satisfactory power density. The results of these studies will be used as input to a future AoA. Recommended development efforts to sufficiently mature MVDC systems so that they can be included in AoAs for future ships are outlined in Subsection 7.1.3 and Section 7.2. Depending on the extent of risk reduction necessary to satisfy requirements, advanced prototypes of major components may need to be built and integrated within representative technical power system architecture.

High energy pulse weapon and sensor loads were identified as a naval power and energy

system primary driver. These loads are targeted to be fielded in multiple platforms during the near-term but may not meet the Navy's MIL-STD-1399 electrical interface requirements. For existing power system architectures, the ship to load interface may require an intermediate power and energy system to enable integration. Although each load could provide a unique stove piped intermediate system, it is advantageous to pursue a common modular, scalable intermediate power and energy system or EM. This system should be capable of servicing single and multiple advanced loads as well as supporting load growth over time. For new construction, energy storage should be integrated into the ship's distribution system. This IPES enables the integration of loads directly with the distribution system and minimizes any additional electrical equipment.

7.0 Near-term (2016-2025) Development Recommendations

Chapter 6.0 described the requirements to support multiple high energy mission systems on a variety of existing and new ship platforms. It also provided background and status of the potential common, modular scalable intermediate power system for forward fit and back fit applications known as EM. The concept of an IPES for future ship platforms is also described as well as the potential for leveraging EM investments into IPES. This section makes specific development recommendations related to those requirements.

7.1 Research & Development

Figure 15 shows notional EM configurations providing power to single and multiple high energy mission systems while protecting the ship's power system from damaging electrical pulses.

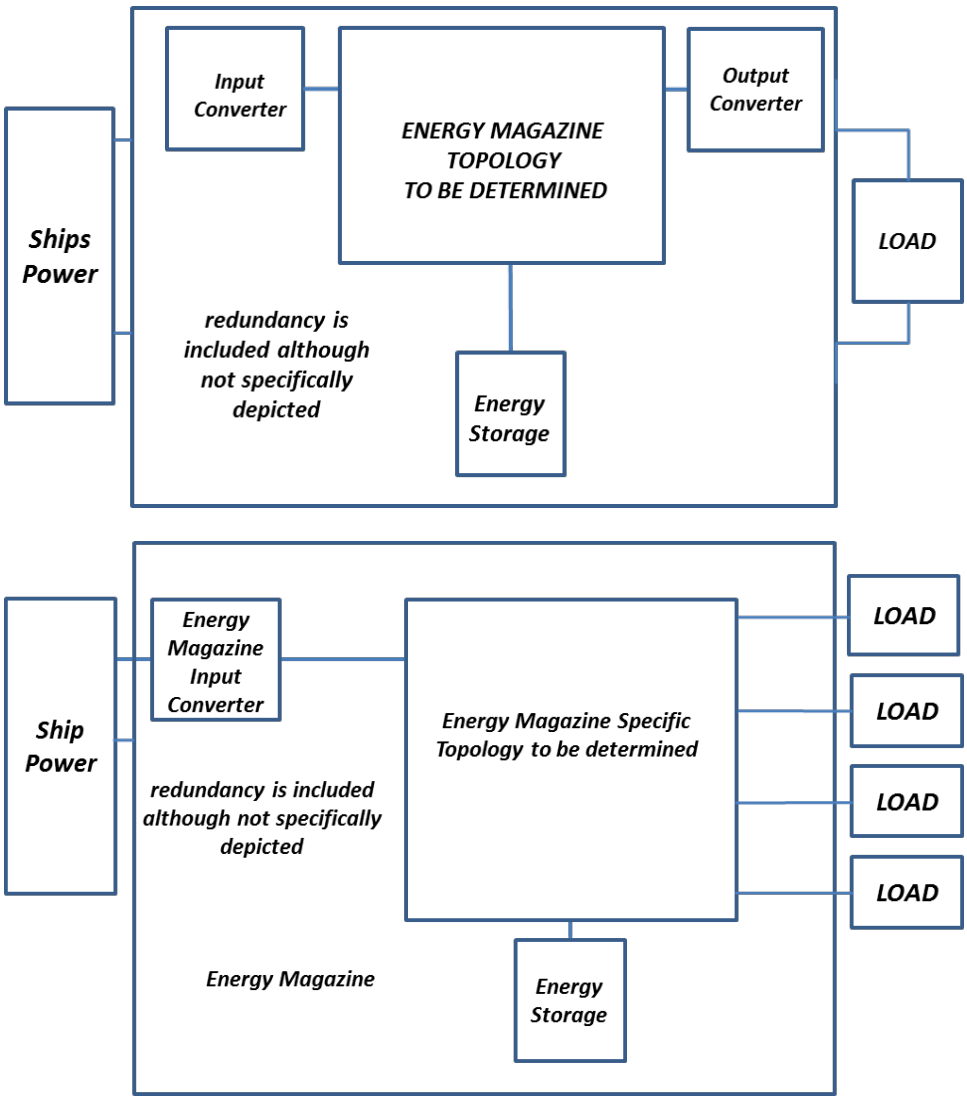

Figure 15: Notional Energy Magazine Configurations

The notional configurations in Figure 15 represent a common intermediate power system with

the final functionality still to be determined. The trade space should include directly powering the load via conversion with no energy storage, using energy storage to augment power directly supplied from the ship, and powering the load solely via the energy storage. This approach will be initially designed to integrate a low power pulse load on a legacy platform with a 450VAC ship's power interface with the capability to be isolated from the main ship service bus. Future applications are envisioned for integration into MVDC and MVAC architectures to power a variety of loads.

The system should combine advances in energy storage media, power conversion, distribution and associated protection schemes. Energy capacity, power, and unique load demands, such as ramp rate and pulse repetition rate will drive performance requirements. Early definition of load interfaces will enable parallel development of the intermediate power system and advanced weapons and sensors. The input converter that provides the interface with the ship service bus may be bidirectional so that the energy storage can support overall power management, load leveling and/or emergency power.

The EM will use a modular approach, with notional required functionality as shown in Figure 16 below.

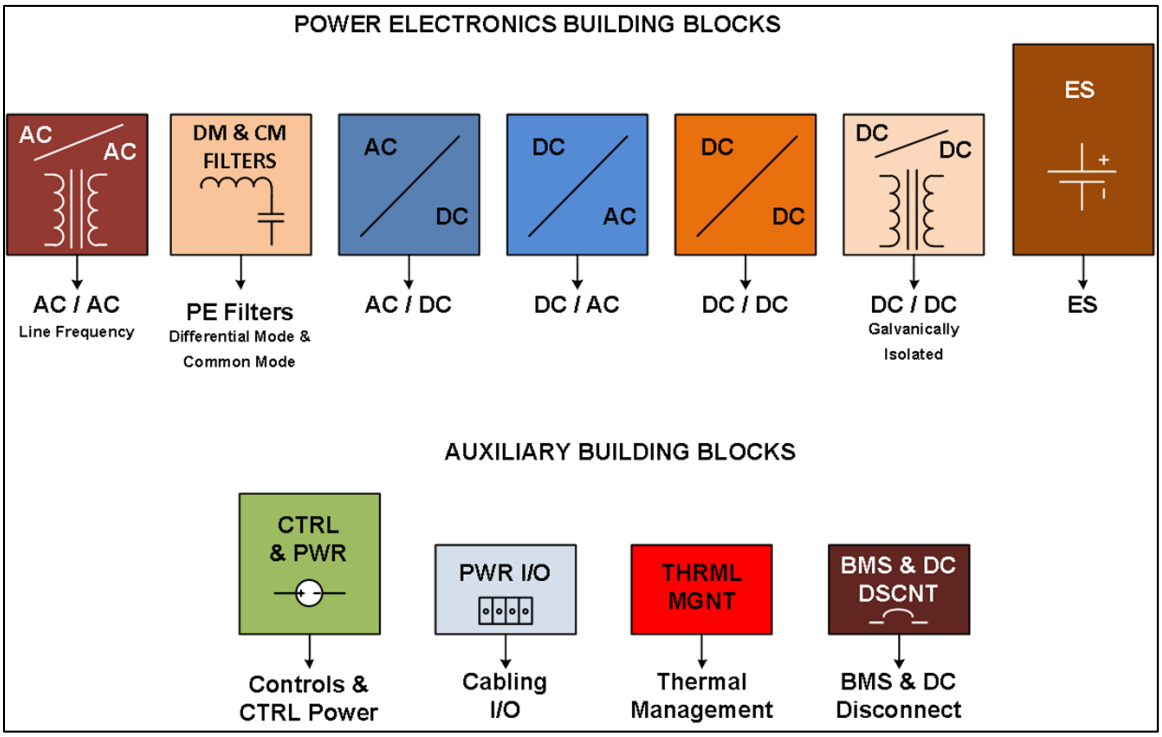

Figure 16: Energy Magazine Module Functionality

As new mission systems become available for ship integration, functionality can be expanded to accommodate multiple loads by providing the appropriate power conversion and energy storage. This multifunction approach may be a distributed system which introduces survivability and design complexity. Advanced controls will be required and different mission systems may require different interfaces, placing different demands on the common intermediate power system. A standard set of interface definitions for future weapons and sensors will enable an open architecture approach for multifunctional capability.

7.1.1 Energy Magazine for Forward Fit and Back Fit Applications

In the case where EM is installed onto an existing distribution system, either during new construction within an existing power system design or back fit into ship already in service, it will be an extension of the ship's electrical power system performing the function of a flexible load interface. Bi-directionality can enable the system to provide stable back-up power while supporting mission system requirements. The ability to feed multiple loads will enable meeting ubiquitous requirements such as commonality, flexibility, maintainability and energy security.

The following additional requirements should be considered throughout the development of EM:

- System compatibility with distribution voltages on multiple platforms
- System stability while providing quality power to the load
- Bidirectional power conversion that is power dense and galvanically isolated
- Energy storage that is power dense, safe, capable of meeting rapid, flexible charge and discharge profiles

7.1.2 Energy Magazine Functionality in New Ship Design

In new ship design and construction, the EM function will be fully integrated into the ship's electric power system rather than as an intermediate system between the ship's power system and the mission systems. The intent is to optimize the ship electric power system as a whole vice sub optimizing conversion for each mission system. This will enable minimizing the overall size and maximizing the energy and power density as well as performance of the IPES.

Earlier in chapter 5.0, it was shown that beginning system development as early as possible in the development cycle is advantageous. Reduced scale testing using M&S, control hardware in the loop (CHIL), power hardware in the loop (PHIL) and functionally equivalent components allows the Navy to begin to understand complex system behaviors and make advances at affordable investment levels. These demonstrations in the near-term enable meeting near-term platform requirements as well as technology development timelines for candidate mid-term ships such as future surface combatants.

7.1.3 Energy Magazine Recommendations

- Demonstrate a MVDC power distribution system in the 2017- 2018 timeframe using M&S, CHIL, PHIL, and functionally equivalent components. The demonstrations should initially focus on a modular, scalable EM and further evolve a notional MVDC ship electrical power system as an IPES candidate for the mid-term ship classes. The demonstrations should confirm the technical feasibility of a common intermediate power system for multiple platform and mission system applications and de-risk the following:
    - Shared energy storage
    - MVDC fault detection, isolation and reconfiguration
    - System level functionality to service multiple high power mission systems on multiple platforms
    - System control requirements, especially related to the approach for advanced controls to regulate the MVDC bus voltage, power sharing and system stability
- Demonstrate at full scale a modular, scalable EM to be incorporated into existing platform designs and satisfying the needs of multiple mission systems ready for ship installations beginning in 2021.

7.2 Integrated power and energy system recommendations

In order to continue to develop a common, modular scalable intermediate power system and a fully integrated power and energy system for mid-term ships, the following specific efforts are recommended in the near-term. Many of the recommendations below focus on MVDC architectures since it is believed to have the highest potential to reduce overall power density and also the highest amount of system risk to be reduced. However, it is expected that other alternatives such as MVAC and MVMF will also be included in future ship studies.

- Develop advanced MVDC circuit protection (devices, controls, etc.) with faster response times to be available in 2019. This activity is covered under the FY2014 ONR Future Naval Capability (FNC) entitled "Efficient and Power Dense Architecture and Components" and will reduce the size of MVDC equipment to sizes appropriate for shipboard applications as well as develop circuit protection capable of operating above approximately 1kV (Phase I) and 10kV (Phase II).
- Develop advanced energy storage options available in 2020. This activity is covered under the FY2015 ONR Multi-Function Energy Storage Module (MF-ESM) FNC. Advanced energy storage will enable safe operation of energy storage systems, enable affordable high power and energy dense storage, enable multi-function system development and support sharing energy storage capacity among different applications, and support back fit on existing platforms and operate with future systems on new platforms.
- Develop a combat power and energy management system approach by 2020 to:
    - Provide total ship power and energy management and enable the servicing of multiple dynamic high power loads, including pulsed loads, from multiple and shared energy generation and storage devices
    - Manage associated cooling and auxiliary system demands
    - Interface with the ships combat system, and by maintaining a hierarchy of tactical power conditions to anticipate, allocate and pre-position power and energy
    - Select configurations in context of mission and energy efficiency through the application of advanced autonomy concepts, optimizing resource allocation
    - Meet existing and projected cybersecurity requirements
- Develop design tools that assist in the optimization and evaluation of NPES that:
    - Incorporate NPES attributes in combat system mission effectiveness analysis
    - Supports interface optimization
    - Correlates total ship power and energy demand with mission effectiveness metrics
- Investigate the volume and area available on a future surface combatant for ship's power system including generation, distribution, and propulsion
- Perform the following studies for an architecture incorporating MVDC:
    - Assess the changes required to NSTM 300 to incorporate an MVDC system.
    - Assess the changes required to NSTM 300 in order to incorporate energy storage into the distribution system.
    - Determine shore power options for an MVDC system.
- Investigate the best options for providing casualty power
- Develop a Ship Continuity and Quality of Power Model that has the capability to perform dynamic end to end analysis from the shipboard voltage interface up to and including the loads. The model must include all interconnected power conversion and energy storage components between the shipboard voltage interface and the loads.

- Evaluate propulsion options including but not limited to forward propulsors, pods, and contra-rotating systems.
- Develop and demonstrate an IPES for future surface combatants beginning in 2020 and completing in 2025. The goals of this effort are to:
    - Conduct the necessary investigation into the loads, physical integration and power requirements to inform the development of the power and propulsion system architecture within the projected range of hull forms and ship sizes. This should include tradeoff analyses of distribution voltages and frequencies.
    - Reduce risk to the extent necessary to be considered in the ship analysis of alternatives and satisfy the DOD 5000 acquisition requirement to achieve TRL 6 by milestone B. TRL 6 for power systems is considered a full scale demonstration at a land based test site.
    - Develop any advanced technologies determined to be required to provide a satisfactory solution following the analysis of alternatives in order to satisfy capability and power density requirements
    - Demonstrate in an integrated approach the efforts listed below and described in detail in the preceding paragraphs:
        - A notional MVDC ship electrical architecture incorporating EM functionality to provide power to all of the loads
        - MVDC circuit protection
        - Total ship power and energy management via a combat power and energy management system
        - Advanced energy storage options

At this time key operational, performance, power density, and other requirements affecting the IPES have not yet been determined. Additional information is expected upon the completion of the CBA and AoA; however demonstration should be performed at the appropriate scale to sufficiently derisk system design and integration.

7.2.1 Gas Turbine Recommendations

Section 3.5 discusses the potential need for a 9-14 MW gas turbine generator set in order to fill a power level gap and to provide maximum flexibility for future naval power and energy system options. The Navy should perform a study to determine the demand signal for the engines and the technical benefits. Additionally, based on the potential benefits of a twin spool gas turbines discussed in Section 3.5, the following gas turbine investments are recommended:

- Twin spool gas turbine development efforts
    - Refurbish and test an existing LM500 GTGs to clarify transient response capability. It is critical to understand the transient response capability of a prime mover as part of design and upgrading NPES.
    - Design, fabricate, and qualify a twin spool GTG in the 4 MW range for future platform and back fit application ready for ship installation by FY2023.

The Navy has initiated an effort to develop advanced coatings for gas turbine components that can inhibit damage to a gas turbine caused by running the turbine at extended periods of time at close to its rated power. As such, the TDR recommends the following:

- Continue advanced materials to inhibit Type 1 corrosion in gas turbines
    - Continue development and demonstration of advanced materials and an engine rotor that inhibits the damage caused by the hot corrosion common in engines operated at higher rated power. This can reduce the number of turbines running

at any given time leading to reduced overall fuel consumption, completed by FY18.
    - Perform production engineering, acquire test assets and conduct testing to transition advanced materials and coatings for 3 to 6 MW and 20-40 MW engines to support development of upgrade kits.
    - Integrate the material and coating upgrade kits into 3-6 MW engines starting in FY20 and upgrade kits into the 20-40 MW engines starting in FY21.

7.2.2 Continuation of Ongoing NPES Efforts

A number of naval power and energy system hardware development efforts in the near-term are ongoing. It is recommended that the following efforts continue or be expanded as described below:

- Continue AMDR Power Conversion Module (PCM) development effort
- Continue DDG 51 Hybrid Electric Drive (HED) electric propulsion for backfit fuel efficiency
    - HED uses electric power from the ship's generators to provide propulsion up to approximately 11kts without the need for operating LM2500 main engines on DDG 51 Class ships.
- Continue Advanced Power Generation Module (APGM) forward fit development effort
    - The APGM effort will deliver a new, high power gas turbine generator in FY18 to upgrade the current GTG on ships.
- Complete the development and qualification of medium voltage (4160V) VCB switchboards that fit within the existing Air Circuit Breaker (ACB) switchboard envelopes by 2015 and expand development efforts to higher voltages

7.3 Science & Technology and Other Recommendations

Technology advances with potential naval applicability were identified earlier in Chapter 3.0. These advances could be used to meet ubiquitous requirements and mitigate ship integration challenges. Innovations with immediate expected benefit to the Navy require near term focus. These focus areas will help mature and advance NPES technologies by leveraging industry advances towards products suitable for Navy use, tailoring and demonstrating system solutions unique to the Navy's needs and fostering innovation and research in development in areas that might not be pursued by industry alone. The Navy should:

- Develop techniques to better understand power system and component failure mechanisms in order to more accurately predict power systems reliability. System reliability is a key factor in NPES design.
- Address ship platform thermal management issues resulting from increased use of high power weapons, sensors, and other systems including:
    - Build and demonstrate an intermediate temperature cooling water system
    - Build and demonstrate a direct refrigerant cooling system. This system may utilize phase change heat transfer
    - Build and demonstrate an advanced thermal management system
- Build and demonstrate a modern technology HVAC family of components and optimizing energy efficiencies through the bundling of advanced component technologies. Also, complete new catalog of advanced HVAC system components that include fans, cooling coils and ductwork.
- Develop a scalable, readily adaptable heat exchanger prototype for energy recovery. The system should be suitable for the high thermal transient operation of naval prime

movers and be available by 2020. Previous Navy experience in energy recovery systems has demonstrated that the scalability of the heat exchanger was a primary impediment to implementation. Generally, commercial heat exchangers in the size ranges required for NPES are not currently in use in naval environments.

7.3.1 Discovery and Invention Recommendations

High risk, high reward technologies pursued in the near term may influence mid and far-term term ships. Discovery and Invention (D&I) investments are focused on basic research. Discovery and Invention investments in the following areas have been identified as beneficial to continued advancements in NPES.

- Develop an impedance based tool to predict, evaluate and verify the stability of three-phase AC systems at Navy operating power and voltage levels. This tool should:
    - Enable testing of whole power systems and individual components quickly and effectively. Note: the current method of impedance measurement in AC systems is very time consuming.
    - Address the wide range of operating points of individual components as well as the overall system.
    - Incorporate knowledge into end user stability requirements, specifications and standards.
- Advanced conductors:
    - Reduce the size, weight and cost of conductors used in electrical equipment on future ships.
    - Improve the efficiency of the NPES and components
    - Make further advancements towards room temperature superconductivity by applying advances in material science such as HTS, carbon nanotubes and covetics.
- Advanced solid state energy recovery:
    - Enable thermal-to-electric energy recovery which is quiet, reliable, and has no moving parts
    - Allow simplified energy recovery from prime movers through a reduction in required auxiliary system complexity. With additional development, future heat exchangers could either contain thermo-to-electric material or be constructed entirely out of thermal-to-electric material.
- Continue advanced energy storage investigations including but not limited to superconducting magnetic energy storage and cryogenic capacitors.

Many of these technologies are heavily material dependent with the current focus on obtaining desirable material properties and acceptable costs. Figure 17 displays an integrated technology development and acquisition schedule for the near-term:

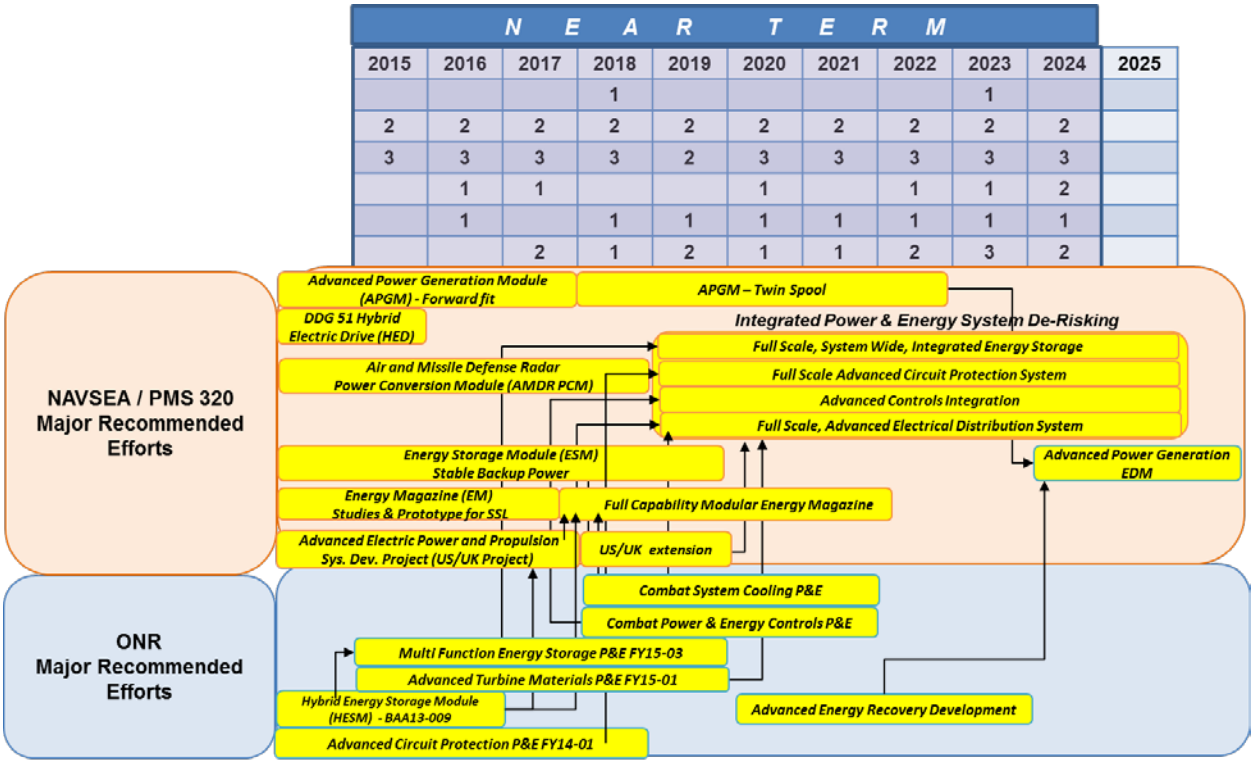

Figure 17: Integrated Technology Development and Acquisition Schedule (2016-2025)

Table 7 below contains the list of product areas and their near-term target metrics. The metrics listed in the TDR are not necessarily focused on individual products but based on the hardest to obtain category and designed to establish targets for industry. Near-term investments should focus on meeting or exceeding the performance identified in the table below.

Recommendations in the near-term are dominated by efforts necessary to mature NPES technologies, and subsystems. The Integrated Technology Development and Acquisition Schedule shown in Figure 17, illustrates the major efforts and their timing. Any deviation from the development efforts and timelines prescribed may increase the risk of fielding mature technologies in time to meet near and mid-term platform need dates.

Table 7: Near-term Functional Area Metrics

Technology Product Area		Benchmark	Development Targets
Electric Rotating Machines: Motors		*Hybrid Electric Drive Motor*	
	Nominal Power Level	3.73 MW	2-4 MW
	Power Density:	250 kW/m^3	380 kW/m^3
	Packaging$^{\alpha}$	Hardened (Grade B Shock)	Military Hardened
		Main Propulsion Motor	
	Nominal Power Level	32-34 MW	20-26 MW
	Gravimetric Torque Density	12.8 N*m/kg	30–50 N*m/kg
	Volumetric Power Density	200 kW/m^3	681–889 kW/m^3
	Gravimetric Power Density	0.20 kW/kg	0.5 - 0.7 kW/kg
	Speed	150-170 rpm	150-170 rpm
	Packaging	Military Hardened	Military Hardened
Prime Movers w/Generators		*Prime Movers for Auxiliary Power or Ship Service*	
	Nominal Mechanical Power	4 MW	4 – 10 MW
	Specific Fuel Consumption at 100%	0.29 kg/kW-hr	0.23 kg/kW-hr
	Volumetric Power Density$^{\beta}$	0.030 MW/m^3	0.04 – 0.05 MW/m^3
	Gravimetric Power Density$^{\gamma}$	0.076 kW/kg	0.105 kW/kg
		Prime Mover/Generator (High Power)	
	Nominal Power Level	21-36 MW	24-30 MW
	Volumetric Power Density	0.25 – 0.40 MW/m^3	0.35 – 0.50 MW/m^3
	Gravimetric Power Density	0.25-0.40 kW/kg	0.35 – 0.50 kW/kg
	Machinery Space Stack up length for prime mover and generator	<39 feet	<39 feet

$^{\alpha}$ Packaging: Military Hardened refers to meeting Navy environmental requirements (e.g., Mil-Std-901 Grade A, Mil-Std-167, Mil-Std-810)
β Volumetric Power Density includes prime mover, generator, enclosure, and base w/ shock mounts
γ Gravimetric Power Density includes prime mover, generator, enclosure, and base w/ shock mounts

	Critical Metrics	Benchmarks	Development Targets
Energy Storage		*Benchmark 1*	
	Nominal Power Level:	625kW	Scalable to 12-13MW
	Nominal Energy Storage:	31.2 kW-hr / 112 MJ (~40A-hr)	1-1.1 MW-hr / 3600-4000 MJ
	Package:	Hardened (Grade B Shock)	Military Hardened
	Lifetime:	240 Cycles 80%DoD / 10yr Application Life	2000 Cycles 80%DoD / 10yr Application Life
	Large System Safety	Yes	Meets Naval Safety Standards
	Discharge rate:	20C / (~800A)	30-33C / (~30kA)
	Charge Rate:	1/3 C / (<15A)	4-4.5C / (~5kA)
	Package Power Density:	177 kW/m3	750-850 kW/m3
	Package Energy Density:	21.3 MJ/m3	225-250MJ/m3
		Benchmark 2	
	Nominal Power Level:	60 MW	Scalable to 12-13MW
	Nominal Energy Storage:	60 MJ	360 MJ
	Package:	Military Hardened	Military Hardened
	Lifetime:	50yr Ship Life	40yr Ship Life
	Large System Safety	Meets Naval Safety Standards	Meets Naval Safety Standards
	Discharge rate:	60 MJ in 1 sec / (~10kA)	180 MJ in 1 sec / (~30kA)
	Charge Rate:	60 MJ in 60 sec / (~1kA)	360 MJ in 60 sec / (~6kA)
	Package Power Density:	2,680 kW/m3	2,680 kW/m3
	Package Energy Density:	2.74 MJ/m3	30.0 MJ/m3
Conversion	*Low Power Converter*		
	Nominal Power Level	3 MW	800 kW - 4 MW
	Package:	Military Hardened	Military Hardened
	Cabinet Power Density	0.25 MW/m^3	0.33 - $1MW/m^3$
	Efficiency	96%	98%
	Interface-1 voltages	4.16kVAC, 450VAC	13.8kV, 4.16kV, 450VAC, 12kVDC, 6kVDC, 1kVDC
	Interface-2 voltages	1kVDC	300-1kVDC
	Functionality	Unidirectional Galvanically Isolated	Bi-directional Galvanically isolated
	High Power Converter		
	Nominal Power Level	34 MW	scalable to

	Critical Metrics	Benchmarks	Development Targets	
			6-10 MW	
	Package:	Military Hardened	Military Hardened	
	Cabinet Power Density	0.45 MW/m^3	0.33 – 1MW/m^3	
	Efficiency	96%	98%	
	Interface-1 voltages	4.16kVAC	6, 12, 18kVDC, 4.16kVAC, 13.8kVAC	
	Interface-2 voltages	--	6, 12kVDC	
	Functionality	MV Motor Drive	Bi-directional Galvanically Isolated	
	with Transformer:			
	Nominal Power Range	3 MVA	3-5 MVA	
	Volumetric Power Density	300 kW/m^3	600 kW/m^3	
	Gravimetric Power Density	0.3 kW/kg	0.6 kW/kg	
Distribution	*with Vacuum Circuit Breaker:*			
	Switchboard Level Power Density	8 MVA/m^3	8 MVA/m^3	
	Improved Safety		Dead-front, grounding means, continuous thermal monitoring, arc-fault protection	
	Breaker/System:	*Existing Navy Shipboard Circuit Protection Equipment*	Circuit Protection FNC Protection Device 1	
			Threshold	Obj.
	Voltage	MVAC	1kVDC ungrounded	
	Current	4000A	1000A	4000A
	Response Time	128 ms	8 ms	< 1 ms
	Volumetric Power Density	40 MW/m^3	10 MW/m^3	25 MW/m^3
	Lifetime	30,000 cycles	10,000 cycles	30,000 cycles
	Air-gap Provision		Provided	
	Efficiency	99.80%	99.50%	99.80%
	Interfaceable with	Generators, Converters and Batteries	Generator, Converter, Battery, Capacitor	

	Critical Metrics	Benchmarks	Development Targets
	Protection Capability		Bidirectional
	False trips	5%	3-5%
Cables		Legacy Navy MV & LV cabling	Multiple Navy Qualified 15kV Class Unshielded and Shielded Cables for AC and DC Applications
Controls	Ability to handle multiple types of energy storage	Remote Switchboard Control Machinery Status and Monitoring Conditioned Based Maintenance Capable	Advanced power management capability
	Ability to pass power bi-directionality and to enable multiple loads fed from same energy storage system		
	Ability to energy/power manage in DEPS to control pulse loading seen on electric system.		

8.0 Mid-term (2026-2035) Requirements Analysis

8.1 Background

Aligning technologies to requirements in the mid and far-term periods involves additional uncertainty for both mission systems and ship platforms. It is expected that the power and energy demands of these systems will grow as they are upgraded and as new and successor systems reach maturity and are introduced into the fleet. It is also expected that kinetic energy weapons will need to be integrated onto platforms in the mid-term period.

The Navy's 30 year shipbuilding plan calls for building new design future surface combatants near the midpoint of the mid-term planning period to replace the first of the DDG 51 Flight IIA ships. These ships are expected to have up to a 40 year service life and plan to incorporate space, weight, power and cooling margins into their designs as well as the flexibility and modularity to host new technologies.

The 30 year ship building plan is an evolutionary document due to ever changing threats and economic realities. In order maintain relevance, the NPES TDR approach is to posit future systems, project future power needs based on these systems, and then propose solutions that may require development. This section documents the posit/project/propose approach and results for the mid-term requirements. The intent is to remain flexible enough to enable any or all predicted mission and ship systems derived electric requirements and allow compatibility with future shipbuilding needs as they develop.

8.2 Mid-term Platform Requirements Analysis

Initial explorations have been conducted to investigate candidate power systems to support future surface combatants in the 30 year shipbuilding plan. Projected upcoming sensor and weapons systems will be combined into new mission suites in the mid-term. These suites may include enhanced radars, more capable electronic warfare systems, lasers (already projected for fielding in the near-term), future directed energy weapons, and railguns. Predicted derived electric requirements for the mission suites include:

- Higher power demands
- Larger power pulses
- Multiple power interface requirements
- Higher thermal loads

Additionally, future surface combatants were evaluated in each of the following categories of power system architectures:

- A 4160VAC 60 Hz MVAC power generation and distribution system
- A 13.8kVAC 60 Hz MVAC system
- A 4160V or 13.8kV Medium Voltage Medium Frequency (MVMF) system.
- A 6000V MVDC system

The projected electric requirements of advanced mission loads were evaluated against power and energy system options. Initial power system candidates were analyzed using notional indicative ship designs. All architectures assumed an integrated or hybrid power system. This was primarily because a mechanical drive ship is well understood. The power distribution systems evaluated included both a traditional IPS and one with integrated energy storage.

The mid-term development recommendations in Chapter 9.0 focus heavily on integrating energy storage within a power system. This power and energy system will need the following characteristics:

- High power AND high energy performance
- Intelligent management and prioritization of multiple mission loads
- Common or selectable mission system interface(s)

Other general mid-term requirements include the ability to meet new and emerging capability requirements, upgrade legacy systems, provide extended service life, and improve performance associated with ubiquitous requirements. Meeting these requirements involves continued investment in D&I and advancing the state of the art across all technical areas associated with NPES. Medium voltage advances, both for AC and DC. These areas are of particular interest as total ship electric power demand increases with time. Lastly, any near-term developments that have been successfully demonstrated should be pursued if still applicable. Prioritization should be given to those breakthroughs that could lead to mid-term revolutionary changes in power and energy system capabilities.

Based on the 30 year ship building plan, multiple new platforms are scheduled for construction between 2026 and 2035. It is anticipated that some of these new platforms will field advanced weapons and sensors, and have expected service lives of up to 40 years. The power and energy systems on board these new platforms must be able to meet anticipated power and energy demands as well as unanticipated demands that may emerge to meet future threats throughout the ship's lifecycle.

An IPES was determined to be the power system most capable of meeting these criteria. The system integrates all of the ship's power generation capacity so that it can be available for ship service and propulsion as required. Fully integrating energy storage into IPES means the system remains stable when powering advanced weapons and sensors. Additionally, efforts to advance direct thermal-to-electric technologies and related advancements in heat exchangers during the near-term may lead to the implementation of solid state energy recovery systems on board Navy ships between 2026 and 2035.

9.0 Mid-term (2026-2035) Development Recommendations

Mid-term development recommendations are dominated by the engineering development of the power system for the future surface combatant and other new platforms. During this period, full integration of the energy storage into the power distribution system is expected to continue as power and energy demands of mission systems continue to grow and the electromagnetic railgun is brought into wider service.

The full scale demonstration of an IPES for future surface combatants recommended in the 2020-2025 period de-risks critical technologies and reduces the integration risk in key performance areas of integrated energy, advanced circuit protection, and advanced combat power controls for a generic IPES system. The Navy's 30 year shipbuilding plan currently calls for both a large and a small surface combatant to begin procurement in the mid-term period. During this period the engineering development, system integration and total ship integration efforts consisting of designing, building and testing and integrating actual power and energy system ship hardware will be completed.

9.1 Mid-term Development and Integration Efforts

The following development, integration and engineering efforts are recommended in the mid-term:

- Build & test future surface combatant engineering development models (EDMs) and first article production components for all critical technologies determined to be required to meet capability and power density requirements.
- Develop, complete and validate the detailed, real time NPES system electric and control system M&S capabilities including power mission systems and hardware in the loop options for critical capabilities for future surface combatants. This effort should have started as part of the de-risking efforts in the near-term.
- Conduct NPES system testing for all future surface combatant variants at a land based test site to verify electric integration of the power and energy system at appropriate scale and scope, NPES modularity, and integration of the power system control and combat and mission systems.

9.2 Mid-term Research and Development, Science and Technology Efforts

The following efforts are recommended in the mid-term to mature and transition near-term science and technology investments:

- Demonstrate at full scale and qualify for Navy use advanced conductors developed in the near-term to reduce the size, weight, and cost of cabling in future ships. These technologies could include high or room temperature superconductivity, carbon nanotubes, and covetics.
- Demonstrate a full scale, solid state shipboard energy recovery system. This system should be based on the investments in solid state energy recovery made in the near-term. Initiation of this effort will depend on the maturity level of the underlying technology. Demonstrate at full scale any technology advancement whether developed through Navy investment or independently pursued by industry that supports the Navy's approach to product area utilization as discussed in Chapter 3.0. This recommendation is targeted towards those breakthroughs and developments currently unforeseen.

Table 8 below contains the list of product areas and the target metrics necessary to meet the

Navy's NPES requirements in the mid-term.

Table 8: Mid-term Product Area Metrics

	Critical Metrics	Benchmarks	Development Targets
Electric Rotating Machines	*Main Propulsion Motors*		
	Nominal Power Level	20-26 MW	21-36 MW
	Gravimetric Torque Density	30–50 N*m/kg	30–50 N*m/kg
	Volumetric Power Density	681–889 kW/m^3	681-889 kW/m^3
	Gravimetric Power Density	0.5 - 0.7 kW/kg	.5 -.7 kW/kg
	Speed	150-170 rpm	120-170 rpm
	Packaging	Military Hardened (Grade A Shock)	Military Hardened (Grade A Shock)
	Generator		
	Nominal Power Level	4-10 MW 21-36 MW	4-10 MW 21-40 MW
	Volumetric Power Density	0.7 – 1 MW/m^3	1.5 - 2 MW/m^3
	Gravimetric Power Density	0.24 – 0.65 kW/kg	1.5 - 2 kW/kg
	Machinery Space Stack up length for prime mover and generator	<39 feet	<39 feet
	Prime Movers		
	Nominal Mechanical Power	21-40 MW	25-40 MW
	Volumetric Power Density	0.50 MW/m^3	0.60 – 0.75 MW/m^3
	Gravimetric Power Density	0.50 kW/kg	0.60 – 0.75 kW/kg
	Efficiency	36% @ 100 percent load (LM2500) 28.6% @ 100 percent load (MT5)	5-20% efficiency increase from LM2500 or MT5

	Critical Metrics	Benchmarks	Development Targets
Energy Storage	Nominal Power Level	Scalable to 12-13MW	Scalable to 25 to 30 MW
	Nominal Energy Storage	1-1.1 MW-hr / 3600-4000 MJ	1.5-1.7 MW-hr / 5400-6120 MJ
	Package	Military Hardened	Military Hardened
	Lifetime	10yr Application Life	20-25yr Application Life
	Large System Safety	Meets Naval Safety Standards	Meets Naval Safety Standards
	Discharge rate	30-33C / (~30kA)	30-33C / (~30kA)
	Charge Rate	4-4.5C / (~5kA)	4-4.5C / (~5kA)
	Package Power Density	750-2700 kW/m3	750-2700 kW/m3
	Package Energy Density	30-250MJ/m3	250-540MJ/m3
Conversion	*High Power Converter*		
	Nominal Power Level	6-10 MW	2-10 MW
	Packaging	Military Hardened	Military Hardened
	Cabinet Power Density	0.33 – 1MW/m^3	1.25-2 MW/m^3
	Efficiency	98%	97-99%
	Interface-1 voltages	6, 12, 18kVDC, 450VAC 4.16kVAC, 13.8kVAC	6, 12, 18kVDC, 450VAC 4.16kVAC, 13.8kVAC
	Interface-2 voltages	300 – 1KVDC, 6, 12kVDC	300 – 1KVDC, 6, 12kVDC
	Functionality	Bi-directional Galvanically Isolated	Bi-directional Galvanically Isolated
	Low Power Converter		
	Nominal Power Level	21-40 MW	21-36 MW
	Packaging	Military Hardened	Military Hardened
	Cabinet Power Density	0.35 – 0.78 MW/m^3	1.25 - 2 MW/m3
	Efficiency	96 – 98%	98-99%
	Interface-1 voltages	6, 12, 18kVDC, 4.16kVAC, 13.8kVAC	6, 12, 18kVDC, 4.16kVAC, 13.8kVAC
	Interface-2 voltages	6, 12kVDC	6, 12, 18kVDC
	Functionality	MV Low Harmonic Drive	MV Low Harmonic Drive

	Critical Metrics	Benchmarks	Development Targets	
	with Transformer:			
	Nominal Power Range	3 MVA	3-5 MVA	
	Volumetric Power Density	300 kW/m^3	900 kW/m^3	
	Gravimetric Power Density	0.3 kW/kg	3.0 kW/kg	
Distribution	*Breaker/System:*	Existing Navy Shipboard Circuit Protection Equipment	Circuit Protection FNC Protection Device 1	
			Threshold	Objective
	Voltage	AC	up to 13.8 kV AC, up to 20 kV DC	
	Current	4000A	50A	4000A
	Response Time	128 ms	0.5 ms	1 ms
	Volumetric Power Density	40 MW/m^3	40 MW/m^3	60 MW/m^3
	Lifetime	30,000 cycles	10,000 cycles	
	Air-gap Provision		Provided	
	Efficiency		99.50%	99.80%
	Interfaceable with	Generators, Converters and Batteries	Generator, Converter, Battery, Capacitor	
	Protection Capability		Bidirectional	
	False trips	5%	3-5%	

	Critical Metrics	Benchmarks	Development Targets
Cables	Style	Legacy MV Cabling	Advanced MV Cabling
	Packaging	Shock Harden	Shock Harden
	Bend Radius	8 times diameter	24 inches
	System Weight per meter	8.2-9.7 kg/m	3 kg/m
	Voltage	4160 VAC, 13.8 kVAC, 1 kV DC	4-15 kV AC or 6- 20 kV DC
	Gas flame circuit integrity @ 4-20 kV	3 hours	3+ hours
	Rated Current	400 A / cable	4000A
Controls	Ability to handle multiple types of energy storage	Existing MCS	TBD
	Ability to pass power bi-directionality and to enable multiple loads fed from same energy storage system		
	Ability to energy/power manage in DEPS to control pulse loading seen on electric system.		

10.0 Far-term (2036-2045) Requirements Analysis

Anticipating both required capabilities and available technologies in the far-term involves additional uncertainty, but certain trends have become evident that build upon the assessments performed for the near and mid-term. In the far-term, it is expected that additional systems requiring even more power will become available including directed energy weapons, higher powered large arrays, and modular payloads.

It is likely:

- That Navy platforms will have numerous high power and energy mission systems operating simultaneously
- That the Navy will introduce additional flexible and modular ships designed to accommodate multiple payload packages
- That naval power systems will be required to continue efforts in the following areas:
- System flexibility, adaptability, and modular upgradeability especially to accommodate improved energy storage
- System controls integration and system autonomy
- System volumetric and gravimetric density
- System simplification
- System cost reductions

It is also expected that commercial advances in energy storage and computing capability will continue and that these technological advances will result in ship systems and mission systems that will become more intelligent and autonomous. Robotics and unmanned systems are expected to be in widespread use in the far-term.

11.0 Far-term (2036-2045) Development Recommendations

The following supporting product and system developments will be required in the far-term:

- Build and test a Next Generation Integrated Power and Energy System. This system should be flexible, adaptable, intelligent and upgradeable. It should be a system that:
    - Eliminates centralized load centers/switchboards (inline circuit protection, converters, etc.)
    - Accommodates modular and upgradeable energy storage
    - Reduces electric distribution system weight
    - Provides autonomous reconfigurable power transmission paths
    - Provides adequate circuit protection
    - Leverages commercial developments in energy storage and computing capability
- Continue to develop and qualify advanced conductors to improve the efficiency of the NPES as well as reduce the size, weight, and cost of cabling in future ships. These technologies could include high or room temperature superconductivity, carbon nanotubes, and covetics.
- Build and test an appropriately sized fuel cell power generation system capable of using logistic fuels
    - The use of logistic fuels present in the Navy today is a critical requirement for widespread adoption of fuel cells as a prime mover on future Navy ships. This effort builds on the body of knowledge achieved by the Navy and industry thus far in powering fuel cells from marine diesel and other distillate fuels.
    - Innovation here could potentially lead to wider adoption of fuel cells aboard future Navy ships and even allow multiple, smaller point of use type prime movers.
- Continue to promote and incorporate investments in advanced power semiconductor devices
- Eliminate separate Ethernet cables
    - Combine Ethernet/control signals over power lines
    - Transmit Ethernet/control signals wirelessly
- Demonstrate at an appropriate scale any other technology advancement identified in Chapter 3.0 or pursued independently by industry with potential to meet ubiquitous requirements and mitigate ship integration challenges.

12.0 Conclusion

The primary purposes of the NPES TDR are to align electrical power system developments with warfighter needs and enable capability based budgeting. The NPES TDR is updated biennially, invites innovation and guides investment by DoD, government, industry, and academia to achieve synergistic advances in naval power and energy systems. Recommendations have been provided based on available information, engineering judgment, and projected requirements. Historically, the development timelines for major power system components, such as the gas turbine engine, and new types of power systems, such as the IPS, average around 15-18 years from beginning S&T to transitioning the technology to the fleet. Even smaller subsystems, such as the LHD 8 hybrid electric drive, can take nearly a decade to transition to the fleet. Meanwhile, during technology development, the Navy's long range shipbuilding strategy and the associated 30 year shipbuilding plan are constantly updated as predicted threats to our national security evolve. In the face of uncertainty created by these relative timelines, the NPES TDR proposes multiple recommendations to advance naval power and energy system technology in the near-term, mid-term, and far-term.

This roadmap incorporated a structured approach to predict future power and energy needs. Several fundamental assumptions are implicit in the recommendations for naval power and energy systems developments. In general, these assumptions are based on the fact that many future mission systems will require more energy and electrical power than today's systems. In order to incorporate these mission systems into existing Navy platforms, a back fit approach, such as EM, will be used to provide the necessary interface between new mission systems and the legacy ship power systems. For future ship designs, the Navy needs to develop an integrated approach to power and energy systems in order to achieve required performance in the mid-term and far-term.

A fundamental tenet of technology development and transition is to have the right technology, at the right time, and for the right task. Under this construct, the identified capability requirements represent the "right task" and the NPES TDR presents a plan to develop the "right technologies, at the right time" to support the Navy's long range shipbuilding strategy. This roadmap promotes communication and collaboration amongst the many stakeholders in this arena. It helps inform industry of the Navy's naval power and energy system investment priorities while also enabling the Navy to leverage industry investments.

Technological superiority is critical to maintaining the U.S. Navy's position as the world's premier naval force. This roadmap supports that technological superiority by providing focus on the Navy's planned path forward for naval power and energy systems to help guide investments and development efforts. It provides the Navy, other DoD organizations, industry, and academia a picture of the Navy's needs in the future to the extent that those needs can be forecast today.

List of Acronyms

AAW Anti Air Warfare
A/C Air Conditioning
AC Alternating Current
ACAT Acquisition Category
AEP3 Advanced Electric Power and Propulsion Systems Development Project
AIM Advanced Induction Motor
AMDR Air and Missile Defense Radar
AoA Analysis of Alternatives
ARPA-e Advanced Research Projects Agency-Energy
ASN RDA Assistant Secretary of the Navy for Research, Development and Acquisition
BMS Battery Management System
CBA Capabilities Based Assessment
CBM Condition Based Maintenance
CM Common Mode
CONOPS Concept of Operations
COTS Commercial Off The Shelf
D&I Discovery and Invention
DC Direct Current
DCS Distributed Control System
DEPS Directed Energy Power Systems
DEW Directed energy weapon
DFIA Depth Functional Implementation Architecture
DIACAP DoD Information Assurance Certification and Accreditation Process
DM Differential Mode
DoD Department of Defense
DoDD Department of Defense Directive
DoDI Department of Defense Instruction
DON Department of the Navy
EDM Engineering Development Model
EM Energy Magazine
EMC Electromagnetic Compatibility
EMI Electromagnetic Interference
ESG Executive Steering Group
ESM Energy Storage Module
ESR Equivalent Series Resistance
F Farad
FAT Factory Acceptance Test
FLTCYBERCOM Fleet Cyber Command
FNC Future Naval Capability
FSAD Full Scale Advanced Development
GaN Gallium Nitride
HCCI Homogenous Charge Compression Ignition

HES-C High Efficiency Small Capacity
HME Hull, Mechanical & Electrical
HMI Human Machine Interface
HSI Human System Interface
HVAC Heating Ventilation and Air Conditioning
HZ Hertz
I/O Input/Output
I^2R Current squared times resistance (equals power loss)
IATA Information Assurance Technical Authority
ICS Industrial Control Systems
IEEE Institute of Electrical and Electronics Engineers
IFTP Integrated Fight Through Power
IGBT Insulated-gate bipolar transistor
IPES Integrated Power and Energy System
IPS Integrated Power System
ISR Intelligence, Surveillance and Reconnaissance
IT Information Technology
IWS Integrated Warfare Systems
J Joule
kW Kilowatt
LBES Land Based Engineering Site
LNG Liquefied Natural Gas
LVAC Low Voltage Alternating Current
M&S Modeling & Simulation
MARPOL The International Convention for the Prevention of Pollution from Ships
MCM Thousand Circular Mils
MCS Machinery Control System
MOSFET Metal oxide semiconductor field effect transistor
MOTS Modified Off The Shelf
MVA Mega Volt Ampere
MVAC Medium Voltage Alternating Current
MVAR Mega Volt Ampere Reactive
MVDC Medium Voltage Direct Current
MVMF Medium Voltage Medium Frequency
MW Megawatt
NAVSEA Naval Sea Systems Command
NAVSURFWARCENDIV Naval Surface Warfare Center Division
NCDS Naval Combatant Design Specification
NFPA National Fire Protection Association
NGIPS Next Generation Integrated Power System
NIST National Institute of Standards and Technology
NOx Nitrogen oxides
NPES Naval Power and Energy System
NPS Naval Power System

NSTM Naval Ships' Technical Manuals
OEM Original Equipment Manufacturer
ONR Office of Naval Research
OPNAV Office of the Chief of Naval Operations
OSD Office of the Secretary of Defense
PCCI Pre-Mixed Charge Compression Ignition (PCCI)
PCM Power Conversion Module
PE Power Electronics
PID Proportional Integral Derivative
PLC Programmable Logic Controllers
PM Permanent Magnet
PMS Program Manager, Ship
PrEEs Pre-Engineered Elements
QoS Quality of Service
RCCI Reactivity Controller Compression Ignition (RCCI)
RFI Request for Information
RMF Risk Management Framework
RPM Revolutions per minute
RSAD Reduced Scaled Advanced Development
RWG Requirements Working Group
S&T Science and Technology
SCADA Supervisory Control and Data Acquisition
SEWIP Surface Electronic Warfare Improvement Program
SF_6 Sulfur Hexafluoride
Si Silicon
SiC Silicon Carbide
SID Ship Installation Drawing
SOx Sulfur oxide
SPAWAR Space and Naval Warfare Systems Command
SSL Solid State Laser
SWAP-C Space, Weight, Power and Cooling
SYSCOM System Command
TDR Technology Development Roadmap
TEWAC Totally enclosed water to air cooled
TFCA Task Force - Cyber Awakening
TRL Technology Readiness Level
TWG Technology Working Group
UNTL Universal Naval Task List
UPS Uninterruptible Power Supply
VAR Volt-Ampere Reactive
VCB Vacuum Circuit Breaker
VSD Variable Speed Drive
VVO Voltage and VAR Optimization
W Watt

Appendix A - Naval Power Systems Specifications and Standards

INTRODUCTION

Naval warships are increasingly becoming more electric. The electrification of the warship is driven by the need to support the electrical power demands of advanced weapons and combat systems as well as in the move towards electric propulsion to reduce fuel consumption and the move to electric auxiliaries to reduce total ownership costs. While historically, shipboard power systems have employed low voltage (450 volts ac) for power generation and distribution, higher power levels and the need for improved reliability (quality of service) and survivability have led to the introduction of medium voltage ac (MVAC), and medium voltage dc (MVDC) systems into the fleet. To reduce the weight and cost of distribution cabling, larger warships have incorporated zonal electric distribution systems (ZEDS) instead of the more traditional radial distribution systems.

These changes in power system technologies require an extensive updating of standards, specifications, handbooks, and guides that comprise the electric warship technical architecture. This appendix describes existing standards and specifications as well as ongoing and potential future projects to create or update standards and specifications to support future electric warship acquisitions. To organize the discussion, the technical architecture will be discussed in terms of the different electric system functions as defined for the IPS in the NGIPS Roadmap[99]:

- **System Design and Engineering** design and integrate power systems.
- **Power Generation** convert fuel to electric power.
- **Power Distribution** consist of switchgear and cabling necessary to distribute the power.
- **Power Conversion** convert power from one voltage /frequency to another.
- **Energy Storage** store energy provided by and provided to the electric power system.
- **Loads** use electric power.
- **Propulsion Motors and Drives** convert electric power into propulsion for the ship.
- **Power Control** consists of software necessary to operate the power system.

ELECTRIC WARSHIP TECHNICAL ARCHITECTURE

The electric warship technical architecture applies to electric power systems for naval ships from concept exploration through delivery of the ship.

Figure 1 shows the relationships of the various technical documents. At the lowest level are commercial and military standards that provide rules, test requirements, best practices, and interface requirements. These standards are usually invoked through commercial and military specifications which collect all the requirements from the commercial and military standards in addition to equipment requirements into a document that can, along with owner preferences, be directly employed to buy power system components or equipment. These specifications can either be performance specifications which describe the equipment in terms of the performance,

[99] Naval Sea Systems Command, "NGIPS Technology Development *Roadmap" NAVSEA Ser 05D / 349 of 30 Nov 2007.*

interfaces, and testing requirements, or detail specifications which specify the precise design for the equipment along with manufacturing methods and acceptance test procedures. The military standards and specifications should invoke commercial standards and specifications to the greatest extent practical. Military standards should only be used for military unique requirements, for those areas where no commercial standards exist, or for those areas where the Navy has deemed it beneficial to choose one or a few commercial standards to support where there are many commercial standards available. In some cases, a commercial specification may meet all naval requirements. In these cases, the Navy need only issue a letter of adoption of this commercial specification.

While the specifications are used to describe the requirements for procuring equipment, the processes for design and design verification are described in military handbooks and design data sheets. These military handbooks and design data sheets should use existing documented commercial processes when applicable to naval ships. The Naval Combatant Design Specification (NCDS) describe requirements at the total ship and the ship system level for non-nuclear naval surface warships. The NCDS relies upon the military handbooks, specifications and standards in addition to design data sheets. These documents are not ship specific, and those that are important to the design and construction of electrical power systems are part of the electric warship technical architecture. This technical architecture is applied to the requirements for a specific ship to produce a ship design. The ship design and its systems architecture are captured in the ship specification.

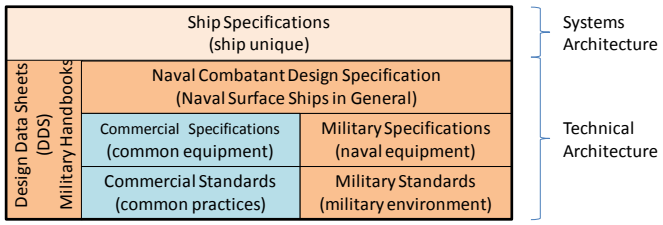

Figure 1. Technical Documentation Relationships

STANDARDS DEVELOPMENT

Figure 2 shows that specification and standard development should be an active consideration during the entire technology development process. In general, the specifications and standards should be viewed as one of the primary transition products. Additionally, it should be clear that complete specifications cannot be considered finished until a body of knowledge based on engineering and analysis is developed. The product of advanced technology development and its Advanced Development Model (ADM) should be a draft generalized specification or standard (either commercial or military). This draft should be validated / updated through the successful procurement and testing of an Engineering Development Model (EDM). This specification or standard is transitioned to an acquisition program as either a formal specification or standard, or as a Project Peculiar Document (PPD) developed for incorporation into the ship specification. Eventually, if repeated procurements are anticipated, a specification or standard (commercial if possible, otherwise military), leveraging commercial specifications and standards, should be created.

While Figure 2 shows how specification and standards development should be incorporated into technology development programs, the realization of this process in existing programs has been weak. Explicitly addressing specification and standards development in technology transition agreements could improve this process.

It is important to recognize that creating and maintaining specifications and standards has a real

cost. This cost is an investment to ensure procured systems meet military requirements, reduce the cost of producing ship specifications, improve the quality of specification by reflecting lessons learned, and reducing rework by continuous incorporation of lessons learned in the specifications. Specifications and standards also enable industry to produce product lines in anticipation of Navy needs. Over-reliance on PPDs force industry to operate reactively to the Navy needs expressed at the time of the ship's detail design contract and may preclude the ability to offer the most affordable solutions.

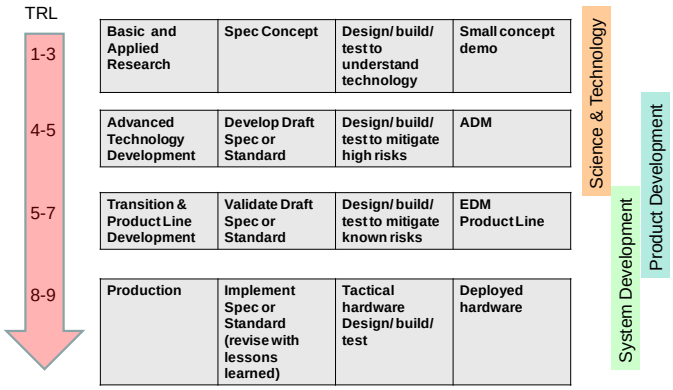

Figure 2. Technology Maturation and Product Development

Military Technical Standards

The NAVSEA technical standards procedures[100] provide the details for developing, revising, reviewing, approving, issuing, maintaining, canceling and adopting technical standards within NAVSEA. As managed by SEA 05S, the procedural steps for creating or revising a technical standard are:

a. Conduct market research. This may include conducting an industry day or issuing a request for information.

b. Determine whether a new standard, an update to an existing standard, or adoption of a non-government standard is warranted.

c. Initiate the project using a "Project Initiation Form" and a "Project Initiation Approval Request" (PIAR). In general the project initiation must be approved by the Technical Warrant Holder (TWH), the Deputy Warranting Officer (DWO), and the Standards Improvement Board (SIB).

d. If funding is required, additional steps are required to gain approval to expend funds to complete the project

e. The document is updated or created, and approved by the TWH. (Note: A best practice is to involve industry and interested government stakeholders in the process)

f. SEA05S reviews the document and makes any necessary formatting or editorial changes to comply with established document requirements.

g. Document is circulated for government and industry review. Comments are compiled into a tracking spreadsheet and adjudicated.

h. The final document is reviewed and approved by the SIB.

[100] Naval Sea Systems Command, "NAVSEA TECHNICAL STANDARDS PROCEDURES," 30 Aug 2006.

i. The final document is issued.

The Naval Sea Systems Command is currently reviewing and updating the many military specifications, standards, and handbooks under its responsibility. Where possible, the Navy employs commercial standards and specifications in an effort to reduce cost while maintaining military effectiveness. Military effectiveness in the varied environment that military systems must operate in must not be compromised.

Commercial Standards
A number of professional societies issue standards documents. For the electric warship, IEEE, IEC, NEMA, ASTM, SAE and API are likely to be the sources of most commercial standards used. The IEEE Standards Association manages the development of IEEE standards. Typical of commercial standards development, the process for creating / updating an IEEE standard as described in the IEEE-SA Standards Board Operations Manual [101] is:

a. A sponsor is identified and a Project Authorization Request (PAR) is developed then approved by the IEEE-SA Standards Board.

b. Conduct meetings to develop the document, ensuring the meetings are open to all interested parties.

c. A standard "ballot" is conducted as part of the final review of the document.

d. If the "ballot" is successful, IEEE publishes the document.

Incorporating the Electric Warship Technical Architecture into acquisition
The ship specification and the associated detail design and construction contract statement of work are the primary methods for incorporating the electric warship technical architecture into a ship acquisition program.

ONGOING STANDARDS AND SPECIFICATION EFFORTS

The following documents are currently being developed or updated. New revisions should be available within the next 2 years.

Specifications
MIL-DTL-XX653 Switchgear, Power, Shock-Mounted-Low Voltage, Naval Shipboard, in Government Industry Review

MIL-DTL-XX654 Arc Fault Protection System (AFPS)

MIL-DTL-XX655 Power Electronic Conversion Equipment, Naval Shipboard

MIL-DTL-17060, Motors, Alternating Current, Integral-Horsepower Shipboard Use, in Government Industry Review

MIL-DTL-17361, Circuit Breaker Types AQB, NQB, Air, Electric, Low Voltage, Insulated Housing (Shipboard Use), General Specification for: general update.

MIL-DTL-17587, Circuit Breakers, ACB, Low Voltage, Electric Power, Air, Removable Construction, General Specification for: general update.

MIL-DTL-17588, Breakers (Automatic -ALB-1) and Switch, Toggle (Circuit Breaker, Non-Automatic- NLB-1) Air, Insulated Housing, 125 Volts and Below A.C.: general update.

MIL-PRF-17773 Switches, Bus Transfer, Electric Power, Automatic and Manual

[101] *IEEE, "IEEE-SA Standards Board Operations Manual," December 2010.*

MIL-PRF-24640, Cables, Lightweight, Low Smoke, Electric, for Shipboard Use, General Specification for.

MIL-DTL-24643 Cables, Electric, Low Smoke Halogen-Free, for Shipboard Use, General Specification for.

MIL-DTL-24765, Power Supply, Uninterruptible, Static (Naval Shipboard): general update.

MIL-DTL-32483 Switchgear, Power, Hard-Mounted and Shock-Mounted, Medium Voltage, Naval Shipboard: General Update, in Government Industry Review

MIL-PRF-32272 Integrated Power Node Center (IPNC) general update.

Standards

The following 4 documents will eventually become chapters of a Design Criteria Manual

1. MIL-STD-3052, Design Criteria Standard for the Architecture of Machinery Control Systems: (Standard is complete, but not yet issued pending incorporation into the Design Criteria Manual)
2. MIL-STD-X647, Design Criteria Standard for Machinery Control System (MCS) and Ship Control System (SCS) Graphical User Interfaces: Initial Development
3. MIL-STD-X648, Standard Practice for Machinery Control System (MCS) and Ship Control System (SCS) Software Naming Conventions
4. MIL-STD-X649, Interface Standard for Machinery Control Systems (MCS) and Ship Control Systems (SCS)

MIL-STD-X659, Cybersecurity Requirements for Shipboard HM&E Control and Monitoring Equipment

MIL-STD-1399 section 300B amendment to include: high resistance grounding for 450 VAC Type 1 power, L-G voltage requirements, and power interruption requirements associated with QOS and survivability.

MIL-STD-1399 section 377 Electrical Controller Peer-to-Peer Security Interface Requirement

MIL-STD-1399 section 680 amendment to include: general update that will include those in section 300.

MIL-STD-2003 Electric Plant Installation Standard Methods for Surface Ships and Submarines

MIL-STD-2037, Procedure to Obtain Certification for Electric Motor Sealed Insulation Systems, being reviewed for cancelation. In Government-Industry Review

IEEE P45 Recommended Practices for Electrical Installations Shipboard: major update.

IEEE P45.1 Recommended Practice for Electrical Installations on Shipboard - Design: initial development.

IEEE P45.3 Recommended Practice for Shipboard Electrical Installations - Systems Engineering: Entering Balloting.

IEEE P1580.1 Recommended Practice for Marine Insulated Bus Pipe (IBP) for Use on Shipboard and Fixed or Floating Platforms: initial development.

NAVSEAINST 9304.1 Shipboard Electrical Cable and Cableway Inspection and Reporting Procedures: In Government-Industry Review

Handbooks and Design Data Sheets

NSTM Chapter 300, Electric Plant – General: revision.

NAVSEA T9300-AF-PRO-020 Design Practices and Criteria Manual for Electrical Systems is being updated to reflect new technologies. Manual will reference DDS or Handbooks and provide tailoring guidance for commercial and military specifications and standards.

RECOMMENDED FUTURE STANDARDS ACTIVITIES

In the future standards activities should generally center on maturing the MVAC and ZEDS architectures as well as incorporating total ownership cost reduction initiatives in existing specifications and standards. The MVAC and ZEDS architectures can leverage specific platform specifications and lessons learned, including: LHD 8, T-AKE 1, DDG 1000, and other ships. Wherever possible commercial specifications and standards should be invoked. In some cases it may be possible to adopt commercial specifications and standards without having to create an accompanying military specification or standard to provide military unique requirements.

Standards and specifications for MVDC applications require more development. Where reasonable, the requirements for MVDC applications should be folded into revisions of existing documents, minimizing the creation of new documents.

Commercial standards should be continuously evaluated for naval warship application.

System Design and Engineering
A new MIL-STD-1399 section for MVDC is needed. Recommend accomplishing as soon as funding is available

A new MIL-STD-1399 section for LVDC is needed. DDG1000 and DDG51 specification efforts should be leveraged. Recommend accomplishing as soon as funding is available

A new standard (either military or commercial) for MVDC protection systems needed. Recommend completing before the development of a specification for a MVDC FSAD, FSED, or shipboard system.

A new design data sheets for stability analysis and module criteria allocation for each architecture with large power conversion components. Recommend completing before the development of a specification for a MVDC FSAD, FSED, or shipboard system.

MIL-STD-2003A(SH) Electric Plant Installation Standard Methods for Surface Ships and Submarines requires updating to address MVDC. Recommend completing before the development of a specification for a MVDC FSED, or shipboard system.

Power Generation
MIL-R-2729D Military Specification: Regulator-Exciter Systems, Voltage, A.C. General, Naval Shipboard Use. General requires an update to ensure applicability to MVAC and MVDC systems. Alternately create a new specification that heavily leverages commercial standards. Recommend completing before the development of a specification for a MVDC FSAD, FSED, or shipboard system.

MIL-G-21296B Generator Set, Diesel Engine, Direct and Alternating Current (Naval Shipboard Use): Consider a general update including incorporation of electronic governors, and allowance for magnetic bearings. Cover requirements for MVAC and MVDC. Alternately create a new specification that heavily leverages commercial standards. Recommend completing before the development of a specification for a MVDC FSAD, FSED, or shipboard system.

MIL-G-22077C: Generator Sets, Gas Turbine, Direct and Alternating Current, Naval Shipboard Use: Consider an update to cover Gas Turbine Generator Sets above 3,500 kW. Cover requirements for MVAC and MVDC. Alternately create a new specification that heavily

leverages commercial standards. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend accomplishing the specification update within 2 years of the completion of R&D project.

MIL-M-24350B Monitors, Reverse Power and Power-Sensing, Electrical Power (Naval Shipboard Use): Review for possible update for MVAC and MVDC. Alternately create a new specification that heavily leverages commercial standards. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend accomplishing the specification update within 2 years of the completion of R&D project.

A new specification (either commercial or military) for fuel cell power generation needed. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend accomplishing the specification update within 2 years of the completion of R&D project.

A new standard (either commercial or military) for MVDC voltage regulation and power sharing is needed. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend accomplishing the specification update within 2 years of the completion of R&D project.

Energy Storage
A new performance specification (either commercial or military) for energy storage is needed. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend accomplishing the specification update within 2 years of the completion of R&D project.

Power Distribution
Update MIL-PRF-17773C Switches, Bus Transfer, Electric Power, Automatic and Manual to include functionality for a controllable bus transfer. Alternately create a new specification that heavily leverages commercial standards. Recommend accomplishing as soon as funding is available.

Update MIL-DTL-24643C Cables, Electric, Low Smoke Halogen-Free, for shipboard use, general specification for. Include medium voltage cables up to 20 kV and cables for propulsion motors with high harmonic currents. Recommend completing before the development of a specification for a MVDC FSAD, FSED, or shipboard system.

Consider developing insulated bus pipe specification. Leverage IEEE P1580.1 IEEE Recommended Practice for Marine Insulated Bus Pipe (IBP) for use on shipboard and fixed or floating platforms. Recommend accomplishing within two years after IEEE P1580.1 is issued.

Consider creating a new specification for medium voltage transformers, possibly extend MIL-T-15108C to include medium voltage applications. Recommend accomplishing as soon as funding is available.

Consider creating a new specification for three phase 450-120VAC and 120-120 VAC three phase transformers. Possibly extend MIL-T-15108C to include 3 phase applications. Recommend accomplishing as soon as funding is available

A new standard (either commercial or military) for MV shore power connections is needed. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend accomplishing the specification update within 2 years of the completion of R&D project.

Power Conversion
Revise MIL-PRF-32272 Integrated Power Node Center (IPNC) to include additional power

modules and improved efficiency of modules. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend accomplishing the specification update within 2 years of the completion of R&D project.

Develop a new performance specification for PCM-1A functionality. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend developing the specification within 2 years of the completion of R&D project.

Propulsion Motors and Drives
A new specification (either commercial or military) for propulsion motor and drives is needed. Likely will invoke IEEE Std 1566-2005, IEEE Standards for Performance of Adjustable Speed AC Drives Rated 375 kW and Larger. Recommend accomplishing as soon as funding is available.

A new specification (either commercial or military) for forward retractable propulsion units is needed. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend developing the specification within 2 years of the completion of R&D project.

A new specification (either commercial or military) for podded propulsion units is needed. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend developing the specification within 2 years of the completion of R&D project.

Power Control
New specifications for power control modules needed. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend developing the specification within 2 years of the completion of R&D project.

A new handbook for describing the architecture and integration method for power control is needed. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend developing the specification within 2 years of the completion of R&D project.

Other Technical Documents That Should Be Updated
While these standards are not part of the electric warship technical architecture, updating these standards is recommended to improve affordability and applicability to modern systems:

MIL-HDBK-217F Notice 2, Reliability Prediction of Electronic Equipment, of 28 Feb 1995: Consider including modern electronic and power devices. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend developing the specification within 2 years of the completion of R&D project.

MIL-STD-461F Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment of 10 Dec 2007: Consider updating to reflect what is affordably achievable for high power equipment – provide common criteria for relaxing rules for power system elements. These criteria can either be incorporated in MIL-STD-461F or contained in another document such as NCDS. Requires R&D funding at earliest opportunity to develop and transition technology. Recommend developing the specification within 2 years of the completion of R&D project.

MIL-E-24142B Enclosures for Electrical Fittings and Fixtures, General Specification for of 17 Dec 1990 should be updated to reflect acceptable COTS products. Recommend accomplishing as soon as funding is available.

EXISTING STANDARDS AND TECHNICAL DOCUMENTS

System Design and Engineering

Specifications

MIL-DTL-917F(SH) Detail Specification, Electric Power Equipment Basic Requirements for of 4 August 2014.

Standards

IEEE 1826-2012 IEEE Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems rated above 100kW.

MIL-STD-1399 section 300B Electrical Power, Alternating Current, 24 April 2008.

MIL-STD-1399 section 680 High Voltage Electric Power, Alternating Current of 24 April 2008.

MIL-STD-2003A(SH) Electric Plant Installation Standard Methods for Surface Ships and Submarines of 3 September 2009.

NAVSEAINST 9300.1A Shipboard Alternating Current Electric Power of 28 Sep 1988.

Handbooks and Design Data Sheets

DDS 200-1 rev 1 Calculation of Surface Ship Endurance Fuel Requirements of 4 October 2011.

DDS 200-2 Calculation of Surface Ship Annual Energy Usage, Annual Energy Cost, and Fully Burdened Cost of Energy dated 7 August 2012.

DDS 310-1 rev 1 Electric Power Load Analysis (EPLA) for Surface Ships dated 17 Sept 2012.

DDS 320-2 rev 1 Electrical system interface – voltage & current harmonic calculations of 24 September 2013.

NSTM Chapter 300, Electric Plant-General, January 24, 2012.

NAVSEA T9300-AF-PRO-020 NAVSEA Design Practices and Criteria Manual Electrical Systems for Surface Ships Chapter 300, December 31, 1992.

Power Generation

Specifications

MIL-R-2729D, Military Specification: Regulator-Exciter Systems, Voltage, A.C. General, Naval Shipboard Use of 28 JAN 1992.

MIL-G-3124E, Generator, Alternating Current, 60-Hertz (Naval Shipboard Use) of 1 April 2014.

MIL-G-21296B Generator Set, Diesel Engine, Direct and Alternating Current (Naval Shipboard Use) of 21 Mar 1994.

MIL-G-21410A Military Specification, Governing Systems, Speed & Load Sensing, Naval Shipboard Use of 23 December 1991.

MIL-G-22077C Generator Sets, Gas Turbine, Direct and Alternating Current, Naval Shipboard Use of 3 November 1993.

MIL-M-24350B NOTICE 2, Monitors, Reverse Power and Power-Sensing, Electrical Power (Naval Shipboard Use) of 11 February 2005.

Handbooks and Design Data Sheets

DDS 311-1 Frequency regulation of AC ship service electric power systems of 1 Dec 1970.

DDS 311-2 Voltage regulation of AC ship service electric power systems of 1 Oct 1972.

Energy Storage

Specifications

MIL-DTL-24765A Power Supply, Uninterruptible, Static (Naval Shipboard) of 26 April 2010.

Standards

DOD-STD-2134 Notice 1 - Storage Battery Arrangement for Minimum Stray Magnetic Field of 21 April 1989.

NAVSEAINST 9310.1B Naval Lithium Battery Safety Program, March 18, 2009.

Handbooks and Design Data Sheets

MIL-HDBK-2053 Requirements for Employing Standard Batteries of 18 January 1995.

Power Distribution

Specifications

MIL-DTL-915G - Cable, Electrical, for Shipboard Use, General Specification for, of 22 August 2002.

MIL-DTL-2212K, Contactors and Controllers, Electric Motor AC or DC and Associated Switching Devices, of 14 January 2014

MIL-T-15108C, Transformers, Power, Step Down, Single Phase, 60 Hertz, 1 Kilovoltampere Approximate Minimum Rating, Dry Type, Naval Shipboard, of 20 Nov 1975.

MIL-DTL-16036M - Switchgear, Power, Low Voltage, Naval Shipboard, of 7 March 2013.

MIL-DTL-17361G, Detail Specification: Circuit Breaker Types AQB/NQB, Air, Electric, Low Voltage, Insulated Housing (Shipboard Use), General Specification for, of 19 Sep 2006.

MIL-DTL-17587C, Circuit Breakers, ACB, Low Voltage, Electric Power, Air, Removable Construction, General Specification for, of 28 June 2007.

MIL-C-17588E Circuit Breakers (Automatic - ALB1) and Switch, Toggle (Circuit Breaker, non automatic NLB-1) Air, Insulated Housing, 125 volts & Below, AC & DC (Naval Shipboard Use) of 26 November 1985.

MIL-PRF-17773C(SH) Switches, Bus Transfer, Electric Power, Automatic and Manual, of 21 November 2006.

MIL-DTL-23928F, Panels, Electrical, Power Distribution and Manual Transfer, Circuit Breaker Type, of 26 June 2008.

MIL-C-24368B Connector Assemblies; Plugs and Receptacles, Electric Power Transfer, Shore to Ship and Ship to Ship, General Specification for of 25 March 1987.

MIL-DTL-24640C Supplement 1 - Cable, Light-Weight, Electric, for Shipboard Use, General Specification for, of 8 Nov 2011.

MIL-DTL-24643C SUP 1A Cables, Electric, Low Smoke Halogen-Free, for Shipboard use, General Specification for, of 13 Dec 2011.

MIL-DTL-24705B, Penetrators, Multiple Cable, for Electric Cables, General Specification for, of August 23, 2010.

MIL-PRF-32150B Static Automatic Bus Transfer Switch (SABT) on Surface and Submarine Naval Vessels, of 15 Jul 2013.

MIL-DTL-32483 Switchgear, Power, Hard-Mounted, Medium Voltage, Naval Shipboard, of 8 Nov 2013.

MIL-PRF-32484, Performance Specification: Protective Relays and Attachments, Medium Voltage Vacuum Circuit Breaker Applications, of 08-Nov-2013.

MIL-DTL-32485, Detail Specification: Circuit Breakers, Vacuum Type (VCB), Electric Power, Medium Voltage, Alternating Current, Draw-Out Removable Construction, Without Internal Overcurrent Protection of 8 Nov 2013

Standards

MIL-STD-1683B, Design Criteria, Connectors and Jacketed Cable, Electric, Selection Standard for Shipboard Use of 31 March 1989.

MS18299, Shipboard Power Demand Factors 450 Volt, 7 April 1972 (Note: This has been incorporated into DDS 310-1 rev 1)

Handbooks and Design Data Sheets

MIL-HDBK-299 - Cable Comparison Handbook, Data Pertaining to Electrical Shipboard Cable of 15 Oct 1991.

DDS 300-2 Fault current calculations and protective device coordinations for 60 and 400 Hz power systems supplied by rotating machinery of 28 June 1995.

DDS 314-1 Calculations of fault currents and coordination of protective devices for 400 Hz. Power systems supplied by solid state frequency changers of 21 June 1991.

Power Conversion

Specifications

MIL-T-15108C Transformers, Power, Step Down, Single Phase, 1 Kilovoltampere Approximate Minimum Rating, Dry Type, Naval Shipboard, of 3 Jul 1985.

MIL-PRF-32272 Integrated Power Node Center (IPNC) of 29 October 2007.

Loads

Specifications

MIL-DTL-2212J Contactors and Controllers, Electric Motor AC or DC, and Associated Switching Devices, of 22 Jan 2008.

MIL-DTL-16377J SUP 1 Fixtures, Lighting; and Associated Parts; Shipboard Use, General Specification for, of 30 June 2014.

MIL-DTL-17060G, Motors, Alternating Current, Integral-Horsepower Shipboard Use, of 8 Jan 2009.

MIL-PRF-32168 Variable Speed Drive System for Induction and Synchronous Machines of July 27, 2004.

Handbooks and Design Data Sheets

DDS 302-1 Motor and controller application requirements (AC and DC) dated 3 May 1979 with replacement pages 1 and 20 of 4 Feb 1987.

Power Control

Specifications

MIL-PRF-32006 - Programmable Controller, Naval Shipboard, of 29 June 2004.

Standards

IEEE 45.2-2011 IEEE Recommended Practice for Electrical Installations on Shipboard - Controls and Automation of 1 Dec 2011.

IEEE 1676-2010 Guide for Control Architecture for High Power Electronics (1 MW and Greater) used in Electric Power Transmission and Distribution System of 11 February 2011.

Note: Military standards and specifications listed in this document are available from the online ASSIST database located at https://quicksearch.dla.mil.

Copies of design data sheets are available (subject to distribution statements) from Commander, Naval Sea Systems Command, ATTN: SEA 05S, 1333 Isaac Hull Avenue, SE, Stop 5160, Washington Navy Yard DC 20376-5160, or by email at CommandStandards@navy.mil with the subject line "DDS request"

Appendix B – DoD TRL Definitions and Descriptions

Since its utilization by NASA in the late 1980's, the technology readiness level has become the standard by which the maturity of evolving technologies (materials, components, devices, etc.) prior to incorporating that technology into a system or subsystem. In 1999, the DoD began implementing the TRL as a metric to assess the maturity of a program's technologies before its system development begins. Once the technology / technologies are sufficiently proven, it / they can be incorporated into a system or subsystem. TRLs accurately capture this evolution via the nine-level scale in a manner that is almost universally applicable. The current DoD TRL definitions and descriptions follow in Appendix B.

TRL	Definition	Description
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment. (Functional product)
7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.

TRL	Definition	Description
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.